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Spatiotemporal Dynamics of Macrobenthic Communities and Environmental Factors in the Aquatic Vegetation Restoration Zone of Baimao Bay

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Abstract: Lake Taihu, China's third-largest freshwater lake, faces severe eutrophication challenges and therefore requires innovative ecological restoration strategies. This study systematically evaluates the ecological effects of aquatic vegetation restoration in Baimao Bay through comprehensive analysis of macrobenthic communities and environmental parameters, demonstrating significant water quality improvements including a 42.9% decrease in total phosphorus, a 69.4% decline in chl-a concentration, a 34.8% reduction in ammonium nitrogen, and a 81.2% increase in water transparency. Multivariate analysis revealed a fundamental ecological driver shift where post-restoration pH and transparency replaced nutrients as dominant factors, reducing total nitrogen/total phosphorus influence by 40–60%, while filter-feeding species (predominantly bivalves and gastropods) became the dominant macrobenthic biomass group (72.4%) with pollution-tolerant oligochaetes decreasing by 69.1% in abundance, alongside distinct spatial heterogeneity showing pH-regulated lakeshore communities (8.37 to 8.45), transparency-governed shallow-water communities ($H' = 1.35$), and a residual nutrient-influenced deep-water area, with a shallow-water area (<2.5 m) unexpectedly exhibiting 3.2 times higher biomass (222.51 g/m^2) than deep waters, highlighting vegetation-mediated habitat optimization. These findings advance restoration ecology theory by elucidating ecosystem transition mechanisms from nutrient-driven to light-regulated systems while providing a replicable technical framework for global shallow eutrophic lake restoration, establishing quantitative benchmarks including target transparency (>64 cm) and chlorophyll-a levels (<10 μg/L) for effective eutrophication reversal.

Keywords: aquatic plants; environmental factors; eutrophication; macrobenthic

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1. Introduction

Eutrophication refers to the excessive enrichment of water bodies with nutrients (such as nitrogen and phosphorus), leading to harmful algal blooms, oxygen depletion, and biodiversity loss [1]. This process can occur naturally but is often accelerated by human

activities including agricultural runoff, industrial discharges, and urbanization [2]. Studies show that during the 1980s–1990s, eutrophication in the Black Sea intensified significantly, with nitrogen loads increasing from 400 kt/year to 900 kt/year and phosphorus loads rising from 40 kt/year to 115 kt/year [3,4]. Eutrophication causes multiple environmental issues, including foul odors, frequent cyanobacterial blooms, and biodiversity decline [5]. In China, particularly, many lakes suffer severe eutrophication that compromises water quality and ecosystem health [6].

Lake Taihu, China's third-largest freshwater lake located in the southern Yangtze River Delta, serves as a critical drinking water source for major cities like Shanghai, Suzhou, Wuxi, and Huzhou, while supporting aquaculture, tourism, and transportation [7]. However, chronic overexploitation has made Taihu one of China's most severely eutrophic lakes, exhibiting marked water quality deterioration, frequent cyanobacterial blooms, progressive aquatic vegetation degradation, and widespread ecosystem damage [8]. These issues underscore eutrophication's significance in lake management and water resource protection, demanding urgent nutrient control and ecological restoration measures to mitigate aquatic ecosystem impacts.

Macrobenthos serve as pivotal biological components in aquatic ecosystems, fulfilling dual roles as ecological engineers and bioindicators [9]. As keystone fauna in lake ecosystems, they constitute critical links in aquatic food webs (providing essential food sources for fish and other organisms) while driving nutrient cycling and organic matter decomposition—processes that are vital to maintaining ecosystem functionality [10]. Due to their sensitivity to pollutant types and concentrations, macrobenthic organisms are widely employed as effective biomonitors; the presence/absence of specific taxa directly reflects ambient water-quality conditions [11,12]. Systematic ecological assessments can be established by quantifying their community structures (e.g., diversity indices, functional guild composition) [13,14]. Notably, macrobenthic community assembly and biodiversity are strongly regulated by key physicochemical parameters including pH, water temperature, transparency, and nitrogen/phosphorus levels [15,16]. Compared to aquatic plants, algae, and fish, macrobenthos exhibit superior sedentariness and stable life-history traits, making them ideal sentinel organisms for monitoring the health of specific aquatic ecosystems [17,18]. Existing studies have demonstrated that the effective restoration of aquatic plants greatly improves the water environment and significantly affects the distribution of macrobenthic communities [19].

According to the multiple steady-state theory of shallow lake ecosystems [20], during the treatment of eutrophic lakes, by imposing specific human influences on aquatic ecosystems, such as the introduction of fine aquatic grass varieties, the degree of eutrophication of aquatic ecosystems can be reduced, and aquatic vegetation in degraded water ecosystems can be restored [21]. Aquatic plants, with primary production and environmental and ecological functions, are essential to lake ecosystems. On the one hand, aquatic plants can reduce sediment resuspension, absorb dissolved nutrients from the water, reduce the nutrient salt load, and provide shelter for zooplankton that feed on phytoplankton [22]. On the other hand, aquatic plants can inhibit algae growth through the secretion of allelochemicals, thus improving the transparency of the water and the water quality [23]. Submerged macrophytes provide both food resources and refuge habitats for macrobenthic organisms, while their varying community compositions enhance spatial heterogeneity in macrobenthic microhabitats. Research has demonstrated that the presence of submerged macrophytes significantly increases species richness and population density of macrobenthic communities [24]. However, the understanding of whether aquatic vegetation restoration can alter the structure and diversity of macrobenthic communities in shallow lakes remains limited.

This study was conducted in the aquatic vegetation restoration zone of Baimao Bay in Meiliang Bay, Lake Taihu, systematically analyzing variations in macrobenthic community composition and their influencing factors. This study proposes three hypotheses: (1) Will aquatic vegetation restoration significantly improve water quality in Baimao Bay?, (2) Will the vegetation restoration project alter the composition of macrobenthic communities and modify their habitats?, and (3) Which environmental factors will emerge as key drivers restructuring macrobenthic communities? The findings not only reveal synergistic mechanisms between aquatic vegetation restoration and environmental factors on macrobenthic organisms, but also provide significant practical guidance for maintaining ecosystem health and biodiversity conservation in both Baimao Bay and Lake Taihu.

2. Materials and Methods

2.1. Study Area

Baimao Bay (31°26′21″ N, 120°12′28″ E) is located on the east coast of Meiliang Bay, belonging to the southeastern monsoon climate zone in the transition from northern subtropical to central subtropical. The average annual sunshine hours are 2000–2200 h, the average annual total solar radiation is 460–502 kJ/cm^2, the average annual temperature is 14.9–16.2 °C, the average annual frost-free period is about 222 days, the average annual relative humidity is 80%, the average annual evaporation from the water surface is 935 mm, and the evaporation from the land surface is 756 mm. The annual wind direction is dominated by the south-easterly wind, the easterly wind, and the northeasterly wind. The annual average wind speed is 4.2 m per second and the average water depth is 1.9 m. The engineering area is 433,383 square meters and the sediment depth is between 10 and 60 cm, with most of the area having a sediment depth of 10 to 20 cm, and the sediment is yellow clay. Higher aquatic plants are scarce in the bay, with only a few reeds, water peanuts, foxtail algae, etc., and the vegetation cover is only 3%. The water quality of the lake is the IV standard for surface water, indicating mild eutrophication. As a vital part of the Lake Taihu Basin, Baimao Bay provides essential ecological services—including fisheries, navigation, and flood control—to neighboring industrial cities like Changzhou and Wuxi, serving as an important pillar for regional economic development. The entire Lake Taihu Basin contributes approximately 10% to the regional Gross National Product (GNP), demonstrating its crucial position in the Yangtze River Delta economic zone [25].

This study is based on the preliminary ecological investigation of the topography, hydrological conditions, and project implementation in the sampling area. A total of 41 water quality sampling points, including 3 reference sampling points outside the project area, have been established according to the Technical Guidelines for Water Quality Sampling (HJ 494–2009) and Technical Guidelines for Sampling the Water Quality of Natural and Artificial Lakes (GB/T 14581-93) issued by the Ministry of Ecology and Environment. In addition, 19 macrobenthic macroinvertebrate monitoring points were set up in accordance with the Technical Guidelines for Biodiversity Monitoring—Freshwater Macrobenthic Macroinvertebrates (HJ 710.8-2014) issued by the Ministry of Ecology and Environment. An ecological buffer zone, fishing traps, and rubber fences were used to surround Baimao Bay to build a closed ecological space and create isolation from the external environment (Figure 1).

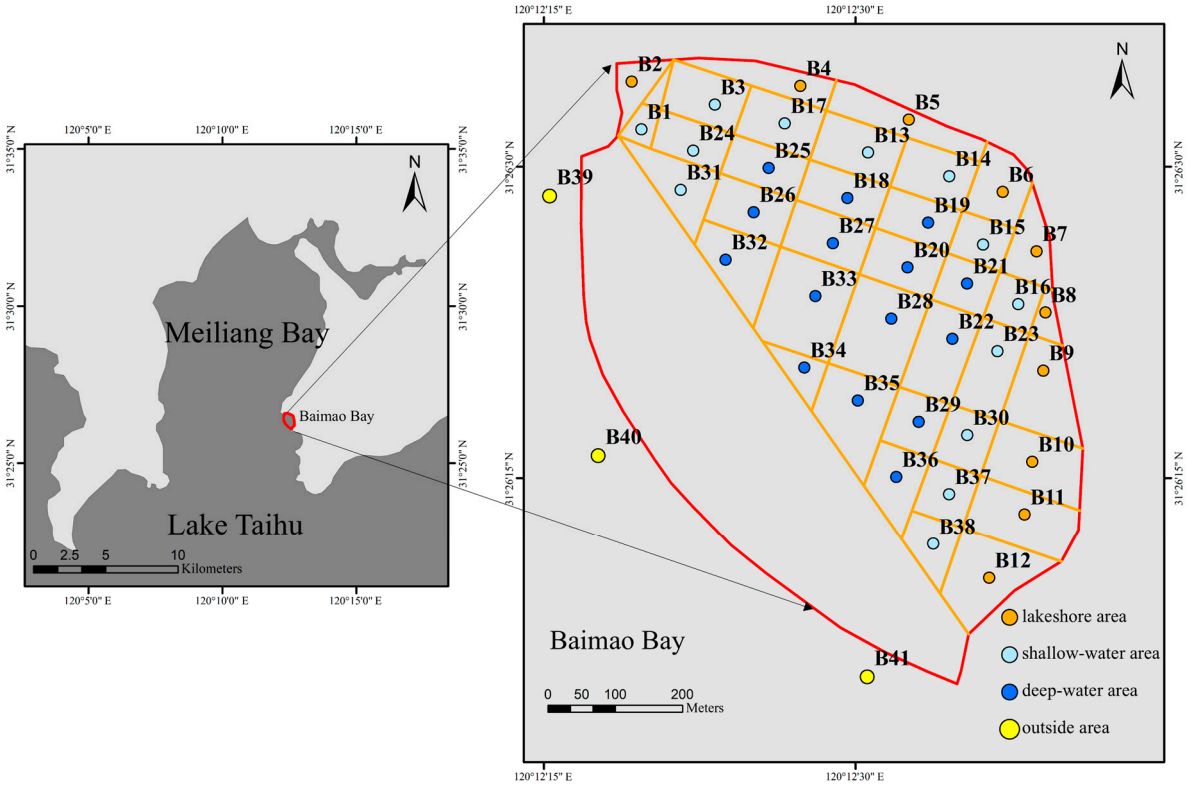


Figure 1. Display map of the Aquatic Plant Restoration Project area in Baimao Bay. (B1 represents the first sampling point in Baimao Bay).

The 41 sampling points are divided into four different areas according to water depth: lakeshore area (water depth < 0.5 m), shallow-water area (0.5 m < water depth < 1.5 m), deep-water area (1.5 m < water depth < 2.0 m), and outside area (water depth > 2.0 m) (Figure 1). Priority is given to aquatic plant species with strong environmental adaptability and pollution tolerance in the local Lake Taihu basin. In the way of seasonal rotation, *Vallisneria natans* was planted in the autumn of 2021; *Hydrilla verticillata* and water chestnuts were planted in the spring of 2022; and *Myriophyllum spicatum* and *Potamogeton malaianus* were planted in the summer of 2022.

2.2. Field Sampling and Index Determination

The species and coverage of plants were recorded on site. At each sample point, 1 × 1 m sample squares were laid out, the species and number of aquatic plants in the sample squares were recorded. The pH and Secchi disc depth (SD) were measured onsite by a portable pH meter (pH850) and Sayer's disc. At the same time, 500 mL water samples were collected from each point, and ammonium nitrogen (NH_4^+-N), total phosphorus (TP), total nitrogen (TN), permanganate index (COD_{Mn}), and chlorophyll-a (Chl-a) were analyzed according to national standard methods in China (GB 7480-87, GB 7479-87, GB 11893-89, GB 11894-89, and HJ 897-2017, respectively).

The routine monitoring period of macrobenthic animals was from June 2021 to March 2023, once every quarter in March, June, September, and December of each year. A modified Peterson mud sampler of 0.045 m^2 was used at each macrobenthic sampling point to collect macrobenthic samples. The mud samples were screened and washed through a 0.45 mm screen, and the macrobenthic animals were removed one by one in a white porcelain dish and stored in a 75% ethanol solution. In the laboratory, specimens were identified to the lowest possible taxon via anatomic mirrors and microscopes, according to the relevant literature [26].

2.3. Statistical Analysis

The statistical analysis of environmental factors in Baimao Bay was conducted using one-way analysis of variance (ANOVA) followed by Duncan's multiple comparisons test in R software (version 4.3.1). Prior to ANOVA, data normality was verified using Shapiro–Wilk tests ($p > 0.05$ for all variables) and homogeneity of variances was confirmed through Levene's tests ($p > 0.05$). For variables that did not meet parametric assumptions, appropriate data transformations (log-transformation) were applied before analysis. Principal component analysis (PCA) was used to evaluate and visualize changes in environmental factors after planting aquatic plants. Mantel tests and canonical correspondence analysis (CCA) were used to assess the relationships between environmental factors and the macrobenthic community. The multivariate analyses (PCA/CCA) were performed using the 'vegan' package (version 4.3.1) in R, with results visualized through 'ggplot2' for enhanced graphical representation. PAleontological STatistics (PAST, version 4.17) software was used to calculate the Margalef's species richness (d), Shannon–Wiener index (H'), and Pielou evenness index (J) by abundance [27].

3. Results

3.1. Environmental Characteristics

The results show the changes of environmental factors before and after planting of aquatic plants in the Baimao Bay project area and the effects of ecological restoration measures through multidimensional analysis (Figure 2). The principal component analysis (Figure 2A, PC1 = 58.17%, PC2 = 15.92%) showed that in the unplanted stage (before December 2021), due to the frequent occurrence of algal blooms in Baimao Bay, the environmental parameters in each area showed obvious spatial heterogeneity. The lakeshore and shallow-water areas showed strong positive correlations with SD and Chl-a. The deep-water and outside areas showed strong positive correlations with TN and TP. After planting aquatic plants in December 2021, the PCA results (Figure 2B, PC1 = 49.22%, PC2 = 26.74%) indicated increased synergistic effects of environmental factors. During the plant-growing season (June to September 2022), NH_4^+-N and COD_{Mn} decreased significantly by 34.8% and 6.3%, respectively, indicating a reduction in organic pollution loads. SD and Chl-a were significantly negatively correlated, indicating that the shading effect of submerged plants inhibited algal growth.

The ecological buffer zone and rubber fences have been effective in maintaining submerged plant colonization since construction of the project area was completed in December 2021. Vegetation cover peaked at 92% in September 2022. However, the sudden drop in cover during winter exposed the lack of hardy species and the need to introduce overwintering species to maintain continuity of ecological function (Figure 2C). Combining Table 1, it can be seen that the successful planting of aquatic plants increased SD, reduced water column nutrient concentrations, and re-established macrobenthic habitats.

Table 1. The changes in the physical and chemical properties of water within the project area of Baimao Bay.

	pH ***	SD ***	TN ***	TP ***	NH_4^+-N ***	COD_{Mn} ***	Chl-a ***
		cm	mg/L	mg/L	mg/L	mg/L	μg/L
Pre-planting	8.37 ± 0.44	35.68 ± 18.36	0.75 ± 0.22	0.07 ± 0.04	0.23 ± 0.12	5.24 ± 0.87	30.94 ± 20.01
After planting	8.45 ± 0.41	64.66 ± 21.77	0.96 ± 0.84	0.04 ± 0.02	0.15 ± 0.06	4.91 ± 0.79	9.48 ± 4.51

Note: SD = secchi disc depth; NH_4^+-N = ammonium nitrogen; TP = total phosphorus; TN = total nitrogen; COD_{Mn} = permanganate index; Chl-a = chlorophyll-a. the data results are presented in the form of mean value ± standard error. ***, $p < 0.01$.

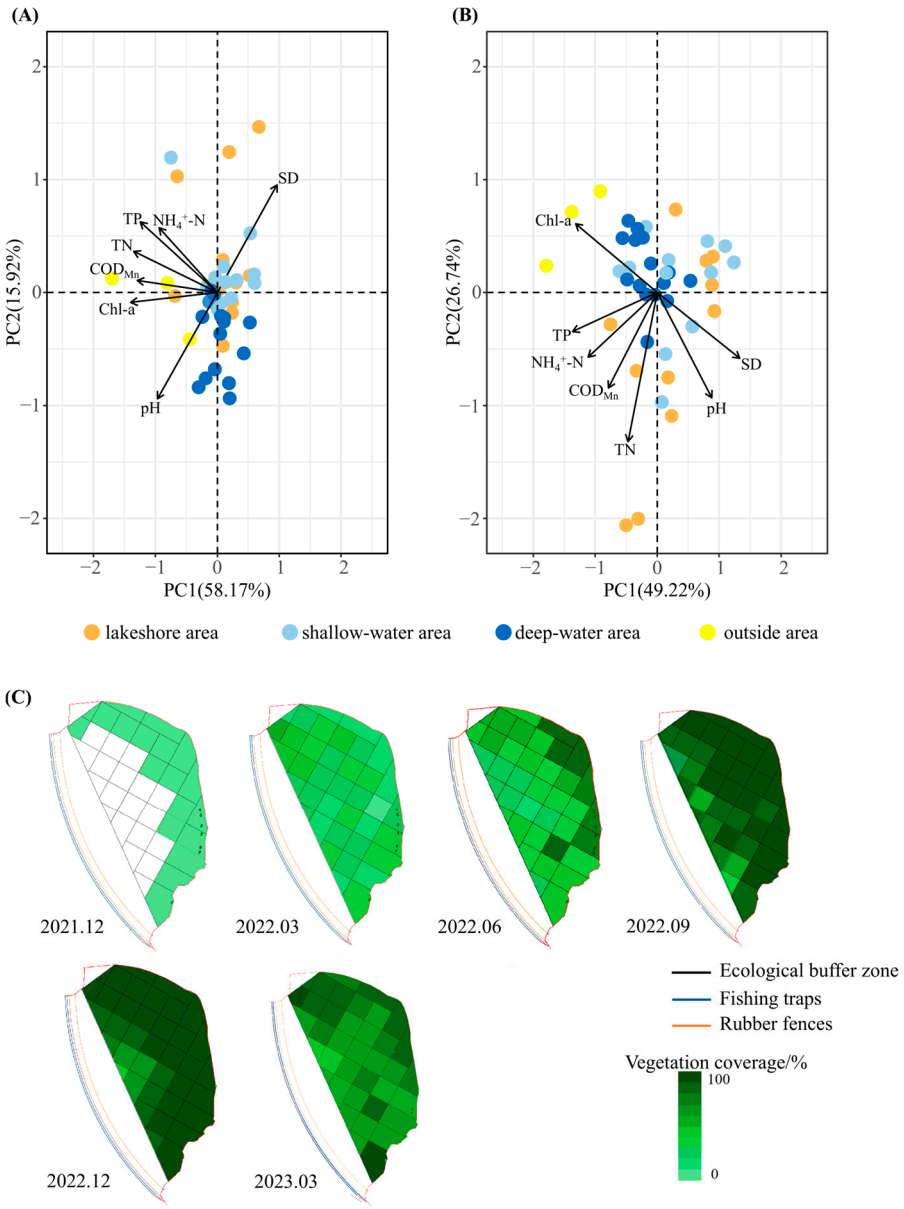


Figure 2. PCA of the environmental factors: (**A**) environmental characteristics before planting aquatic plants; (**B**) environmental characteristics after planting aquatic plants; (**C**) changes in aquatic plant cover. SD = secchi disc depth; NH_4^+-N = ammonium nitrogen; TP = total phosphorus; TN = total nitrogen; COD_{Mn} = permanganate index; Chl-a = chlorophyll-a.

3.2. Distribution of Macrobenthic Species

The results demonstrate significant restructuring of macrobenthic communities in Baimao Bay following aquatic vegetation restoration. After submerged macrophyte planting in December 2021, biomass increased substantially by 166.1%, indicating enhanced habitat provision for bivalve species, while abundance declined moderately by 10.0%, reflecting oligochaete sensitivity to improved water conditions. Diversity metrics showed contrasting trends: the Shannon–Wiener index increased slightly by 1.4%, whereas the Margalef index decreased by 12.8%, suggesting potential trade-offs between community stability and species richness during ecological recovery. These quantitative changes highlight the complex reorganization of benthic assemblages under vegetation-mediated habitat modification.

Through Figure 3, further analysis revealed distinct spatial differentiation patterns in macrobenthic community composition and functional group responses after aquatic

vegetation restoration in the Baimao Bay project area. Post-restoration, the biomass proportion of Bivalvia in the lakeshore area significantly increased from 18% to 52%. In contrast, Oligochaeta abundance declined sharply from 68% to 21%, reflecting their negative response to eutrophication mitigation. In the shallow-water area, the biomass proportion of Gastropoda surged from 9% to 41%. Concurrently, the Malacostraca biomass proportion rose by 17%, mainly due to substantial increases in Corophiidae populations. Collectively, the aquatic vegetation restoration drove a functional shift in macrobenthic communities toward filter-feeding–dominated assemblages through regulation of physical habitat structures and reallocation of food resources.

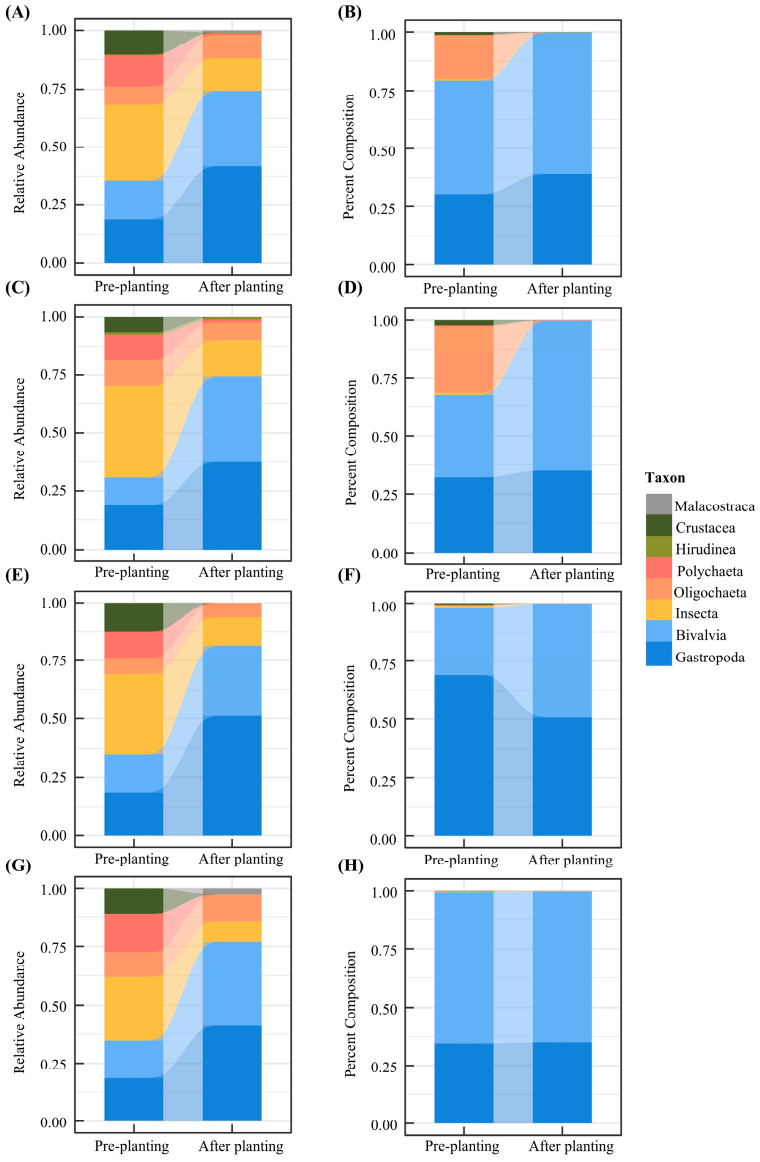
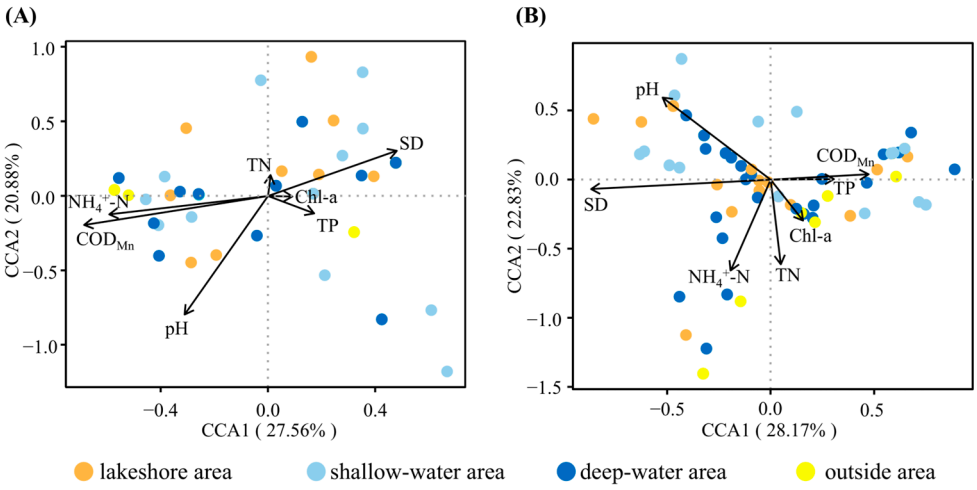


Figure 3. Trend of the macrobenthic community composition: (**A**) abundance of macrobenthic community in the lakeshore area; (**B**) biomass of macrobenthic community in the lakeshore area; (**C**) abundance of macrobenthic community in the shallow-water area; (**D**) biomass of macrobenthic community in the shallow-water area; (**E**) abundance of macrobenthic community in the deep-water area; (**F**) biomass of macrobenthic community in the deep-water area; (**G**) abundance of macrobenthic community in the entire region; (**H**) biomass of macrobenthic community in the entire region.

3.3. Correlation Analysis Between Benthos and Environmental Factors

Canonical correspondence analysis (CCA) revealed significant shifts in the relationships between macrobenthic communities and environmental factors before and after

aquatic vegetation planting in Baimao Bay. Pre-restoration studies demonstrated that macrobenthic communities were primarily driven by NH_4^+-N (r_2 = 0.264, p < 0.05) and COD_{Mn} (r_2 = 0.264, p < 0.05) (Figure 4A,C). Mantel tests confirmed these parameters significantly influenced community structure, particularly in the deep-water area. Following vegetation planting in December 2021, the dominant drivers shifted to pH (r_2 = 0.358, p < 0.001) and SD (r_2 = 0.412, p < 0.001) (Figure 4B,D). Macrobenthic community dynamics shifted from nutrient-driven (40–60% reduction in TN/TP impacts) to a system dominated by light environment (SD) and pH. Increased spatial heterogeneity revealed different zonal drivers: pH-dominated lakeshore area, SD-dominated shallow-water area, and nutrient-influenced deep-water area.



(C)

	r_2	*P-value*
pH	0.434	0.001***
SD	0.214	0.013**
TN	0.011	0.762
TP	0.031	0.509
NH_4^+-N	0.264	0.006**
COD_{Mn}	0.361	0.001***
Chl-a	0.006	0.88

(D)

	r_2	*P-value*
pH	0.358	0.001***
SD	0.412	0.001***
TN	0.223	0.002**
TP	0.050	0.142
NH_4^+-N	0.274	0.001***
COD_{Mn}	0.122	0.011**
Chl-a	0.065	0.075

Figure 4. CCA of environmental factors and benthos: (**A**) environmental factors associated with macrobenthic organisms before aquatic planting; (**B**) environmental factors associated with macrobenthic organisms after aquatic planting; (**C**) main driving environmental factors before aquatic planting; (**D**) main driving environmental factors after aquatic planting. SD = secchi disc depth; NH_4^+-N = ammonium nitrogen; TP = total phosphorus; TN = total nitrogen; COD_{Mn} = permanganate index; Chl-a = chlorophyll-a. **, 0.01 < p < 0.05; ***, p < 0.01.

Through integrated analysis of abundance and biomass, identification of the top 15 dominant macrobenthic species and elucidation of their environmental responses were achieved using multivariate statistics (Figure 5). Bivalvia (e.g., *Corbicula fluminea*) and Gastropoda (e.g., *Bellamya aeruginosa*) dominated (72.4% combined biomass), showing significant positive correlations with SD (r = 0.68, p < 0.01), indicating that submerged vegetation's shading effect improved habitat suitability by reducing suspended solids. Pollution-tolerant species like Oligochaeta (e.g., *Limnodrilus hoffmeisteri*) and *Chironomus plumosus* correlated positively with TN (r = 0.52, p < 0.01) and NH_4^+-N (r = 0.47, p < 0.01). Notably, *Grandidierella taihuensis* exhibited positive associations with pH (r = 0.61, p < 0.01)

and COD_{Mn} ($r = 0.34$, $p < 0.05$), suggesting its potential role in oxidizing organic matter in sediment interstitial water to alleviate anaerobic stress.

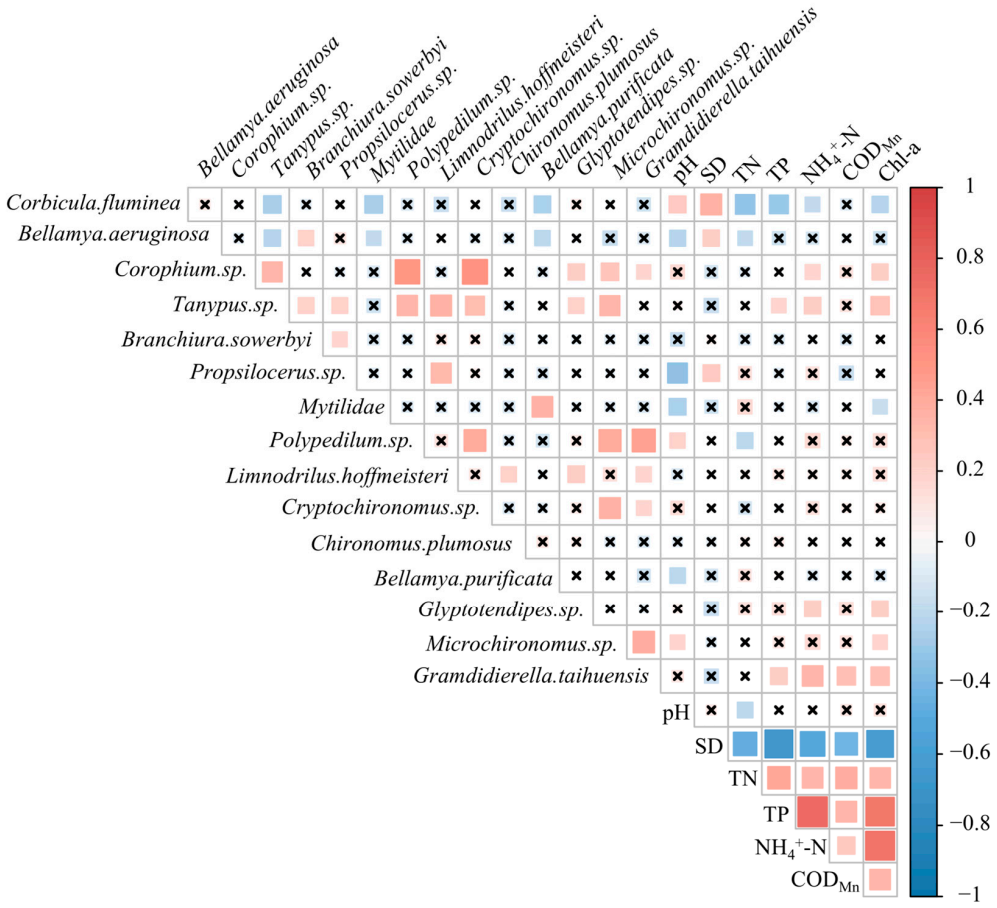


Figure 5. Heatmap of the correlations between environmental factors and TOP15 benthos. SD = secchi disc depth; NH_4^+-N = ammonium nitrogen; TP = total phosphorus; TN = total nitrogen; COD_{Mn} = permanganate index; Chl-a = chlorophyll-a. The "×" in the figure indicates no significant correlation or absence of a meaningful relationship between the corresponding variables.

4. Discussion

Macrobenthic communities serve as robust ecological indicators due to their sensitivity to physicochemical and biological perturbations [28]. This study elucidates the structural reorganization of macrobenthic communities in Baimao Bay following aquatic vegetation restoration, providing critical insights into ecosystem recovery mechanisms and adaptive lake management strategies [29].

4.1. Will Aquatic Vegetation Restoration Significantly Improve Water Quality in Baimao Bay?

Principal component analysis (PCA) and canonical correspondence analysis (CCA) identified pH, SD, TN, NH_4^+-N, and COD_{Mn} as primary drivers of macrobenthic community composition (Figure 4). Sany et al. [30] found that spatial factors play a major role in the structure of macrobenthic animal communities, which is consistent with our research. Post-restoration, the dominance of nutrient-driven factors (TN/TP) diminished by 40–60%, replaced by pH and SD as key regulators (Figure 4B,D). This shift reflects submerged macrophytes' dual role in stabilizing sediments and altering water chemistry [31]. Notably, SD increased by 81.2%, while Chl-a decreased by 69.4%, consistent with global observations of submerged vegetation suppressing algal growth via shading and nutrient competition [32–34]. In the Baimao Bay, submerged macrophytes have high coverage, good

plant growth, and significantly improve SD and the lake's water quality. The submerged macrophyte community can stabilize the basement, reduce sediment resuspension caused by hydraulic disturbance, and improve water transparency [35,36]. Seasonal planting strategies tailored to species-specific growth cycles further enhanced vegetation coverage (>90% in peak seasons), stabilizing sediment resuspension and improving water clarity [37].

4.2. Will the Vegetation Restoration Project Alter the Composition of Macrobenthic Commu-Nities and Modify Their Habitats?

This study found that the restoration of aquatic plants can cause changes in the structure of macrobenthic communities (Figures 3 and 5). Bivalva and Gastropoda collectively accounted for 72.4% of total biomass (Table 2), thriving in high-transparency habitats (SD > 60 cm, $p < 0.01$). Their proliferation is closely related to the role of underwater vegetation in stabilizing substrates and reducing turbidity [38]. Oligochaeta decreased by 69.1%, respectively, correlating with reduced TN and NH_4^+-N. This supports the hypothesis that nutrient mitigation disrupts eutrophication-adapted taxa [39–41]. Existing studies have demonstrated a negative correlation between oligochaete abundance and aquatic vegetation density, where more luxuriant plant growth corresponds to lower oligochaete abundance [42]. The well-rooted *Vallisneria natans* secretes root exudates into the substrate microenvironment, solubilizing phosphorus (P) and enhancing plant uptake of bioavailable phosphorus [43,44]. Furthermore, submerged macrophytes release organic acids into sediments, creating localized acidic conditions that may inhibit pollution-tolerant taxa such as oligochaetes [45]. However, vegetation-mediated oxygenation simultaneously improves sediment redox potential, favoring aerobic organisms like *Grandidierella taihuensis*, which exhibited strong positive associations with pH and COD_{Mn}, suggesting their role in oxidizing organic matter under stabilized conditions [46].

Table 2. The changes in macrobenthic communities within the project area of Baimao Bay.

	Abundance ***	**Biomass**	***d***	***H′***	***J*** ******
	(ind./m^2)	**(g/m^2)**			
Pre-planting	202.37 ± 197.60	83.61 ± 105.79	0.39 ± 0.32	0.74 ± 0.53	0.57 ± 0.21
After planting	182.26 ± 132.16	222.51 ± 177.46	0.34 ± 0.22	0.75 ± 042	0.68 ± 0.15

Note: d = Margalef's species richness; H' = Shannon–Wiener index; J = Pielou evenness index. The data results are presented in the form of mean value ± standard error. **, $0.01 < p < 0.05$; ***, $p < 0.01$.

4.3. Which Environmental Factors Will Emerge as Key Drivers Restructuring Macrobenthic Communities?

The spatial analysis revealed distinct ecological zonation across Baimao Bay, driven by habitat heterogeneity from aquatic vegetation restoration. In the lakeshore area, pH emerged as the dominant factor, favoring Gastropoda proliferation due to stabilized alkaline conditions [47,48]. The shallow-water area exhibited maximal biodiversity (H' = 1.35) and biomass (222.51 g/m^2), attributed to elevated water transparency (SD > 60 cm) that enhanced light availability and substrate stability. In contrast, the deep-water area retained residual nutrient effects (TN > 0.9 mg/L), yet macrobenthic biomass remained suppressed due to prolonged organic matter mineralization and limited food availability [49,50]. Notably, this spatial pattern deviated from classical depth-biomass paradigms [49], as shallow zones surpassed deep-water regions in both biomass and diversity—a divergence linked to vegetation-mediated habitat complexity. The Margalef index (d) declined with depth, underscoring light attenuation and substrate limitations in deeper regions, which constrained species colonization and resource accessibility. These findings highlight how submerged

macrophytes reshape macrobenthic zonation, prioritizing functional optimization over traditional depth-dependent productivity gradients.

5. Conclusions

This study demonstrates that the aquatic vegetation restoration project in Baimao Bay significantly improved water quality, with an 81.2% increase in transparency, a 69.4% reduction in Chl-a, and marked decreases in TP, NH_4^+-N, and TN. These improvements were driven by submerged macrophytes, primarily *Vallisneria natans* and *Myriophyllum spicatum*, which stabilized sediments, suppressed algal growth, and restructured nutrient cycling.

The macrobenthic community underwent substantial restructuring, with filter-feeding functional groups dominated by Bivalvia and Gastropoda accounting for 72.4% of total biomass, while Oligochaeta declined by 69.1% in abundance. Canonical correspondence analysis (CCA) revealed that post-restoration, pH, and water transparency replaced nutrients (TN/TP influence reduced by 40–60%) as the dominant drivers of community assembly, exhibiting spatial heterogeneity: the lakeshore area was regulated by pH, the shallow-water area by light availability, and the deep-water area retained residual nutrient effects. In conclusion, aquatic vegetation restoration in Baimao Bay successfully transitioned the ecosystem from nutrient-driven degradation to light-mediated resilience, offering a replicable model for eutrophic lake recovery.

These findings not only validate the efficacy of aquatic vegetation restoration but also fully confirm our three key hypotheses. However, several challenges emerged, including seasonal nutrient rebounds from plant decomposition, a winter vegetation coverage decline to 15% highlighting cold-tolerance limitations, and a 12.8% reduction in Margalef's species richness (d) suggesting habitat simplification. Future efforts should focus on developing year-round restoration strategies through cold-adapted species integration, long-term monitoring to assess ecosystem stability, and complementary bioindicator systems such as meiofauna to capture finer-scale ecological responses. These advancements would further refine the application of this model across diverse eutrophic freshwater systems.

Author Contributions: W.W.: conceptualization, visualization, writing—original draft. N.H.: visualization, writing—original draft. C.L.: conceptualization. C.Y.: visualization, writing—review and editing. K.M.: writing—review and editing. Y.W.: methodology. X.X.: visualization. Y.Z.: conceptualization. Y.Y.: project administration. L.L.: project administration. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

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