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1 **Macroinvertebrates and environmental responses to dredging and submerged**  
2 **macrophytes transplantation**

3 Hong Fu <sup>1,2,3</sup>, Jun Xu<sup>1\*</sup>, Jorge García Molinos <sup>4</sup>, Huan Zhang <sup>1</sup>, Huan Wang <sup>1</sup>, Min  
4 Zhang <sup>5\*</sup>, Megan Klaar <sup>2</sup>, Lee E. Brown<sup>2</sup>

5 <sup>1</sup> Donghu Experimental Station of Lake Ecosystems, State Key Laboratory of  
6 Freshwater Ecology and Biotechnology of China, Institute of Hydrobiology,  
7 Chinese Academy of Sciences, Wuhan, 430072, P. R. China

8 <sup>2</sup> School of Geography and water@leeds, University of Leeds, Leeds, West  
9 Yorkshire, United Kingdom

10 <sup>3</sup> University of Chinese Academy of Sciences, Beijing 100049, P. R. China

11 <sup>4</sup> Arctic Research Centre, Hokkaido University, Sapporo, Japan

12 <sup>5</sup> College of Fisheries, Huazhong Agricultural University, Hubei Provincial  
13 Engineering Laboratory for Pond Aquaculture, Freshwater Aquaculture  
14 Collaborative Innovation Centre of Hubei Province, Wuhan, P. R. China

15

16 \* Correspondence authors: Jun Xu (xujun@ihb.ac.cn, No.7 Donghu South Road, Institute  
17 of Hydrobiology, Chinese Academy of Sciences, Wuhan, 430072, P.R. China); Ming  
18 Zhang (zhm7875@mail.hzau.edu.cn).

19

20 **Abstract**

21 1 Eutrophication of freshwater ecosystems is a major global problem, but restoration  
22 can be difficult due to ongoing problems relating to water pollution, sedimentary  
23 nutrient stores, and altered aquatic biodiversity. Mitigation of water quality stressors  
24 is often conducted alongside transplantation of submerged macrophytes and  
25 dredging, but knowledge of ecosystem response to post-dredging transplantation of  
26 submerged macrophytes is limited.

27 2 Here, we report a long-term (2008-2018) in-situ monitoring study to evaluate the  
28 effects of two different restoration measures: dredging only (Dredged) and dredging  
29 with post-dredging transplantation of submerged macrophytes (Dredged with  
30 macrophytes) conducted in five subtropical eutrophic lakes in Lake Taihu basin,  
31 China. Water and sediment nutrients, bloom-forming algae *Microcystis*, and  
32 macroinvertebrate were monitored every two years for each treatment and compared  
33 with reference areas (Control) established in unrestored parts of the same lakes.

34 3 Dredging only decreased sediment nutrients (nitrogen, phosphorus, total carbon and  
35 water total phosphorus significantly, however, this effect diminished about five  
36 years later. Dredged with macrophytes had a stronger, longer-lasting positive effect  
37 on water quality than Dredged alone. Disturbance caused by dredging (without  
38 macrophytes transplantation) decreased the biomass of *Microcystis*, while  
39 transplantation of submerged macrophytes shortly after dredging did not contribute  
40 to the decreasing of *Microcystis* biomass. The biomass of *Microcystis* in Dredged  
41 with macrophytes areas was always similar with Control over the period of our  
42 monitoring.

43 4 A positive effect of submerged macrophytes transplantation post-dredging was  
44 found for macroinvertebrate abundance and diversity: Dredged with macrophytes

45 areas had significantly higher macroinvertebrate biomass and richness than Dredged  
46 areas after 9 years' recovery. Macroinvertebrate richness in Dredged with  
47 macrophytes areas nearly doubled compared to Control; while Dredged areas were  
48 just restored to Control levels.

49 5 Synthesis and applications. Our study provides an in-situ long-term field monitoring  
50 with new findings about the benefits and caution of submerged macrophytes  
51 transplantation post-dredging, and the effect of partial restoration, which could  
52 inform eutrophic waterbody restoration schemes.

53 **Keywords:** Biodiversity; Eutrophication; Partial restoration; Beta-diversity;  
54 *Microcystis*; Time-Series; Nutrients

## 55 **1 Introduction**

56 Dredging of deposited sediment is practiced around the world to enhance water  
57 conveyance and storage in flood prone areas and for commercial sand mining (Mohan et  
58 al., 2016). Dredging is also used for remediating nutrient pollution in shallow  
59 waterbodies (Riza et al., 2023); a practice that has become particularly popular in China  
60 (Liu et al., 2019). Previous studies have highlighted successful decreases of excess  
61 sediment N and P concentrations following dredging (Oldenborg and Steinman, 2019).  
62 However, where dredging is not complemented by reductions of external pollutant  
63 loadings, nutrients typically re-accumulate quickly in the lake sediment (Liu et al.  
64 (2016). Nonetheless, Li et al. (2021) reported that the internal P loading could be  
65 decreased successfully by transplanting submerged macrophytes in subtropical  
66 aquacultural lakes. This raises the possibility that restoration of eutrophic waters could  
67 be maintained and enhanced by the establishment of submerged macrophytes post-  
68 dredging.

69 Establishment of submerged macrophytes can provide essential and complex  
70 habitat for macroinvertebrates by offering protection from predators and a range of food  
71 sources (Wolters et al., 2019). A major impact of dredging is the profound alteration of  
72 benthic habitats and biodiversity. The colonization by macroinvertebrates of newly  
73 exposed surfaces after dredging typically takes months to several years depending on  
74 the type of organisms, local physical/chemical parameters, and metacommunity  
75 processes that influence dispersal (Wilber and Clarke, 2007). Whatley et al. (2014)  
76 noted that the decline of benthic invertebrate assemblages in eutrophic water was  
77 triggered by the deterioration in water quality and the loss of submerged macrophytes.  
78 In turn, benthic invertebrate assemblages can improve the physicochemical habitat

79 conditions of sediment-water interface through actions such as burrowing, playing  
80 central roles in nutrient cycling (Zhang et al., 2010), and linking benthic and pelagic  
81 food webs to support fishery production (Johannsson et al., 2000). Given many benthic  
82 macroinvertebrates are sediment-dwellers, they do not have the ability to escape from  
83 dredging and offer a good target group to assess the impacts and subsequent success of  
84 restoration (Zou et al., 2019).

85 Many studies demonstrated that aquatic submerged macrophytes have decreased  
86 rapidly worldwide because of eutrophication. In contrast, once their communities are  
87 established, submerged macrophytes improve water clarity and the stability of aquatic  
88 ecosystems via various buffer mechanisms (Bai et al., 2020). Therefore, aquatic  
89 macrophytes transplantation has been widely applied in the restoration of eutrophic  
90 waterbodies in China (Fang et al., 2016) and elsewhere (e.g., Hilt et al., 2006; Knopik  
91 and Newman, 2018) . Nevertheless, the type and extent of the benefits offered by  
92 submerged macrophytes transplantation post-dredging as opposed to dredging only  
93 remains unclear.

94 Here, we present a long-term (2008-2018) monitoring study of five eutrophic  
95 shallow lakes in the Taihu basin, China, to investigate (i) the effects of dredging on  
96 sediment and water chemistry, *Microcystis* (bloom-forming algae) and community  
97 structure of benthic macroinvertebrates; (ii) the effects of submerged macrophytes  
98 transplantation post-dredging as a potential restoration measure compared to dredging  
99 only. We hypothesized that (H<sub>i</sub>) dredging would decrease sediment and water nutrients  
100 by reducing internal loading after the removal of the nutrient-enriched sediment  
101 (Oldenborg and Steinman, 2019). We further expected that submerged macrophytes  
102 transplantation post-dredging would improve and consolidate these effects via the  
103 uptake and bioaccumulation of nutrients by the plants (Wang et al., 2021), and reduce

104 the risk of sediment resuspension (Zhu et al., 2015). We also expected that (H<sub>ii</sub>)  
105 dredging would reduce the biomass of *Microcystis* due to disturbance as reported by  
106 Wan et al. (2021), while the transplantation of submerged macrophytes is expected to  
107 further limit *Microcystis* via light and nutrient competition and allelopathic influences  
108 (Amorim and Moura, 2020). Finally, we anticipated (H<sub>iii</sub>) the transplantation of  
109 submerged macrophytes to accelerate the recovery of benthic macroinvertebrate  
110 communities impacted by dredging, due to the provision of improved habitats. The  
111 implications of our study could be considered in the management of eutrophic shallow  
112 lakes in subtropical regions.

## 113 **2 Material and methods**

### 114 **2.1 Study area**

115 The Taihu Basin (30°07′-32°15′ N, 119°02′-121°58′ E) has a watershed of 36,895  
116 km<sup>2</sup>, accommodating 4.4% of the country's population (59.20 million) and accounting  
117 for 10.4% of China's gross domestic product (5418.8 billion RMB) in 2012 (Wu et al.,  
118 2018). To quantify the effect of ecological restorations and determine if responses could  
119 be generalized in space and time, five lakes (Dongjiu, Xijiu, Gehu, Yangcheng,  
120 Shanghu) were monitored over a ten-year period (2008-2018) throughout the basin (Fig.  
121 1; Table 1). All lakes have been subject to the restoration of specific areas of the lake,  
122 which is a popular restoration practice in China. As a compromise solution between  
123 budgetary constraints and the improvement of water environment, some institutions opt  
124 to improve the aquatic environment as opposed to restoring the entire waterbody,  
125 especially for areas with public affluence such as proximity to parks or commercial  
126 public buildings.

## 127 **2.2 Field sampling and data collection**

128 An in-situ field monitoring study was used to assess the effect of partial  
129 restorations across the five lakes. Pre-dredging samples were collected in 2008 (August  
130 to October) before dredging took place in 2009 (January to February). The monitoring  
131 comprised three different areas (treatments) in each lake (Fig. 2): (1) a reference area  
132 comprising a non-dredged area without macrophyte cover located close to the dredged  
133 area (Control); (2) a Dredged area and (3) a dredged area with posterior transplantation  
134 of submerged macrophytes (Dredged with macrophytes). In each area, five sampling  
135 points were relatively evenly distributed. A buffer area of at least 300 m to avoid edge  
136 effects was maintained between each monitored area. Non-dredged areas with  
137 transplantation of submerged macrophytes were not available in our study, as this  
138 treatment was not implemented by the third parties (local institutions). Planting of  
139 submerged macrophytes without dredging was considered likely to fail due to the high  
140 probability that the accumulated eutrophic soft sediment on the lake beds, would lead to  
141 anchorage failure as submerged macrophytes tend to occupy relatively hard bottoms  
142 (Dong et al., 2017).

143 Dredged and Dredged with macrophytes areas were all subjected to suction  
144 dredging, with sediment removed to a depth of 0.5-0.8 m. Dredged with macrophytes  
145 areas had two native species of submerged macrophytes (*Vallisneria spiralis* and  
146 *Hydrilla verticillata* bought from local providers) transplanted one to two months after  
147 dredging with a density of 20-30 plants per m<sup>2</sup>. Macrophytes were placed in bay areas  
148 of the lakes where they were less exposed to wave influence. There was no separation  
149 (enclosures) between Control, Dredged and Dredged with macrophytes within lake due  
150 to landscape requirements and the expectation for the future spread of submerged  
151 macrophytes to other parts of the lakes over time. Post-dredging repeated field

152 monitoring was carried out every two years from 2010 to 2018, August to October. The  
153 specific size of each monitoring area in each lake is noted in Table 1. Although the  
154 percentage of Dredged and Dredged with macrophytes areas in each lake was small  
155 (0.8%-18.8%, 0.3%-6.3% respectively), dredging or transplantation of macrophytes is  
156 difficult over the entire area of large lakes, due to complex physiochemical or  
157 hydrological conditions (such as depth and turbidity of water) and financial costs (Paerl,  
158 2018).

159

#### 160 *Sediment and water chemistry*

161 Surface sediment was collected from each sampling point using a 1/16 m<sup>2</sup>  
162 modified Peterson grab (three grabs per point) and sieved in situ through a 250- $\mu$ m  
163 mesh. Sieved replicates at each sampling point were combined, ground with a pestle and  
164 mortar, passed through a 2 mm sieve, stored in bottles before laboratory analysis.  
165 Phosphorus fractions in the sediment samples were determined using the sequential  
166 extraction procedure. Exchangeable phosphorus (Ex-P), aluminum-bound phosphorus  
167 (Al-P), iron-bound phosphorus (Fe-P), occluded inorganic phosphorus (Oc-P), and  
168 calcium-bound phosphorus (Ca-P) were extracted sequentially using NH<sub>4</sub>Cl, NH<sub>4</sub>F,  
169 NaOH, Na<sub>2</sub>S<sub>2</sub>O<sub>4</sub>, H<sub>2</sub>SO<sub>4</sub> solutions, respectively (Zhang et al., 2022). TP was determined  
170 by treating the sediment sample at 450 °C, followed by HCl extraction. Total carbon  
171 (Carbon) and total nitrogen (TN) were analysed with a C/N elemental analyser (Flash  
172 EA 1112, Thermo Fisher Scientific, Waltham, MA, USA).

173 Water samples were collected at a depth of 0.5 m at each sampling point, stored  
174 in acid-cleaned bottles (200 mL). TN, nitrate nitrogen (NO<sub>3</sub>-N), ammonia nitrogen  
175 (NH<sub>4</sub><sup>+</sup>-N), orthophosphate (PO<sub>4</sub>-P) and TP were then measured using an ultraviolet  
176 spectrophotometer (PhotoLab S12, WTW Company, Munich, Germany). NO<sub>3</sub>-N and

177  $\text{NH}_4^+$ -N were determined from samples filtered by 0.45  $\mu\text{m}$  Whatman GF/F filters  
178 (Whatman, Kent, Great Britain). Chemical oxygen demand (COD<sub>Cr</sub>) was determined  
179 with the potassium dichromate method. All storage and chemical analysis were  
180 performed following national standard analytical methods for water and wastewater  
181 (National Environmental Protection Bureau, 2002).

182

### 183 *Microcystis*

184 To determine the biomass and density of *Microcystis* sp., 1 L of surface water was  
185 collected using a polymethyl methacrylate sampler at each sampling point and fixed  
186 with Lugol's iodine solution (1% final concentration), then concentrated to 50 mL  
187 (Huang et al., 1999). *Microcystis* cell numbers were counted from colonies and single  
188 cells using an inverted microscope (Olympus SZ-40, Olympus Corporation, Tokyo,  
189 Japan). *Microcystis* biomass (mg fresh weight/L) was estimated from its geometric cell  
190 volume, assuming a mean density of 1 mg/mm (Zhang et al., 2007). Cells of colonial  
191 *Microcystis* were separated using an ultrasonic device (JY88-II, Scientiz, Ningbo,  
192 Zhejiang, China) before enumeration.

193

### 194 *Benthic macroinvertebrate*

195 Benthic macroinvertebrates were sampled from the material retained on the  
196 sieve of the three Peterson grab samples collected per sampling point for the sediment  
197 sampling. The samples were preserved with 7% formalin solution and stored in a cool  
198 box for sorting and identification in the laboratory. Specimens were identified to the  
199 lowest feasible taxonomic level under a dissection microscope (Olympus® SZX10)  
200 using taxonomic keys (Morse et al., 1994; Wang, 2002). Macroinvertebrate biomass  
201 (wet mass) was then expressed by reference to the sediment area sampled ( $\text{mg}/\text{m}^2$ ).

### 202 **2.3 Data analysis**

203 Principal component analysis (PCA) was applied separately to sediment (Carbon,  
204 TP, TN, Oc-P, Ca-P, Fe-P, Ex-P, Al-P) and water (TN, TP,  $\text{NH}_4^+\text{-N}$ ,  $\text{COD}_{\text{Cr}}$ ,  
205 *Microcystis*) variables. Spearman Rank correlation analysis was performed to calculate  
206 the correlation coefficients which were detected by PCA. Sediment TP and Carbon,  
207 water TP and TN were selected accordingly to reduce multicollinearity and based on  
208 their contributions to the first two Principal Components (Figs 2 and S1). *Microcystis*  
209 biomass was also selected due to the importance of Cyanobacteria blooms in the Taihu  
210 basin. Taxonomic richness and Shannon-Wiener index were calculated as representative  
211 indices to describe the variation of macroinvertebrate community.

212 The response of sediment and water nutrients, *Microcystis*, and macroinvertebrate  
213 community indices in the three areas across time were assessed by fitting generalized  
214 linear mixed models (GLMMs): with a Gamma distribution (log link) for sediment TP  
215 and Carbon, water TP and TN. Similarly, GLMMs were developed for  
216 macroinvertebrate biomass (Gaussian distribution with log link), richness (negative  
217 binomial distribution, Poisson family, log link), and *Microcystis* biomass (Gaussian  
218 family, log link). Shannon diversity of macroinvertebrates was not analysed further as it  
219 was significant positively correlated with richness. Time (continuous) and treatment  
220 (categorical) were included as fixed effects, and “LakeID/Treatment” was considered as  
221 a nested random effect for all models to account for replication within the same  
222 monitoring area. Interaction effects between time and treatment were included in all  
223 models. For the *Microcystis* biomass model, water TP, TN and sediment carbon were  
224 also added as fixed effects. *Microcystis* biomass were added 1 to deal with zero values  
225 before  $\log_{10}$  transformation, and macroinvertebrate biomass were square root  
226 transformed + 1, to constrain the influence of extreme values. Time was introduced as a

227 quadratic term to account for non-linear responses to treatments over time. For each  
228 model, the most parsimonious model was selected based on Akaike's Information  
229 Criterion (AIC) scores (< 2 AIC units). For example, we had added “time \* treatment \*  
230 lake ID” as fixed term into all the models, while lake ID was deleted from the fixed  
231 term finally because no significant difference were detected, Model residuals were  
232 tested for compliance with model assumptions (Crawley, 2002).

233         Macroinvertebrate community structure in 2018 was further investigated to  
234 determine the long-term influence of the restoration treatments relative to Control.  
235 Variations of benthic macroinvertebrate community structure among treatments were  
236 visualized using non-metric multidimensional scaling (NMDS) based on the Bray–  
237 Curtis distance of Hellinger transformed density. Macroinvertebrate communities were  
238 then examined via the permutational homogeneity of dispersion (PERMDISP2) test for  
239 the analysis of multivariate homogeneity of group dispersions (variances); a  
240 multivariate analogue of Levene's test for homogeneity of variances (Anderson, 2006).  
241 Permutational multivariate analysis of variance (PERMANOVA) and analysis of  
242 similarities (ANOSIM) were then performed for pair-wise comparisons of  
243 macroinvertebrate communities among treatments. Similarity percentage (SIMPER)  
244 analysis was used to identify which taxa contributed the most to the average Bray-Curtis  
245 dissimilarity between the groups detected by ANOSIM and SIMPER. Indicator species  
246 of the three treatments were determined via multi-level pattern analysis (De Cáceres et  
247 al., 2010) to look at the association between species patterns and treatment across lakes.

248         Finally, beta diversity (BD<sub>total</sub>) of macroinvertebrates between treatments over  
249 time and among lakes was calculated and decomposed into species richness difference  
250 (RichDif) and species replacement (Repl), using the Podani family decomposition  
251 (Legendre, 2014) with presence-absence data (BD<sub>total</sub> = RichDif + Repl).

252 All data analysis and figures were completed using relevant functions from  
253 packages ‘vegan’ (Dixon, 2003), ‘indicpecies’ (De Cáceres et al., 2010), and  
254 ‘adespatial’ (Dray et al., 2017) in R v 4.0.1 (R Core Team 2020, [https://www.R-  
255 project.org/](https://www.R-project.org/)). Temporal trends of beta diversity partitions for each treatment and lake  
256 were examined with the ‘ggplot2’ package (Wickham et al., 2016) using a loess  
257 smoother.

## 258 **3 Results**

### 259 **3.1 Sediment and water chemistry**

260 The PCA biplot (Fig. 3) and Spearman rank correlation analysis showed weak but  
261 significant positive correlation between sediment TP and Al-P ( $\rho = 0.39, p < 0.001$ ). In  
262 contrast, sediment Carbon showed a much stronger positive correlation with TN ( $\rho =$   
263  $0.77, p < 0.001$ ). Furthermore, water TP was positively correlated with *Microcystis* cell  
264 density and biomass ( $\rho = 0.52, p < 0.001$ ).

265 According to the results of GLMMs, both Dredged and Dredged with macrophytes  
266 were efficient at the initial reduction of sediment nutrients (Fig. 4a-b, Fig. S2, Table  
267 S2). Specifically, for Dredged areas, the concentrations of sediment TP and Carbon  
268 showed an initial period of rapid decline (2009-2012), then levelled off or even slightly  
269 increased during 2012-2018. Compared to Dredged areas, Dredged with macrophytes  
270 areas had similar trends (decreased first then increased slowly) over time, however  
271 Dredged with macrophytes areas tended to accumulated more nutrients in sediment,  
272 particularly Carbon. While for Control, the concentrations of Carbon decreased over the  
273 entire monitored period, TP initially increased then decreased after 2012 with an  
274 opposite pattern compared to Dredged or Dredged with macrophytes areas (Fig. 4a-b).

275           Although Dredged with macrophytes areas had significantly higher water TP  
276 concentrations than Dredged areas during the first few years after dredging and  
277 transplantation of macrophytes, Dredged with macrophytes areas showed lower water  
278 TP concentrations ( $0.04\pm 0.03$  mg/L) than Dredged areas ( $0.05\pm 0.04$  mg/L) in 2018,  
279 while water TP concentrations were  $0.05 \pm 0.07$  pre-dredging for both Dredged and  
280 Dredged with macrophytes areas. Water TP concentrations of Dredged with  
281 macrophytes and Dredged areas therefore followed opposite trajectories over time,  
282 whereby Dredged with macrophytes areas initially increased then decreased, while  
283 Dredged areas first decreased then increased (Fig. 4c). Interestingly, in contrast to the  
284 overall trend of other nutrients, water TN concentrations increased over time for all  
285 treatments. Control areas continued to have lower TN values than the two dredged  
286 treatments (Dredged and Dredged with macrophytes) (Fig. 4d).

### 287 **3.2 *Microcystis***

288           Spearman rank correlation analysis showed strong and significant positive  
289 correlation between *Microcystis* cell density and *Microcystis* biomass ( $\rho = 0.89$ ,  $p <$   
290  $0.001$ , respectively). The biomass of *Microcystis* decreased consistently over the  
291 duration of the monitored period in areas subjected to dredging only (Fig. 5a, Table S2,  
292 Fig. S3). This effect was not observed in Dredged with macrophytes areas, where the  
293 biomass of *Microcystis* was significantly higher than Dredged areas and did not show  
294 significant difference compared to Control areas over the period of our monitoring (Fig.  
295 5a).

296

### 297 **3.3 Benthic macroinvertebrates**

298 The biomass and richness of macroinvertebrates decreased quickly after dredging  
299 (2009), particularly in areas which did not receive post-dredging transplantation of  
300 macrophytes (Dredged areas), but then started to increase after about 2014 for both  
301 Dredged and Dredged with macrophytes treatments (Fig. 5b-c, Table S2). Compared to  
302 Control, Dredged areas attained similar biomass and richness by the end of the  
303 monitoring (restored to pre-dredged community levels), while these indices were much  
304 higher than Control at Dredged with macrophytes; in particular, the richness indices  
305 almost doubled (Fig. 5b-c).

306 Macroinvertebrate community composition in 2018 showed clear differences  
307 between Dredged with macrophytes and Dredged, as well as Dredged with macrophytes  
308 and Control in the NMDS biplot (Fig. 6). These significant differences were confirmed  
309 by the results from ANOSIM and PERMANOVA (Table S3). No significant difference  
310 was detected between Dredged with macrophytes and Control. However, the  $p$  value of  
311 SIMPER results for the eight species contributing most to overall variation between  
312 Dredged and Dredged with macrophytes, Dredged with macrophytes and Control  
313 (cumulative contribution >60%), were  $> 0.05$  (Table S4). Multi-level pattern analysis  
314 revealed three chironomids (*Microchironomus tabarui*, *Clinotanypus* sp.,  
315 *Glyptotendipes* sp.) and one mussel (*Unio douglasiae*) to be associated strongly with  
316 Dredged with macrophytes in 2018 ( $p < 0.05$ ). Additionally, the mussel *Anodonta*  
317 *woodiana* was associated strongly with both Dredged and Dredged with macrophytes ( $p$   
318  $< 0.05$ ). Macroinvertebrate community variation of Dredged areas was significantly  
319 higher than Dredged with macrophytes areas in 2018 (Fig. S4 a). Similarly, Dredged  
320 with macrophytes areas showed significantly higher Shannon diversity and species

321 richness, while no considerable difference between Dredged and Control was detected  
322 (Fig. S4 b-c).

323 The higher beta diversity between Dredged and Dredged with macrophytes after  
324 2014 in Lake Dongjiu and Lake Xijiu was mainly due to the higher species richness  
325 difference. Total beta diversity between Dredged and Control was similar over time, but  
326 with different variations of species replacement and richness differences among lakes.  
327 For example, species replacement of Lake Gehu and Lake Yangcheng increased and  
328 then decreased after 2014, while the other three lakes decreased first and then generally  
329 increased since 2012. This phenomenon was not obvious between Dredged with  
330 macrophytes and Control. (Fig. 7)

## 331 **4 Discussion**

### 332 **4.1 Sediment and water chemistry**

333 Our long-term (2008-2018) in-situ field investigation confirmed that both Dredged  
334 and Dredged with macrophytes were efficient in decreasing of sediment nutrients  
335 (nitrogen, phosphorus, carbon) immediately after dredging, while areas Dredged with  
336 macrophytes tended to retain more nutrients in the sediment. However, the decreasing  
337 trend was lost after approximately five years post-dredging, becoming similar to  
338 Control by 2018. This indicates that, to have a long-lasting effect, dredging as a  
339 restoration tool should be applied every few years unless sources of pollution to  
340 freshwaters are also reduced. Liu et al. (2016) reported that environmental dredging  
341 reduced internal nitrogen and phosphorus loading for no more than three years if  
342 external pollution sources were not decreased. Clearly, external nutrient loadings were  
343 not eliminated within the Lake Taihu basin, although some restoration projects focusing  
344 on external nutrient reductions, such as sewage treatment inputs and the planting of

345 riparian buffer strips, were performed during the study period (Fu et al., 2021). This  
346 could have contributed to the decreasing trend of sediment TP and Carbon observed in  
347 Control , not just for Dredged and Dredged with macrophytes. On the other hand,  
348 Dredged with macrophytes improved water quality more than dredging only in the long  
349 run, especially for water TP. Even though water TP concentrations of Dredged with  
350 macrophytes and Dredged followed opposite trajectories over time. These findings are  
351 largely supported by Bai et al. (2020), who concluded that submerged macrophyte  
352 communities can govern water nutrients (TN,  $\text{NH}_4^+\text{-N}$ , TP), but enhance nutrient  
353 concentrations (TN, TP, organic matter) in sediment by decomposition.

354 Unlike previous studies (Bai et al., 2020), in our monitoring study, both Dredged  
355 and Dredged with macrophytes did not improve water TN. Compared to Control,  
356 Dredged and Dredged with macrophytes areas were exposed to more anthropogenic  
357 disturbances by being located close to a park or commercial public buildings.  
358 Additional reasons for this phenomenon could be that Dredged and Dredged with  
359 macrophytes areas were too small in each lake to modify the water quality at the lake  
360 level. In particular, surface runoff after rainfall events on August and September in the  
361 Taihu basin often carry high TN concentrations (ranging from 1.2 - 2.83 mg/L) from  
362 diffuse pollution sources (Li et al., 2017). This in line with the finding that even though  
363 the water quality at in the Taihu basin has, in general, improved over the last decade,  
364 water TN concentrations still exceed 2 mg/L (Qin et al., 2019).

#### 365 **4.2 *Microcystis***

366 Transplantation of submerged macrophytes immediately after dredging (one to two  
367 months) did not decrease *Microcystis* biomass. This contrasts with previous studies  
368 which demonstrated that restored submerged macrophytes could inhibit phytoplankton  
369 growth and decrease the risk of algal blooms (Zeng et al., 2017). Specifically, in our

370 study, *Microcystis* biomass in Dredged with macrophytes areas showed no difference to  
371 Control by the end of our monitoring (2010-2018). Biomass of *Microcystis* showed  
372 strong positive relationships with TP concentrations of water in our study, which is  
373 consistent with the findings in Lake Taihu from 2005 to 2014 by Su et al. (2015),  
374 suggesting phosphorus limitation of *Microcystis* growth. Even though Dredged with  
375 macrophytes areas showed a tendency to have lower water TP concentrations compared  
376 to Dredged in 2018, water TP concentrations in Dredged with macrophytes areas first  
377 increased after transplantation of macrophytes post-dredging, then decreased after 2012  
378 but always higher or similar with Dredged areas later. Further, compared to dredging  
379 only, transplantation of submerged macrophytes may have improved water clarity and  
380 lifted the light limitation of *Microcystis* (Brookes and Ganf, 2001).

381 A series of indirect effects could also account for the higher *Microcystis* biomass in  
382 Dredged with macrophytes areas. For example, compared to Dredged, Dredged with  
383 macrophytes usually located in bays less exposed to the influence of waves and with  
384 relatively lower depth of water, to provide a more suitable environment for the living of  
385 submerged macrophytes (Dong et al., 2017). *Microcystis* can aggregate and form  
386 blooms on the water surface which are then pushed by wind-generated waves. Thus,  
387 lake edges or bays can typically function as accumulation zones from the open lake area  
388 (Tan et al., 2009). In addition, it is likely that a proportion of the newly transplanted  
389 submerged macrophytes had failed to establish at the beginning, leading to  
390 decomposition and additional P inputs (Min et al., 2019). However, the survival ratio of  
391 transplanted submerged macrophytes was not recorded in this study. The area of  
392 submerged macrophytes transplantation in each lake could have also been too small to  
393 have any immediate effect. The reestablishment of submerged macrophyte communities  
394 in these lakes will require more time to have the ability to compete with algae such as

395 *Microcystis*. However, our results do demonstrate that dredging as a disturbance could  
396 be useful to mitigate cyanobacterial blooms (Wan et al., 2021), as Dredged areas  
397 showed continuous reductions of *Microcystis* biomass when compared to Control.

#### 398 **4.3 Benthic macroinvertebrates**

399 Compared to dredging only, Dredged with macrophytes was shown to considerably  
400 improve benthic macroinvertebrates biomass and diversity recovery. Specifically,  
401 compared to Control, Dredged areas just attained similar abundance and richness by the  
402 end of our monitoring (2018), while the biomass of macroinvertebrate at Dredged with  
403 macrophytes areas was much higher than Control, and richness almost doubled.  
404 Biomass and richness of macroinvertebrates in Dredged with macrophytes areas were  
405 always higher than Dredged after transplantation of macrophytes post-dredging.  
406 Notably, the biomass and richness of macroinvertebrates in Dredged with macrophytes  
407 areas were significantly higher than Control until 2018 and 2016, respectively. This  
408 implies a prolonged period of recovery after dredging even with macrophyte  
409 transplantations, most likely due to organism dispersal limitations restricting  
410 colonization of restored habitats. A possible explanation for the eventually higher  
411 biomass and richness is that submerged macrophyte beds provide refuge against  
412 predation (e.g. fish) due to extensive plant substrate, with plants also supporting species  
413 with a wider range of ecological habitat needs (Walker et al., 2013).

414 The composition of benthic macroinvertebrate communities differed significantly  
415 between Dredged and Dredged with macrophytes, Dredged with macrophytes and  
416 Control at the end of the monitoring in 2018. Specifically, IndicSpecies analysis  
417 revealed three species of chironomids (*Microchironomus tabarui*, *Clinotanytus* sp.,  
418 *Glyptotendipes* sp.) and one mussel (*Unio douglasiae*) were strongly associated with  
419 Dredged with macrophytes areas in 2018. This reflects that strong association of

420 chironomids with submerged macrophyte communities (Grzybkowska et al., 2020) as  
421 they provide important niches and protection from predators (van Oosterhout et al.,  
422 2020). This also highlights the success of macrophytes transplantation in Dredged with  
423 macrophytes areas, as the chironomids are submerged macrophyte associated taxa  
424 (Brodersen et al., 2001). Additionally, a bivalve mussel (*Anodonta woodiana*) was  
425 highly associated with both Dredged and Dredged with macrophytes ( $p < 0.05$ ).  
426 *Anodonta woodiana* is a native and common filter-feeding mussel across the Taihu  
427 basin (Bian et al., 2009), and often reintroduced as a part of efforts to restore eutrophic  
428 lakes as they can decrease the biomass of pelagic algae (Zhang et al., 2014).

429       The five lakes in our study can be categorized into two groups by the different  
430 variation trend of beta diversity partitions of macroinvertebrates across time between  
431 Dredged and Control: one group is Lake Gehu and Lake Yangcheng, the other is Lake  
432 Dongjiu, Lake Xijiu and Lake Shanghu (Fig. 7). Specifically, species replacement of  
433 Lake Gehu and Lake Yangcheng between Dredged and Control: first increased then  
434 decreased after 2014, while species replacement of the other three lakes first decreased  
435 then gradually increased since 2012. Possible reasons could be that compared to other  
436 three lakes, Lake Gehu and Lake Yangcheng with significantly larger water surface area  
437 and higher environmental heterogeneity, resulting in high beta diversity driven by  
438 species turnover (López - Delgado et al., 2020).

### 439 **4.3 Implications for aquatic ecosystem management**

440       Our long-term in-situ monitoring study demonstrates that partial restorations (such  
441 as dredging and transplantation of macrophyte) without separation at large lakes can  
442 have positive effects on the ecological environment recovery, although the effect could  
443 vanish over time where source pollutants are not controlled sufficiently. Specifically,  
444 dredging only can significantly decrease nutrients (nitrogen, phosphorus, carbon) in

445 sediment and water, but the effect can be lost approximately five years later. We  
446 confirmed that dredging only disturbance could decrease *Microcystis* biomass and cell  
447 density, while transplantation of submerged macrophytes shortly post-dredging could  
448 not decrease *Microcystis* biomass, although other lake characteristics could not be ruled  
449 out. Our results suggest that lake managers should always consider submerged  
450 macrophyte transplantation, as multiple benefits can accrue via significant decreases in  
451 nutrient concentrations plus the recovery of benthic macroinvertebrate communities  
452 destroyed by dredging.

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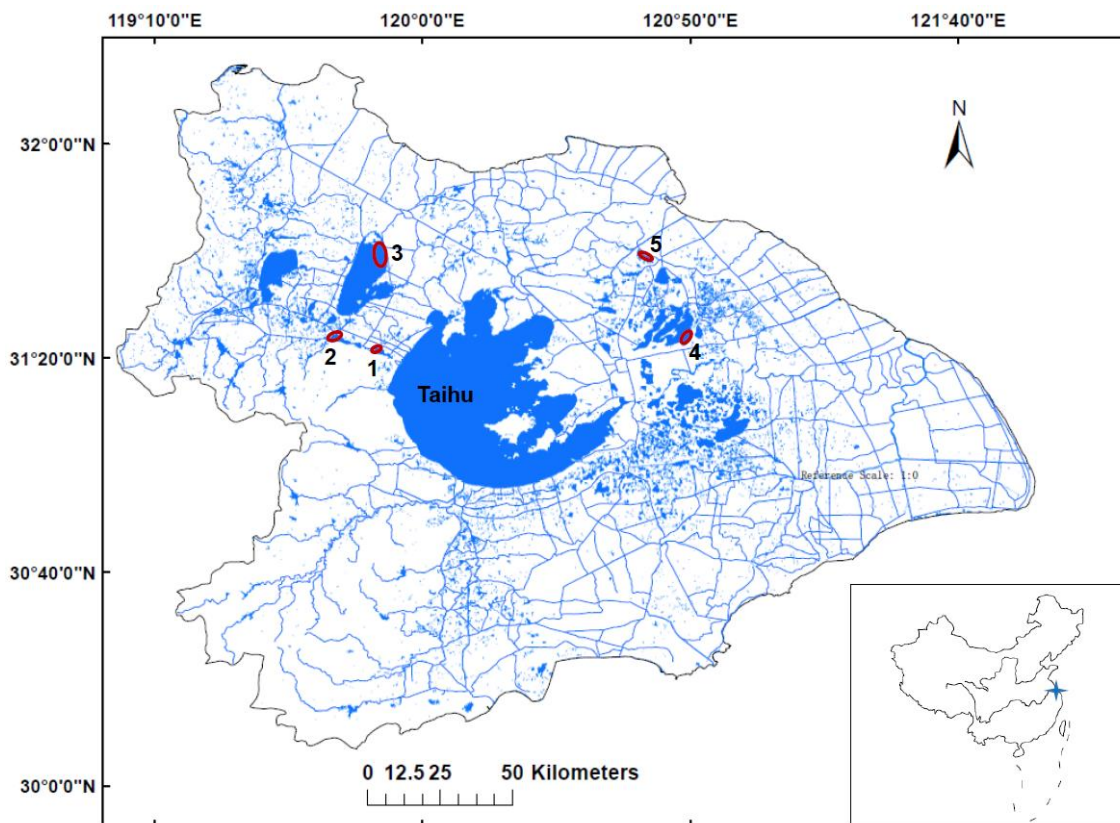
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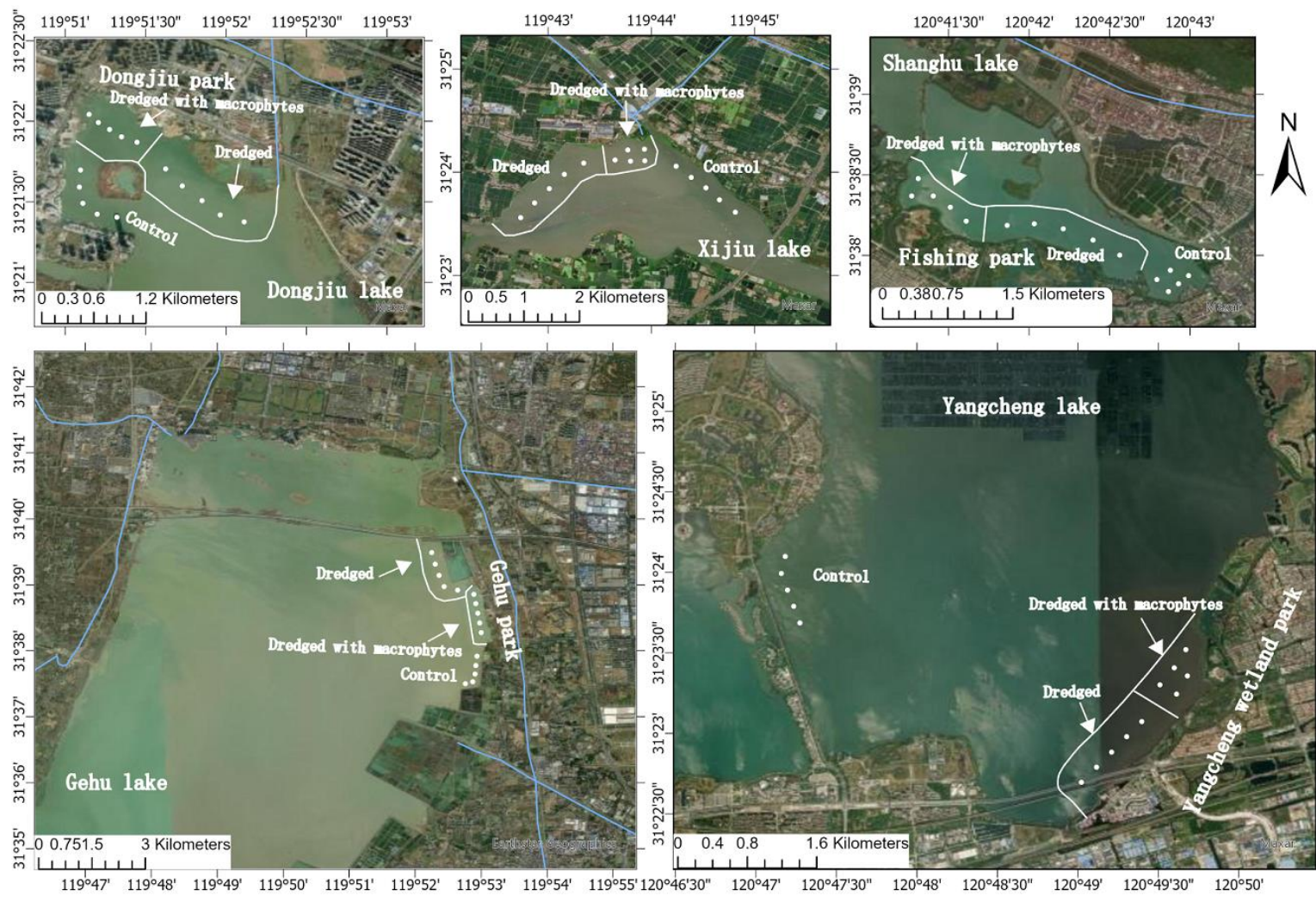
616 **Figure legends**



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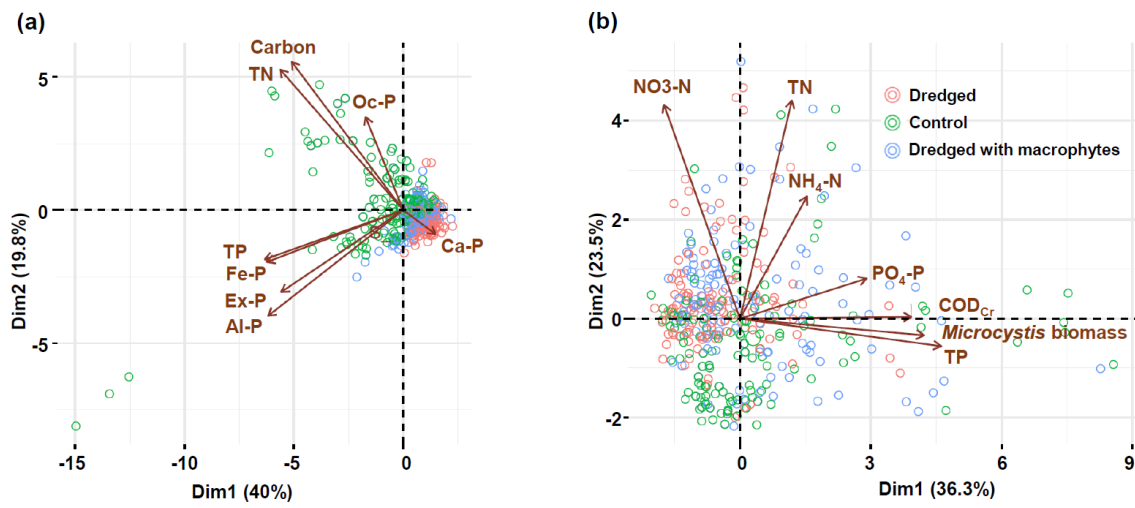
618 Fig. 1. General location of study area in each lake (shown in red circle), in relation to its  
619 location in China (inset panel). Lakes 1, Dongjiu; 2, Xijiu; 3, Gehu; 4, Yangcheng; 5,  
620 Shanghu.

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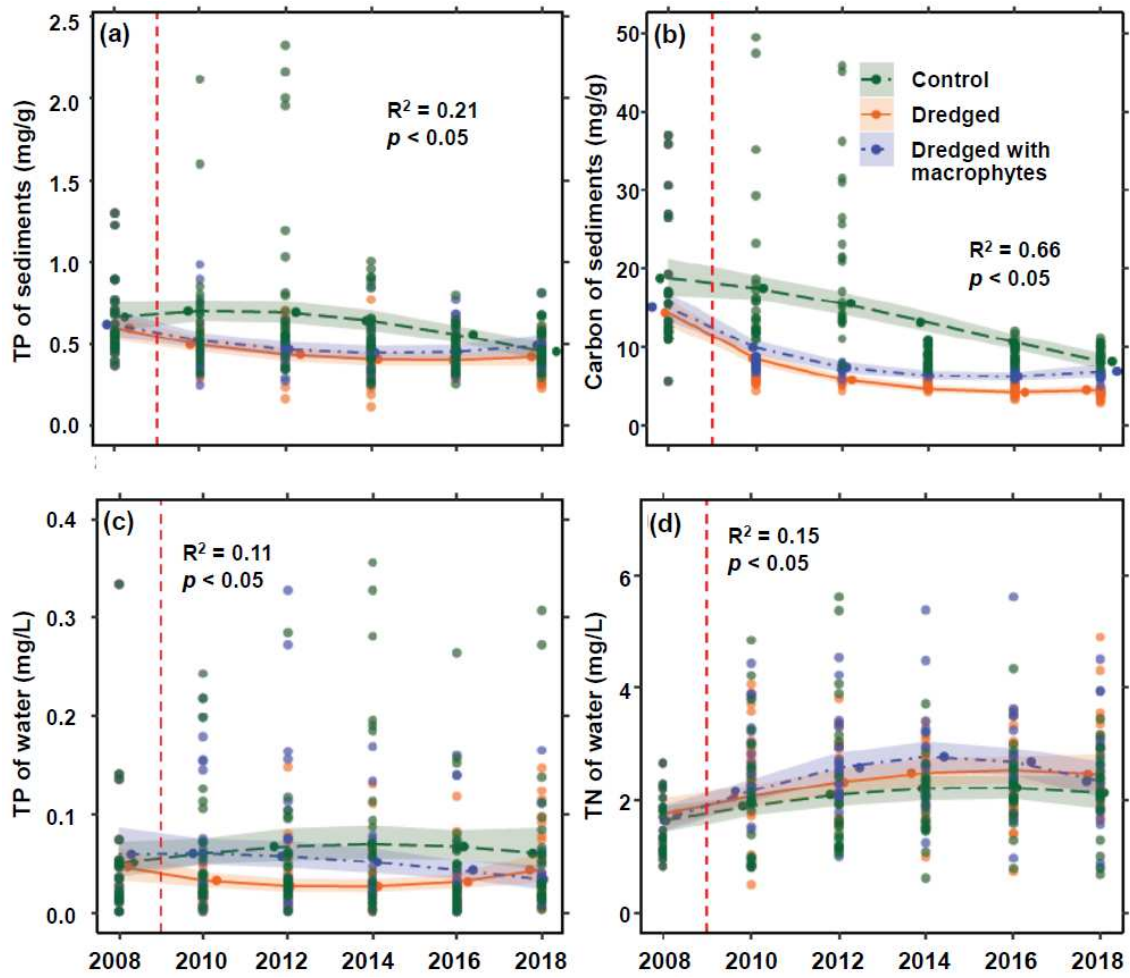
623 Fig. 2. Sketched spatial structure of three treatments and sampling sites (shown in white point) in each lake.



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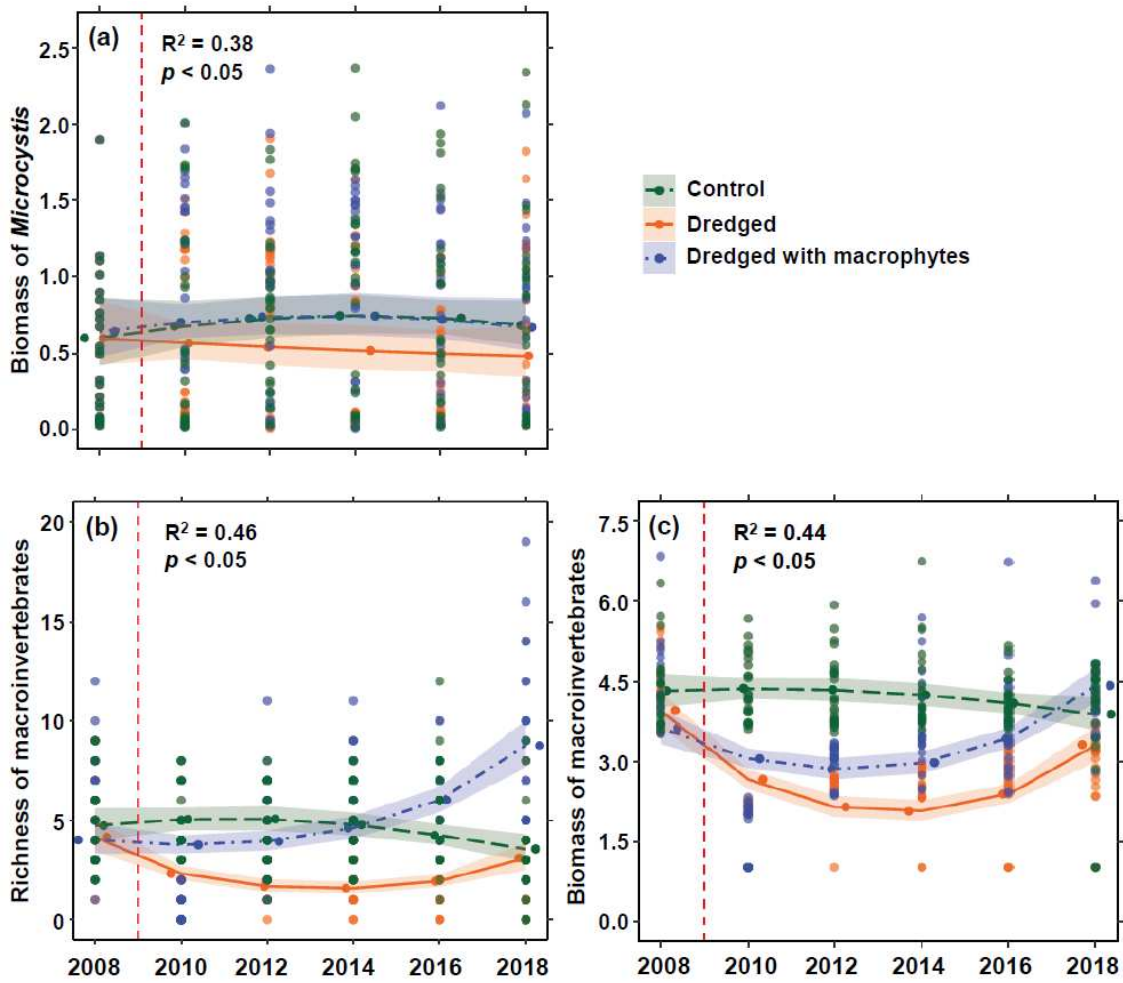
625 Fig. 3. The principal component analysis (PCA) first two dimensions biplot of (a)  
 626 sediment indices and (b) water quality indices. The length of the arrows is proportional  
 627 to the loading score of the variable on each principal component.

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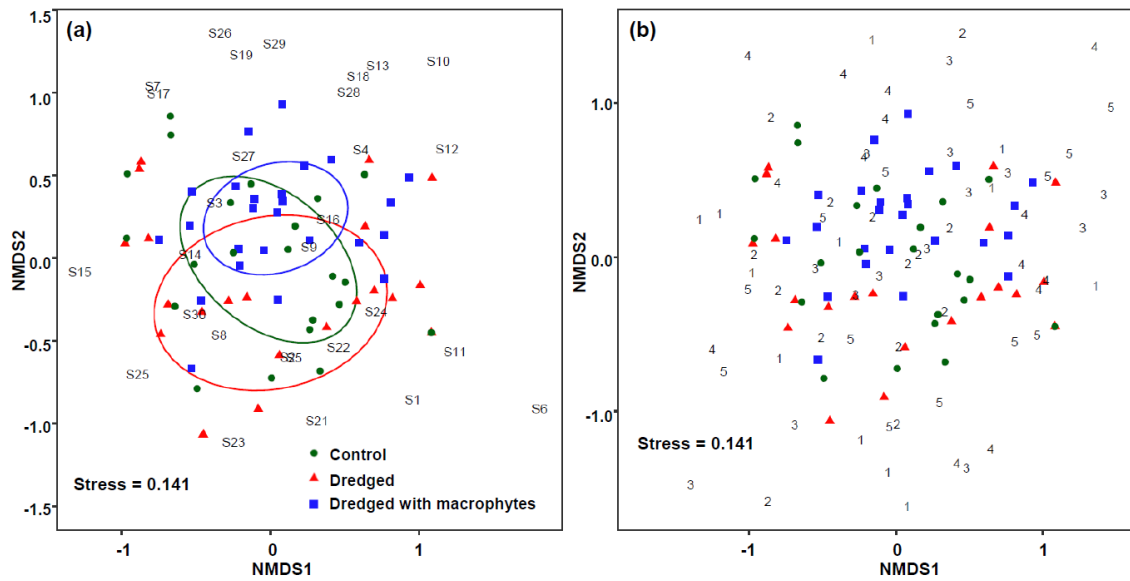
630 Fig. 4. Marginal effects of the indices of (a, b) sediment and (c, d) water nutrients over  
 631 the monitored years. Red dashed lines denote the year of the dredging intervention and  
 632 subsequent transplantation of submerged macrophytes.



633

634 Fig. 5. Marginal effects of (a) *Microcystis* biomass and (b, c) benthic macroinvertebrate  
 635 communities over the monitored years. The red dashed lines denote the year of the  
 636 dredging intervention and subsequent transplantation of submerged macrophytes.

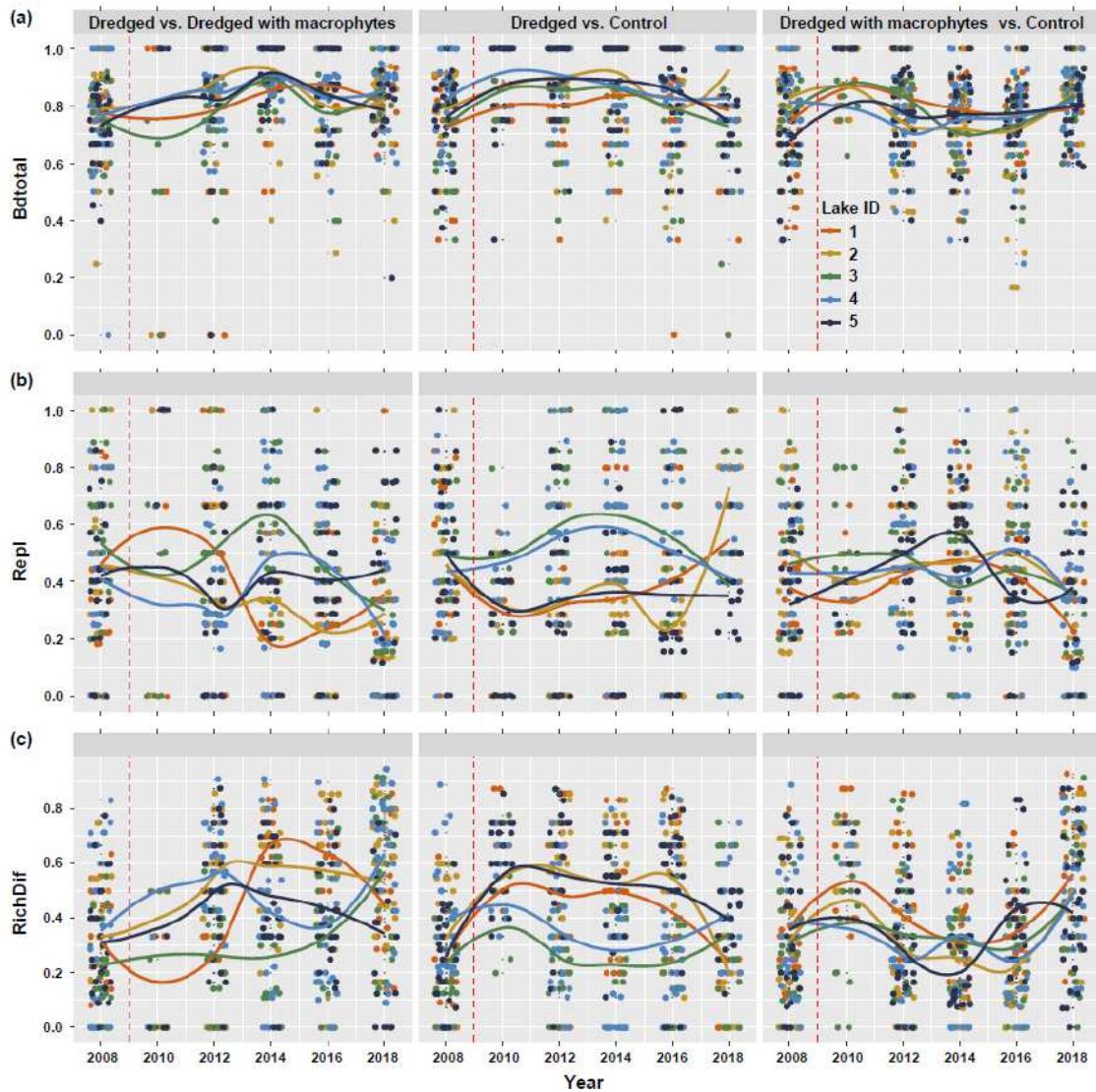
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639 Fig. 6. Non-metric multidimensional scaling (NMDS) biplots of benthic  
 640 macroinvertebrate communities in the three treatments (Dredged, Dredged  
 641 macrophytes, Control) in 2018, with indication of (a) the individual taxa (denoted by S,  
 642 show 50% ellipses) and (b) investigated five lakes (1, Dongjiu; 2, Xijiu; 3, Gehu; 4,  
 643 Yangcheng; 5, Shanghu). Abbreviations for species name see Table S5.

644



645

646 Fig. 7. Temporal variation of beta diversity components for macroinvertebrates between  
 647 different treatments from 2008-2018. Red dashed line denotes dredging intervention and  
 648 submerged macrophytes transplantation post dredging.  $BD_{total} = RichDif + Repl$ ,  
 649  $BD_{total}$ , total beta diversity;  $Repl$ , replacement;  $RichDif$ , species richness difference.  
 650 Lake ID: 1, Dongjiu; 2, Xijiu; 3, Gehu; 4, Yangcheng; 5, Shanghu.

651

652 **Table legends**

653 **Table 1.** Contextual information for the five lakes. Longitude and latitude represent the  
654 center location of the entire monitored area in each lake.

No.	Lake name	Longitude	Latitude	Mean water depth (m)	Surface water area (km <sup>2</sup> )	Dredging area (km <sup>2</sup> )	Planting area (km <sup>2</sup> )
1	Dongjiu	119°51'	31°21'	1.85	8	1.5	0.5
2	Xijiu	119°43'	31°24'	1.79	12.4	2.0	0.5
3	Gehu	119°52'	31°39'	1.27	160	1.5	0.5
4	Yangcheng	120°49'	31°22'	1.8	119.8	1.0	0.4
5	Shanghu	120°41'	31°38'	2.8	8.2	0.9	0.3

655