Migration and transformation of dissolved carbon during accumulated cyanobacteria decomposition in shallow eutrophic lakes: a simulated microcosm study

Zhichun Li [1, 2, 3] , **Yanping Zhao** [4] , **Xiaoguang Xu** [Corresp., 4] , **Ruiming Han** [4] , **Mingyue Wang** [4] , **Guoxiang Wang** [Corresp. 1, 4]

[1] School of Geography Science, Nanjing Normal University, Nanjing, Jiangsu Province, China

[2] School of environmental science and mapping engineering, Suzhou University, Suzhou, Anhui Province, China

[3] National Engineering Research Center of Coal Mine Water Hazard Controlling, Suzhou, Anhui, China

[4] School of Environment, Nanjing Normal University, Nanjing, Jiangsu Province, China

Corresponding Authors: Xiaoguang Xu, Guoxiang Wang
Email address: xgxu@njnu.edu.cn, wangguoxiang@njnu.edu.cn

The decomposition processes of accumulated cyanobacteria can release large amounts of organic carbon and affect the carbon cycling in shallow eutrophic lakes. However, the migration and transformation mechanisms of dissolved carbon (DC) require further study and discussion. In this study, a 73-day laboratory microcosm experiment using suction samplers (Rhizon and syringe) was conducted to understand the migration and transformation of DC during the cyanobacteria decomposition. The decomposition of cyanobacteria biomass caused anoxic and reduction conditions, and changed the acid-base environment in the water column. During the early incubation (days 0-18), a large amount of cyanobacteria-derived particulate organic matter (POM) was decomposed into dissolved organic carbon (DOC) in the overlying water, reaching the highest peak value of 1.82 g/L in the treatment added the high cyanobacteria biomass (470g). After 18 days of incubation, the mineralization of increased DOC to dissolved inorganic carbon (DIC) maintained a high DIC level of overlying water in treatments added cyanobacteria biomass. The treatment added the medium cyanobacteria biomass (235g) presented the lower DOC/TDC ratio than the high cyanobacteria biomass associated with the lower mineralization from DOC to DIC. Due to the concentration differences of DIC at water-sediment interface, the main migration of DIC from pore water to overlying water occurred in the treatment without added cyanobacteria biomass. However, the treatments added the cyanobacteria biomass presented the obvious diffusion of DOC and the low migration of DIC at the water-sediment interface. The diffusive fluxes of DOC at the water-sediment interface increased with the cyanobacteria biomass added, reaching the maximum value of 411.01 mg/(m²·d) in the treatment added the high cyanobacteria biomass. In the overlying water, the group added the sediment and medium cyanobacteria biomass

presented a faster degradation of cyanobacteria-derived POM to DOC and a higher mineralization level of DOC to DIC than added the medium cyanobacteria biomass without sediment. Therefore, during accumulated cyanobacteria decomposition, the biomass of accumulated cyanobacteria and sediment property can influence the migration and transformation of DC, playing an important role in carbon cycling in shallow eutrophic lakes.

1 **Migration and transformation of dissolved carbon during accumulated cyanobacteria**

2 **decomposition in shallow eutrophic lakes: a simulated microcosm study**

3 Zhichun Li[a, b, d], Yanping Zhao[c], Xiaoguang Xu[c*], Ruiming Han[c], Mingyue Wang[c], Guoxiang

4 Wang[b, c*]

5 *a. School of Geography Science, Nanjing Normal University, Nanjing, China, 210023,*

6 *b. School of environmental science and mapping engineering, Suzhou University, Anhui, China,*

7 *234000*

8 *c. School of Environment, Nanjing Normal University, Nanjing, 210023, China*

9 *d. National Engineering Research Center of Coal Mine Water Hazard Controlling, Anhui, 234000,*

10 *China*

11 **Corresponding authors. 1, Wenyuan Road, Xianlin University District, Nanjing 210023, China.*

12 *E-mail address: xxg05504118@163.com (X. Xu); wangguoxiang@njnu.edu.cn (G. Wang)*

23   **Abstract:** The decomposition processes of accumulated cyanobacteria can release large amounts

24   of organic carbon and affect the carbon cycling in shallow eutrophic lakes. However, the migration

25   and transformation mechanisms of dissolved carbon (DC) require further study and discussion. In

26   this study, a 73-day laboratory microcosm experiment using suction samplers (Rhizon and syringe)

27   was conducted to understand the migration and transformation of DC during the cyanobacteria

28   decomposition. The decomposition of cyanobacteria biomass caused anoxic and reduction

29   conditions, and changed the acid-base environment in the water column. During the early

30   incubation (days 0-18), a large amount of cyanobacteria-derived particulate organic matter (POM)

31   was decomposed into dissolved organic carbon (DOC) in the overlying water, reaching the highest

32   peak value of 1.82 g/L in the treatment added the high cyanobacteria biomass (470g). After 18

33   days of incubation, the mineralization of increased DOC to dissolved inorganic carbon (DIC)

34   maintained a high DIC level of overlying water in treatments added cyanobacteria biomass. The

35   treatment added the medium cyanobacteria biomass (235g) presented the lower DOC/TDC ratio

36   than the high cyanobacteria biomass associated with the lower mineralization from DOC to DIC.

37   Due to the concentration differences of DIC at water-sediment interface, the main migration of

38   DIC from pore water to overlying water occurred in the treatment without added cyanobacteria

39   biomass. However, the treatments added the cyanobacteria biomass presented the obvious

40   diffusion of DOC and the low migration of DIC at the water-sediment interface. The diffusive

41   fluxes of DOC at the water-sediment interface increased with the cyanobacteria biomass added,

42   reaching the maximum value of 411.01 mg/(m^2·d) in the treatment added the high cyanobacteria

43   biomass. In the overlying water, the group added the sediment and medium cyanobacteria biomass

44   presented a faster degradation of cyanobacteria-derived POM to DOC and a higher mineralization

45   level of DOC to DIC than added the medium cyanobacteria biomass without sediment. Therefore,

46   during accumulated cyanobacteria decomposition, the biomass of accumulated cyanobacteria and

47   sediment property can influence the migration and transformation of DC, playing an important

48   role in carbon cycling in shallow eutrophic lakes.

49   **1. Introduction**

50   Carbon cycling in lakes, from a macro perspective, refers to the constant migration and

51   transformation between gaseous carbon, dissolved carbon and solid or particulate carbon (Kuntz

52   et al., 2015; Quay, 1986). DC can be found in the whole water column, is an important media for

53   the transformation of other carbon forms and is conducive to absorption and utilization by aquatic

54   plants and microorganisms (Bass et al., 2010; Koehler et al., 2016). DC, including DIC and DOC,

55   originates from autochthonous production or allochthonous input. DIC (CO_2, CO_3^{2-} and HCO_3^-) is

56   an important aquatic nutrient that influences the carbon cycle and is mainly produced in sediment

57   pore water during organic matter oxidation. It is also influenced by soil CO_2 from catchments, the

58   influx or efflux of CO_2 from or to the atmosphere, and the balance between photosynthetic CO_2

59   uptake and respiratory CO_2 production (Vreca, 2003; Mcdonald et al., 2013; Bass et al., 2010).

60   DOC composition has been studied through the quantification of specific compounds, including

61   short-chain organic acids, amino acids, and major classes of biomolecules (Komada et al., 2013;

62   Gómez-Consarn et al., 2012; Bertilsson, et al., 2003). In lake ecosystems, the autochthonous and

63   allochthonous DOC refers to various autotrophic and heterotrophic in situ activities and the

64   hydrodynamic processes of catchments, respectively. Allochthonous DOC, typically deriving from

65   vegetation and soil organic matter, is more stable and resistant to degradation than autochthonous

66   DOC (Catalán et al., 2013; Tranvik, 1992; Jaffé et al., 2015). Autochthonous DOC is derived from

67   planktonic production, photosynthesis of macrophytes, and micro-biological degradation of

68   organic matter (Hu et al., 2011; Assunção et al., 2016). In eutrophic lakes, autochthonous DOC

69   mainly originates from phytoplankton biota detritus, particularly cyanobacteria blooms. The

70   transformation between DOC and DIC includes various biogeochemical processes, e.g.,

71   photochemical reactions, metal complexation, microbial growth, and nutrient and contaminant

72   transport, which affect the environmental behavior of pollutions and the carbon cycle of shallow

73   eutrophic lakes (Attermeyer et al., 2014; Aarnos et al., 2012; Marie et al., 2015; Yang et al., 2016).

74   Therefore, it is crucial to understand the migration and transformation of DC during cyanobacteria

75   decomposition in shallow eutrophic lakes.

76   Cyanobacterial blooms frequently occur in shallow eutrophic lakes. Depending on the

77   meteorological and hydrological conditions, a large amount of cyanobacteria biomass may drift

78   and accumulate along the lake shoreline (Kong and Gao, 2005; Yang et al., 2016), resulting in the

79   formation of an active carbon pool. Subsequently, these accumulated cyanobacteria are subjected

80   to sedimentation and decomposition processes, coupled with the migration and transformation of

81   DC. Compared with aquatic plants, cyanobacteria are relatively easily decomposed due to their

82   smaller grain size and more favorable ratio of nitrogen to phosphorus for microbial utilization (Li

83   et al., 2011; Sun, 2013; Wang et al., 2008; Liu et al., 2010). In addition, the growth period of

84 cyanobacteria is generally shorter than that of aquatic plants, and their growth rates are faster.

85 Therefore, the accumulation, sedimentation, and decomposition of cyanobacteria may accelerate

86 contaminant transport, material cycling (carbon, nitrogen, and phosphorus) and energy flow in

87 lake ecosystems. Studies have previously been conducted on cyanobacteria decomposition related

88 to variability in total organic carbon (Hanamachi et al., 2008; Ye et al., 2011), bacterial community

89 dynamics and biodegradability of cyanobacteria-derived OM (Lee et al., 2016; Shi et al., 2017),

90 qualitative and quantitative variability in specific organic carbon compounds (Liu et al., 2016),

91 and the accumulation and degradation of chromophoric dissolved organic matter (Hulatt et al.,

92 2009). These studies revealed the contribution of cyanobacterial decomposition to the carbon cycle

93 and associated influence factors, including microbial community characteristics, sunlight,

94 temperature, and aerobic and anaerobic conditions. However, few studies have attempted to

95 systemically explore the mechanisms of migration and transformation of DC and to calculate a

96 balance between the aquatic phase and the sediment phase during cyanobacteria decomposition.

97 This study seeks to describe DC release characteristics in overlying water, and the migration

98 and transformation processes during cyanobacteria decomposition in shallow eutrophic lakes.

99 Samples of cyanobacteria and sediment cores were collected from Taihu Lake for laboratory

100 incubation. Variability in DC concentration from the overlying water, bottom water, and pore-

101 water was monitored depending on the thicknesses of the accumulated cyanobacteria layer

102 (cyanobacteria biomass) and the absence or presence of sediments. DOC diffusive flux at the

103 sediment-water interface was calculated by Fick's first law. It was hypothesized that the biomass

104 of accumulated cyanobacteria and the physical, chemical, and biological structures of sediment

105 significantly influence the DOC release intensity, the transformation between DOC and DIC, and

106 DC diffusion processes at the water-sediment interface in shallow eutrophic lakes. These

107 observations may be beneficial to understand the fates of accumulated cyanobacteria and the

108 carbon cycle of shallow eutrophic lakes.

109 **2. Materials and methods**

110 **2.1. Sample collection**

111   As the third largest freshwater lake in China, Taihu Lake is a typical shallow and eutrophic

112 lake where cyanobacteria blooms frequently occur in summer. The summer monsoon drives

113 cyanobacteria blooms to drift and accumulate to lakeshore, forming a high biomass of

114 cyanobacteria scum in aquatic macrophyte-belts (Fig. 1). The accumulated cyanobacteria rarely

115 spreads more widely across the sediment because of the obstruction by aquatic macrophyte-belts

116 and their forming trenches. Subsequently, the massive decline and decomposition of cyanobacteria

117 blooms in high temperatures probably cause negative impacts on the aquatic ecosystem, including

118 the malodorous water, the death of fish and other aquatic organisms and even the occurrence of

119 black bloom (Smith et al., 2008; Feng et al., 2014; Liu et al., 2017).

120   The sampling operation was executed near the Maodu River (N31°24'42.21",

121 E120°00'38.92") along the western shoreline of Taihu Lake in July, 2016 (Fig. 1), including open

122 water and accumulated cyanobacteria area. The overlying water samples from two areas were

123 collected after measuring physical and chemical parameters by calibrated probes from American

124 Hach. The initial physical and chemical parameters as well as the initial concentrations of total

125   nitrogen (TN), total phosphorus (TP), ammonia nitrogen (NH_4^+-N), nitrate nitrogen (NO_3^--N) and

126   DOC of the lake water in the two areas were showed in Table 1. The fresh cyanobacteria were

127   sampled by using a 64-μm plankton net. Three intact core sediments were collected using a KC

128   Kajak core sampler equipped with a plexi-glass tube (inner diameter, 8.8 cm). The overlying water

129   and particulate matter were slowly sucked up using a small pump into the upper part of plexi-glass

130   tubes that kept 25 cm of sediment below the sediment-water interface. The samples were stored in

131   the refrigerator at 4℃ and taken to the laboratory within 8 hours.

132   **2.2. Microcosm system**

133   Before the incubation of intact core sediments in the laboratory, the same volume

134   ($40cm \times \pi \times 4.4^2 cm^2$) of lake water from open water was slowly added into each plexi-glass tube

135   (inside radius, 4.4cm) with minimal disturbance (Fig. 2). A plexi-glass tube without sediment and

136   Rhizon samplers (Seeberg-Elverfeldt et al., 2005; Shotbolt, 2010) served as the control. After one

137   week of incubation, 0g (0cm), 235g (5cm), and 470g (10cm) of wet cyanobacteria biomass that

138   had been washed with high purity water were added into three water columns labeled S, SM, and

139   SH, respectively. Meanwhile 235g (5cm) of cyanobacteria biomass was added to the control

140   system, labeled M. Cyanobacteria biomass was added based on field observations along the

141   lakeshore where cyanobacteria had accumulated at a thickness of 5-10 cm. The incubation

142   experiment was performed in an air-conditioned lab and was always kept at 28℃ using an

143   automatic constant temperature heating rod. To better represent in-situ conditions in Taihu Lake,

144   the upper parts of the plexi-glass tubes were opened and their entire sides protected from light. To

145 collect pore water, three plexi-glass tubes with 25cm intact core sediments were fitted to the

146 Rhizon samplers at 0cm, 2cm, and 4cm depths below the sediment-water interface (Seeberg-

147 Elverfeldt et al., 2005; Shotbolt, 2010).

148 **2.3. Sample analysis**

149 The thicknesses of cyanobacterial layer on surface water and sedimentary detritus layer

150 (cyanobacteria-derived particulates) on surface sediment were measured by straightedge.

151 Dissolved oxygen (DO), pH, and oxidation-reduction potential (Eh) of overlying water were

152 detected using calibrated probes from American Hach. Syringes were used to extract 5mL of

153 overlying water, 5mL of bottom water, and 2.5mL of pore water for the respective groups S, SM,

154 and SH, while 5mL of overlying water for group M was collected. Subsequently, the same volume

155 of lake water with extracted water was supplemented into each column. The overlying water

156 samples were filtered through precombusted (470℃ for 4 h) GF/F glass fiber filters (nominal pore

157 size, 0.7 μm; Whatman International Ltd., Maidstone, England). DIC and total dissolved carbon

158 (TDC) values from filtered overlying water and pore water were directly detected using carbon-

159 nitrogen analyzer (multi N/C® 3100, AnalytikJena, Germany). The carbon-nitrogen analyzer

160 applied the method of combustion oxidation-non-dispersive infrared absorption and the calculation

161 model of minusing, which meant first determining TDC and DIC concentrations and then

162 calculating the DOC concentrations (DOC=TDC-DIC).

163 **2.4 Diffusive flux of DOC at the sediment-water interface**

164 DOC diffusive flux at the sediment-water interface was calculated according to Fick's first

165   law of diffusion:

166
$$J = -\phi D_s \frac{\partial C}{\partial x}$$

167   Where, ϕ is the porosity of surficial sediments. According to Cermelj (1997), the ϕ value in

168   this study was set to 0.68 based on the weight fraction of water after drying the sediments for 24h

169   at 105°C. D_s is the bulk sediment diffusion coefficient for DOC, and the Stokes–Einstein equation

170   yielded a value of 1.22×10^{-6} cm^{-2} s^{-1} according to the average molecular weight for DOC of 8000

171   daltons (Alperin et al., 1994; Holcombe et al., 2001). Therefore, based on the literature on the

172   average molecular weight of pore water DOC (Burdige et al., 1999), the D_s was assumed to be

173   1.22×10^{-6} cm^{-2} s^{-1} to assess the DOC diffusive flux in this study. $\partial C / \partial x$ is the DOC concentration

174   gradient between pore-water and bottom water over the applied distance, where $\partial C / \partial x$ can be

175   approximated by $\Delta C / \Delta x$ (Burdige et al., 1999; Lahajnar et al., 2005). ΔC is the difference in

176   DOC concentration between bottom water and pore water sampled at 2cm depth. Δx is the

177   vertical dimension between two sample points (i.e. Δx =2cm in the microcosm system).

178   **2.5. Statistical analysis**

179   Temporal variability and box-plots for TDC, DOC, and DIC concentrations and DOC

180   diffusive flux were analyzed using Origin version 8.0 and SPSS statistical package 19.0 (SPSS

181   Inc., Chicago). The correlation analysis between the physicochemical indexes and DC

182   concentrations was conducted using the SPSS statistical package for Windows. The criteria of $p <$

183   0.05 was considered as the significant level in this study.

184   **3. Results and Discussion**

185   **3.1. Visual changes and physicochemical environment associated with DC release**

186   During cyanobacteria decomposition, the thickness of the cyanobacteria layer on superficial

187   overlying water and the thickness of sedimentary detritus layer from cyanobacteria-derived

188   particulates at the bottom of overlying water are shown in Fig. 3. In the treatment without

189   cyanobacteria biomass (group S), the water column remained relatively colorless and transparent

190   during the experiment. However, the overlying water in groups with added cyanobacteria biomass

191   (groups SM, SH and M) gradually showed variations in visible color and thickness with a foul

192   smell. From day 2 to day 10 there was a slight odor and a large amount of cyanobacteria-derived

193   particulates dispersed into the water column for groups SM, SH and M. Due to the abundant

194   chlorophyll-a in fresh cyanobacteria (Shoaf and Lium, 1976; Zarel et al., 2015), the overlying

195   water displayed the green color, indicating cyanobacteria hadn't been completely decomposed

196   during early incubation. After 10 days, the water color became yellow-green with a strong odor

197   when the cyanobacteria layers in overlying water became incompact and a low aggregation degree.

198   This indicated the massive decomposition of the cyanobacteria-derived POM. Subsequently, a

199   number of black particles appeared in the overlying water and sediments, which was similar to

200   previous reports (Steinberg, 2003; Duan et al., 2014; Han et al., 2015) and probably related to the

201   settling of POM. After the 20th day, the sedimentary detritus layer at the bottom decreased in

202   thickness and black particles gradually disappeared. These changes might have occurred with the

203   microbial mineralization of cyanobacteria-derived POM (Shi et al., 2017). Therefore, in the

204   treatments added cyanobacteria biomass, the clear color changes in the water column and the

205   morphological changes in the cyanobacteria layer can indicate the degradation level of

206   cyanobacteria-derived POM to some extent.

207   Variations in DO, Eh and pH values in the water column according to incubation time are

208   shown in Fig. 4. Based on the initial DO and Eh values, there was no obvious reduction

209   environment in the overlying water, similar to the data of open water in Taihu Lake (Table 1).

210   After adding cyanobacteria, DO concentrations of the water column in groups SM, SH, and M

211   began to rapidly decrease and remained at a lower level (<1.0 mg/L), compared to group S without

212   cyanobacteria biomass. The change trends between DO and Eh were basically consistent,

213   corresponding to the data of accumulated cyanobacteria in Taihu Lake (Table 1). Meanwhile, DOC

214   and DO in groups M, SM and SH with added cyanobacteria biomass were negatively correlated (r

215   = -0.328～-0.310, $p < 0.05$) (Table 2). This indicated that the DOC release from microbial

216   degradation of organic matter probably consumed oxygen and resulted in anoxic conditions,

217   consistent with previous studies (Shao et al., 2013; Song et al., 2016; Yan et al., 2017). The water

218   column was alkaline at the beginning of the experiment. After adding cyanobacteria, the pH values

219   of the water column in groups SM, SH and M had clear acid-base changes (Fig. 4c). During the

220   first 18 days, the pH values in groups SM, SH and M were lower and fluctuated. Subsequently,

221   they gradually rose to peak values (>8.5) and then dropped after that. In contrast, pH values in

222   group S without biomass fluctuated more than 7.0. DOC and pH in groups SM, SH and M were

223   negatively correlated (r = -0.533～-0.202, $p < 0.05$), as shown in Table 2. It is well documented

224   that the decomposition of cyanobacteria causes biological, physical, and chemical degradation of

225   proteins, lipids, and carbohydrates (Brown et al., 1997; Tibbetts et al., 2015). The degradation

226   process can produce many secondary metabolites and final products, which probably change the

227   acid-base environment, e.g., organic acids (Steinberg, 2003). Meanwhile, the strong positive

228   correlation between DIC and pH (r = 0.581~0.817, p<0.05) as well as high pH values (>8.0)

229   after 26 days of incubation indicated that the growth of microbes utilized DOC to generate CO_2

230   (DIC) in groups SM, SH and M (Shao et al., 2013; Yan et al., 2017), causing the water column to

231   become alkaline. In summary, cyanobacteria decomposition can affect redox (anaerobic

232   dominated) and the acid-base environment in the water column.

233   **3.2. Influence of cyanobacteria biomass on the release of DC in overlying water**

234   Variations in TDC, DOC, DIC and the DOC/TDC ratio during incubation in overlying water

235   are shown in Fig. 5. Obviously, the more cyanobacteria biomass was added, the higher TDC and

236   DOC concentrations were detected. The box-plots also showed that TDC and DOC values in group

237   SH added the high cyanobacteria biomass were much higher than in group S without added

238   cyanobacteria biomass and in group SM added the medium cyanobacteria biomass (Fig. 6a and

239   6b). During cyanobacteria decomposition, various organic carbon compounds found in

240   cyanobacteria are released into the water column as DOC and POC, while different carbon

241   fractions and other elements migrate and transform (Brocke et al., 2015; Chen et al., 2016). In this

242   study, different concentrations of cyanobacteria biomass released different organic carbon

243   compound content into the overlying water under the same physicochemical and biological

244   conditions. In the initial 16 days, the cyanobacteria layer was greater than 0 cm in thickness (Fig.

245 3), DOC and DTC concentrations gradually increased (Fig. 5a and 5b), and there was little changes

246 in DIC concentrations in groups SM and SH (Fig. 5e). This indicated that the release rate of DOC

247 was higher than the conversion rate in overlying water. The more cyanobacterial biomass was

248 added, the higher the peak value of DOC concentrations (S, 153.9 mg/L; SM, 835.1 mg/L and SH,

249 1823.7mg/L). After 16 days, compared with small changes in DIC and DOC concentrations in

250 group S, the obvious decrease in TDC and DOC content and the DOC/TDC ratio, along with the

251 rapid rise in DIC concentrations in groups SM and SH demonstrated that DOC transformed into

252 DIC in overlying water. This was similar to the aquatic macrophytes decomposition (Sobek et al.,

253 2006; Assunção, 2016), probably involving the microbial mineralization of dissolved humic

254 substances (Steinberg, 2003; Marie et al., 2015). In addition, the treatment added the medium

255 cyanobacteria biomass (group SM) presented the lower DOC/TDC ratio than the high

256 cyanobacteria biomass (group SH) associated with the lower mineralization from DOC to DIC.

257 This is probably because the decomposition of high cyanobacteria biomass consumed more

258 oxygen and disturbed a recovering redox state. Cyanobacteria biomass variously affected the

259 release of organic carbon and oxidative transformation from DOC to DIC.

260   In the microcosm with more biomass added, the pH values in overlying water were lower

261 (Fig. 4c), probably due to more organic acids being produced by more cyanobacteria biomass

262 during the decomposition processes. Generally, the more cyanobacteria biomass added, the higher

263 DIC content detected (Fig. 4e). This trend indicated that the decomposition of more cyanobacteria

264 biomass can release more carbon substrates and nutrients supporting microorganism growth in the

265 water column, corresponding to the differences of TN, TP, NH_4^+-N, NO_3^--N and DOC between

266   open water and accumulated cyanobacteria area of Taihu Lake (Table 1). The growth of microbes

267   can promote the microbial mineralization of more DOC and cyanobacteria-derived POM into DIC

268   (Shao et al., 2013; Yan et al., 2017). According to the carbon budget calculation approach in

269   previous studies (Sobek et al., 2006; Cremona et al., 2014), the differences (D-values) between the

270   max TDC concentration during the incubation time and the sum of DOC and DIC values in the

271   final stage can clarify the amount of migration and transformation of TDC into sediment or air,

272   partly based on the presence of odorous substances (Smith et al., 2008; Yu et al., 2016; Liu et al.,

273   2017). D-values comparison between incubation groups is shown in Fig. 6d. Treatments with more

274   cyanobacteria biomass had higher D-values. This confirmed that the amount of migration or

275   transformation of DC was related to the amount of added cyanobacteria biomass. In summary, the

276   added cyanobacteria biomass can affect the acid-base environment in the water column, migration

277   between water and sediment phases, and transformation processes of DC involving the microbial

278   degradation and mineralization during cyanobacteria decomposition.

279   **3.3. Influence of sediment on the release of DC in overlying water**

280   Comparisons of DC release concentrations between presence and absence of sediment during

281   the incubation time are shown in Fig.5b, 5d, 5f and 5h. In the first 16 days, TDC, DOC, and DIC

282   contents with sediments (group SM) were much closer to the treatments without sediments (group

283   M). After that time, however, along with the disappearance of cyanobacteria at the top of overlying

284   water, the releasing intensity of organic carbon became weak. In overlying water, higher values of

285   TDC, DOC, and DOC/TDC ratios in group M but higher DIC values in group SM illustrated a

286   faster DOC degradation rate in group SM. Meanwhile, the thickness of the sedimentary detritus

287   layer in group M was much higher than in group SM. This indicated a faster decomposition of

288   detritus in group SM. These discrepancies were probably related to the addition of sediments. In

289   our microcosm, the abiotic (photochemical) mineralization made a limited contribution to DOC

290   transformation into DIC because of the protection from light for the entire sides of the plexi-glass

291   tubes. Instead, the microbial mineralization might play a major role in these processes

292   (Obernosterer and Benner, 2004). In group SM,the added sediments containing various bacterial

293   communities elevated the microbial abundance and diversity of community structure (Wang et al.,

294   2008; Woszczyk, et al., 2011; Shi et al., 2017), compared with group M only added lake water.

295   Moreover, the added sediments can provide the nutrients to support microbial growth in the water

296   column (De Vittor et al., 2016). By contrast with group M, the more abundant microorganisms in

297   quantity and type involved the mineralization from DOC into DIC in group SM added sediment.

298   Additionally, DOC molecules in overlying water could migrate to the sediments because of the

299   concentration gradient of DOC at the sediment-water interface. Therefore, the sediments

300   containing the abundant microbial populations and the high level nutrients probably promoted the

301   decomposition of cyanobacteria-derived detritus by microorganisms as well as in overlying water

302   the microbial mineralization from DOC to DIC.

303   **3.4. Sediment-water interface DC processes during cyanobacteria decomposition**

304   DC variations at different depths and the diffusive flux of DOC at the sediment-water

305   interface during incubation in treatments with sediment (groups S, SM and SH) are shown in Fig.

306   7. The distribution of DC with sediment depth has been shown to illustrate the migration and

307   transformation of organic carbon at the sediment-water interface (Burdige et al., 1999; Vreca,

308   2003; Chen et al., 2017). In group S, TDC and DIC concentrations had clear differences at

309   sampling depth but no obvious stratification of DOC concentrations. Therefore, the DIC

310   concentration distribution determined the clear stratification of TDC concentrations, when no

311   cyanobacteria biomass decomposed or organic carbons were released in the water-sediment

312   system. The DIC concentration gradient indicated that DIC migrated from pore water to overlying

313   water at the sediment-water interface (Wu et al., 1997; Vreca, 2003). Compared to group S without

314   added cyanobacteria biomass, the DOC concentration gradually decreased with sediment depth

315   after adding cyanobacteria biomass in groups SM and SH (Fig. 7d, 7e and 7f). This was because

316   cyanobacteria decomposition released DOC into the overlying water and increased the DOC

317   concentrations. Contrary to gradients found in previous studies (Alperin et al., 1999; De et al.,

318   2016), these DOC gradients in groups SM and SH revealed that molecules of dissolved organic

319   compounds in overlying water diffused into pore-water at the water-sediment interface. After 43

320   days of incubation, the groups SM and SH showed that the DOC contents at the bottom water was

321   close to values at depths of 2cm and 4cm due to the diffusion. The more biomass added, the higher

322   DOC concentrations were detected at each depth, corresponding to the mass balance on carbon

323   budget (Hu et al., 2011; Cremona et al., 2014). Compared with group S, the groups SM and SH

324   had small differences in DOC concentration stratification with sediment depth, while DIC

325   concentrations first increased with depth and then slightly decreased (Fig 7g, 7h and 7i). In

326   addition, most DIC values in groups SM and SH were higher than in group S. The small differences

327 and higher DIC values indicated that DOC in overlying water of groups SM and SH diffused to

328 pore water and transformed into DIC. This transformation may have resulted from the microbial

329 mineralization of DOC in sediment (Lojen, 2004; Fahrner et al., 2008; Clayer et al., 2016). After

330 40 days, in the treatment added the medium biomass (SM) and after 55 days in the treatment added

331 the high biomass (SH), the DOC contents were lower and DIC contents were slightly falling at

332 each depth, compared with the early incubation period. These changes and the associated D-values

333 (Fig. 6d) indicated that gaseous carbons might be generated in the water-sediment system and then

334 released into air, corresponding to in-situ measurements and the carbon model of previous studies

335 (Kuntz et al., 2015; Liu et al., 2017; Yu et al., 2016). Additionally, a certain amount of DIC in

336 groups SM and SH probably migrated to the overlying water at the water-sediment interface, which

337 prompted the increase of DIC concentrations in overlying water (Fig 5e).

338   The values of DOC flux in groups SM and SH firstly increased and then decreased with

339 incubation time, while group S presented the less DOC flux and little change (Fig. 7j). In general,

340 the diffusive fluxes of DOC at the water-sediment interface increased with the cyanobacteria

341 biomass added in the same time period and displayed a broader range in group SH than groups S

342 and SM (Fig. 8), corresponding to the vertical variation and the statistical distribution of DOC

343 concentration during cyanobacteria decomposition (Fig. 6b, Fig. 7d, Fig. 7e and Fig. 7f). The

344 diffusive fluxes of DOC reached the maximum value of 411.01 mg/(m^2·d) in the treatment added

345 the high cyanobacteria biomass (group SH), which was much higher than in the normal water

346 column (Chen et al., 2017). Moreover, the diffusive flux of DOC at the water-sediment interface

347 was negative, indicating that diffusion of DOC from overlying water toward sediment was

348   occurring. In the latter 16 days, the diffusive flux of DOC gradually declined along the decrease

349   of DOC concentrations in groups SM and SH. Therefore, the decomposition of cyanobacteria in

350   lakes can affect the migration process and the diffusive flux of DOC at the sediment-water

351   interface.

352   **3.5 Implications for the effects of cyanobacteria decomposition on carbon cycling in lakes**

353   To clarify the feedback of cyanobacteria-derived particulate organic carbon associated with

354   the migration and transformation of DC during accumulated cyanobacteria decomposition in

355   shallow eutrophic lakes, a conceptual diagram is presented according to the DC study of this

356   microcosm system and the previous studies involving the developed model of carbon cycling (Hu

357   et al., 2011), bacterial community dynamics (Shao et al., 2013; Shi et al., 2017) and the releasing

358   mechanism of gaseous carbon (Yu et al., 2016; Yan et al., 2017) during cyanobacterial

359   decomposition (Fig. 9). In eutrophic lakes, the summer monsoon drives a large amount of

360   cyanobacteria blooms to drift near lakeshore. A certain biomass of cyanobacteria gradually

361   accumulate in lakeshore and difficultly spread due to the obstruction of macrophyte-belts or less

362   influence of stormy waves in grooves, thus forming abundant scum with POC. The microcosm

363   results and previous studies indicated that the decline and decomposition of these cyanobacteria

364   scum will change the physicochemical environment (DO, pH, and Eh) and the microbial

365   environment (bacterial community) of lake water (Yan et al., 2017; Shi et al., 2017). Meanwhile,

366   the releasing DOC during cyanobacterial decomposition along with the migration and

367   transformation of DC in water-sediment systems, alter the carbon balance at the water-sediment

368   interface and carbon budget of overlying water and pore water in lake ecosystems. These variations

369   for physicochemical and biophysical environment as well as DOC concentration have a profound

370   effect on carbon cycling in lakes. Therefore, the dynamic state of DC during accumulated

371   cyanobacteria decomposition is an important ecological indicator of biogeochemical processes

372   involving the carbon cycling in shallow eutrophic lakes. These biogeochemical processes mainly

373   include the decomposition of cyanobacteria-derived POC into DOC, transformation of

374   cyanobacteria-derived POC into gaseous carbon, the settlement and burial of cyanobacteria-

375   derived POC into sediment, DOC diffusion at the water-sediment interface, the mineralization and

376   methanogenesis of DOC into DIC, CO_2 and CH_4, the decomposition of sediments organic matter

377   into DOC.

378   Moreover, based on visual assessments in the field, the accumulated biomasses of

379   cyanobacteria present the spatial heterogeneity in lake ecosystems due to the differences of

380   lakeshore topographies, lacustrine currents, meteorological factors and ecological types in

381   accumulation areas of cyanobacteria blooms. For example, cyanobacteria blooms in eutrophic

382   lakes are not easy to gather near estuaries but tend to be trapped in macrophyte-belts of lakeshore

383   (Liu et al., 2017; Yan et al., 2017; Huang et al., 2018). The release characteristics of DOC in

384   microcosm added diverse algae biomasses implied that the higher accumulated biomass in lakes

385   can release the more abundant DOC into water column, having the greater potential to change the

386   carbon budget and balance between overlying water and pore water. Meanwhile, the

387   decomposition of diverse cyanobacteria biomasses can cause the differences of physicochemical

388   and biophysical environment and nutrient release (Table 1) among these accumulated

389   cyanobacteria areas, which will have various impacts on the migration and transformation of DC

390   in spatial scale of eutrophic lakes. Therefore, the qualitative and quantitative dynamic of carbon

391   cycling in eutrophic lakes were significantly affected by the cyanobacteria biomass.

392   **4. Conclusions**

393   This study showed that the decomposition of cyanobacteria bloom led to the release of DOC

394   into water column and thus changed the carbon cycling in shallow eutrophic lakes. When the

395   variation range of temperature was not large, the biomass of accumulated cyanobacteria as well as

396   the property of lacustrine sediments can influence the decomposition of cyanobacteria-derived

397   POM to DOC, the mineralization of DOC to DIC, and diffusion processes of DOC and DIC at the

398   water-sediment interface in shallow eutrophic lakes. Furthermore, associated with previous studies

399   about the biogeochemical mechanism of gaseous carbon and solid carbon in lake ecosystems, our

400   study indicated that the dynamic state of DC during accumulated cyanobacteria decomposition is

401   an important ecological indicator of biogeochemical processes in the lacustrine carbon cycling,

402   including the decomposition of cyanobacteria-POC into DOC, the transformation of

403   cyanobacteria-POC into gaseous carbon, the settlement and burial of cyanobacteria-POC into

404   sediment, DOC diffusion at the water-sediment interface, the mineralization and methanogenesis

405   of DOC into DIC, CO_2 and CH_4, the decomposition of sedimentary organic matter into DOC. In

406   the decomposition process of cyanobacteria blooms, more research effort toward detailed analysis

407   of the biogeochemical fate of cyanobacteria-derived organic carbon in aqueous phase, gas phase

408   and solid phase are needed to obtain a better understanding the influence of cyanobacteria bloom

409 and eutrophication on the carbon cycling of shallow lakes.

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Physical and chemical properties and the concentrations of TN, TP, NH_4^+-N, NO_3^--N and DOC in the lake water from accumulated cyanobacteria areas of lakeshore and open water of Taihu Lake.

Lake region	Cyanobacterial thickness (cm)	Depth of water (m)	Temperature (℃)	pH	DO (mg/L)	Eh (mv)	TN (mg/L)	TP (mg/L)	NH$_4^+$-N (mg/L)	NO$_3^-$-N (mg/L)	DOC (mg/L)
Accumulated cyanobacteria areas of lakeshore	4.0-10.0	0. 3-0.6	27.6-28.4	6.7-7.4	0.5-1.5	-222.9 to -64.1	4.45-8.89	0.49-1.89	0.70-5.97	0.01-0.56	23.08-103.60
Open water	0-0.2	0.7-3.1	27.8-28.6	6.9-9.3	6.1-16.4	86.7-219.3	1.59-4.51	0.24-0.44	0.05-0.17	0.63-1.64	15.09-21.34

Pearson correlation coefficients between DCs concentrations and physicochemicalindexes in different treatments (*p*<0.05).

Treatments	DOC			DIC		
	DOC-DO	DOC-Eh	DOC-pH	DIC-DO	DIC-Eh	DIC-pH
S	0.127	-0.017	0.300	0.024	0.015	0.291
SM	**-0.323**	**-0.407**	**-0.471**	-0.152	-0.094	**0.817**
SH	**-0.310**	-0.214	**-0.533**	-0.191	**-0.423**	**0.581**
M	**-0.328**	-0.285	-0.202	-0.197	0.015	**0.768**

Figure 1

Location of the sampling sites, Google Maps of trenches, and accumulated cyanobacteria in aquatic macrophyte-belts in the western shoreline of Taihu Lake, China.

Location of the sampling sites (a), Google Maps of trenches (b), and macrophyte-belts (c).

Map credit: © 2016 Google; Digital Globe.
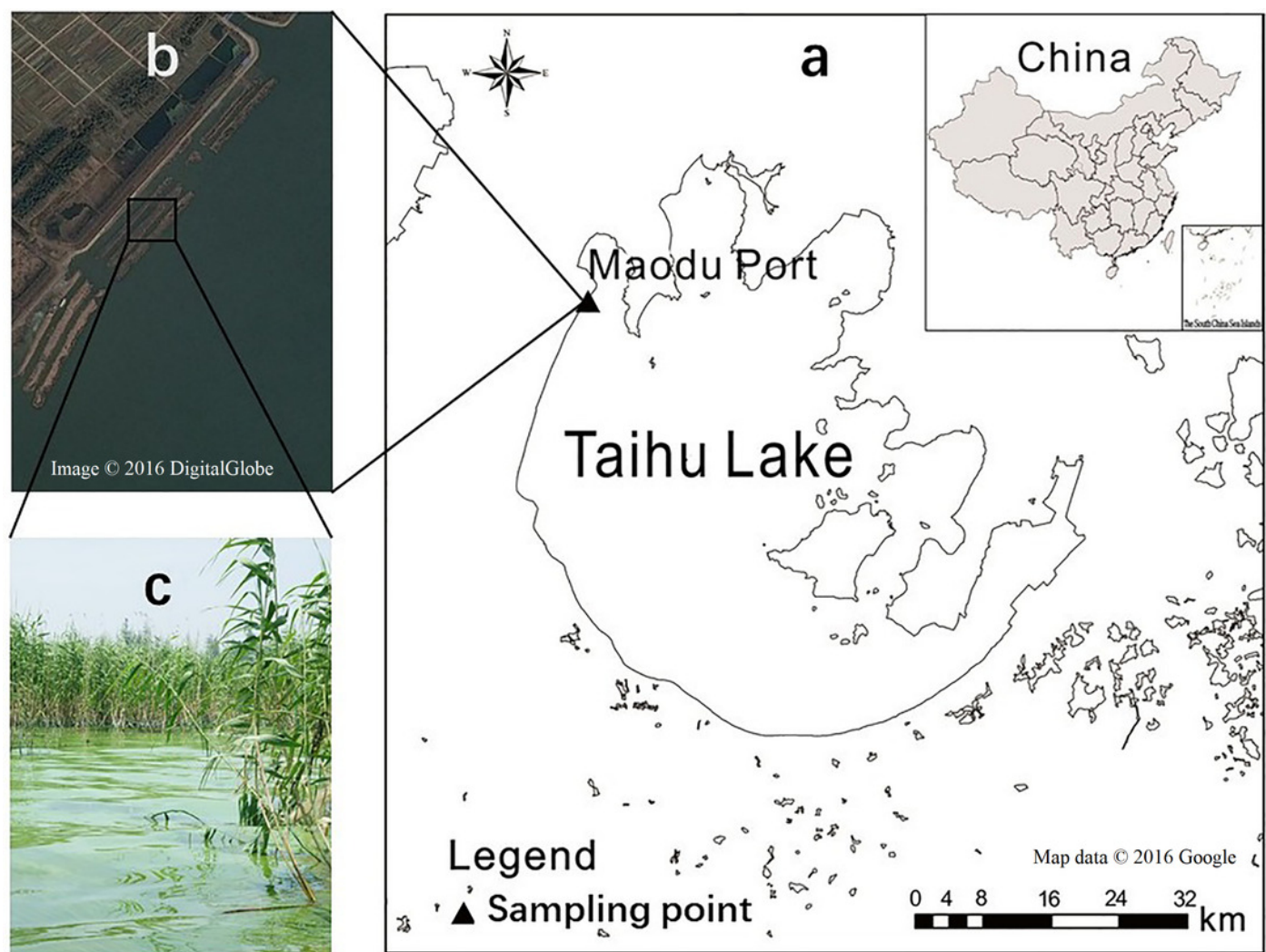
Figure 2

Microcosm system in in the laboratory for simulating the decomposition of accumulated cyanobacteria in lakeshore of Taihu Lake.

0g, 235g and 470g cyanobacteria biomass were added into three water columns with sediment named as S, SM and SH, respectively, while 235g cyanobacteria biomass was added in the control system without sediment, named M. In the system, 235g and 470g cyanobacteria biomass can cause 5cm and 10cm cyanobacteria accumulation layer, respectively.
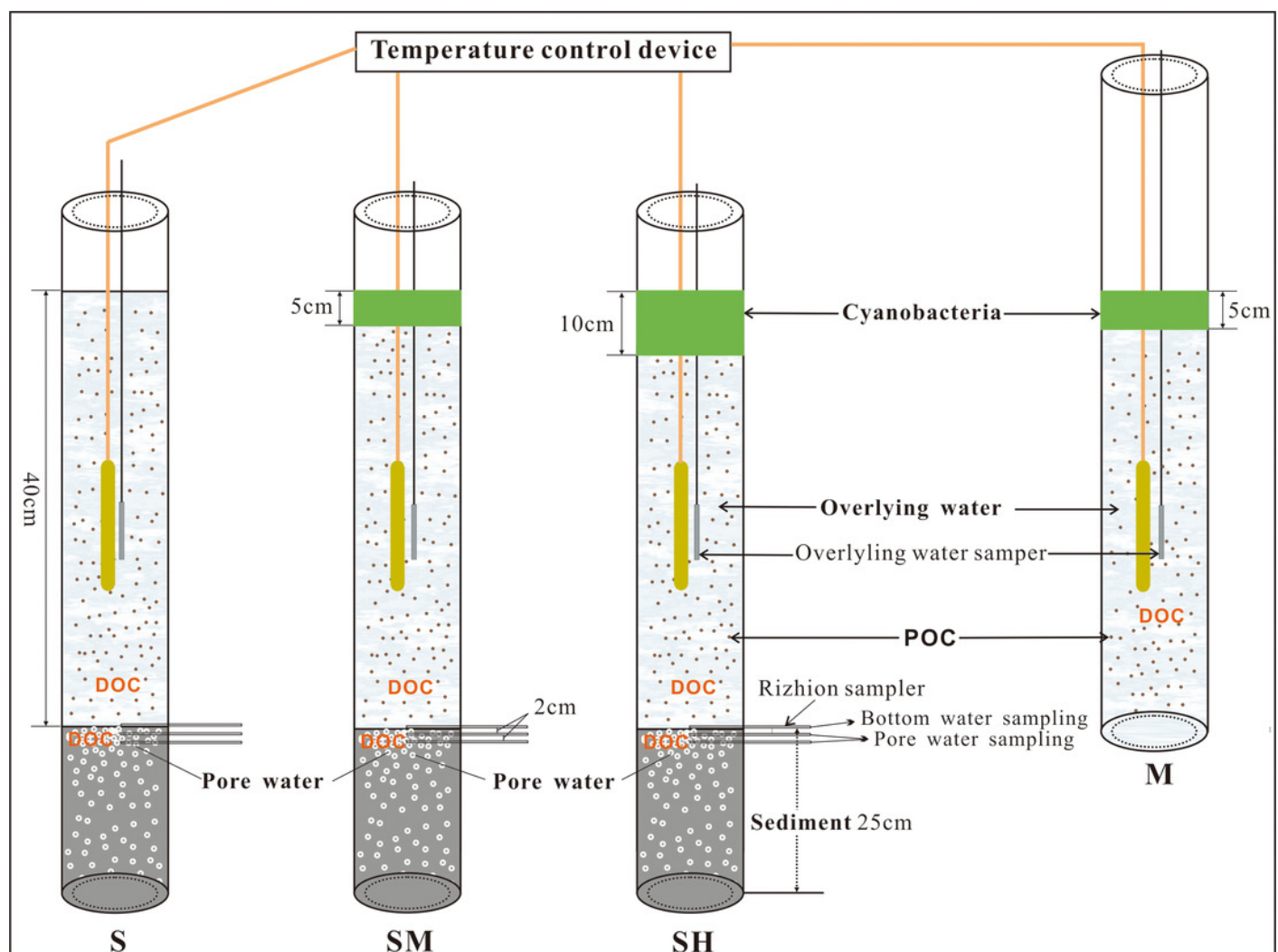
Figure 3

Variations of cyanobacteria thicknesses of superficial overlying water and the thicknesses of sedimentary detritus layer from cyanobacteria particulates at the bottom of overlying water.

Cyanobacteria thicknesses of superficial overlying water (a). The thicknesses of sedimentary detritus layer from cyanobacteria particulates at the bottom of overlying water (b).
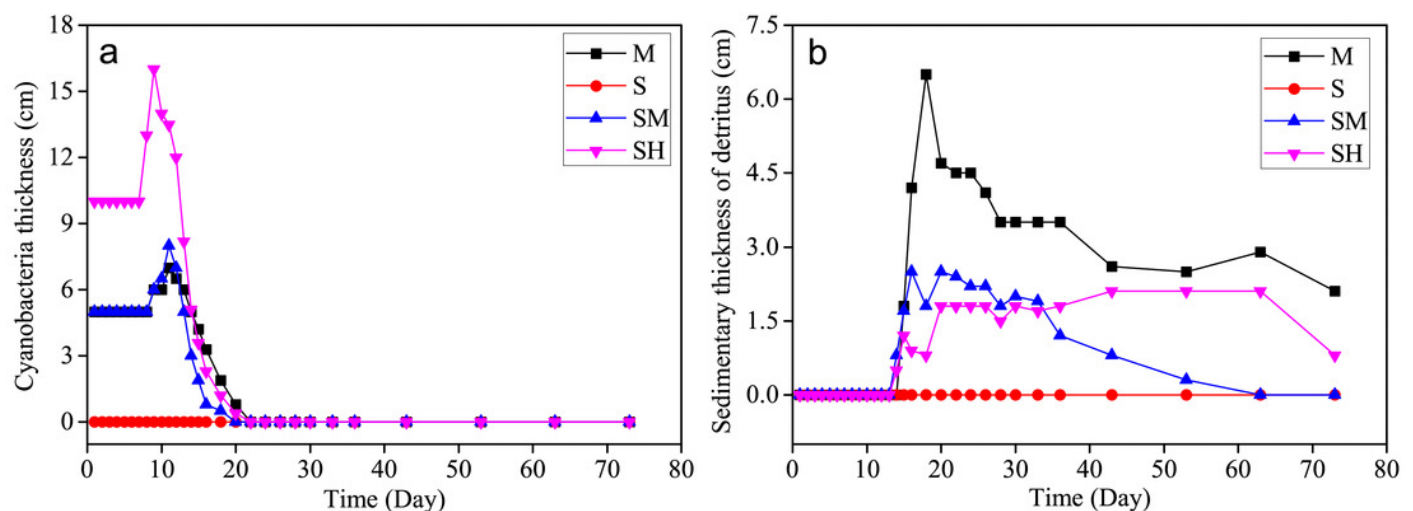
Figure 4

Variations of DO, Eh and pH along with the incubation time in each treatment.

DO (a), Eh (b) and pH (c).
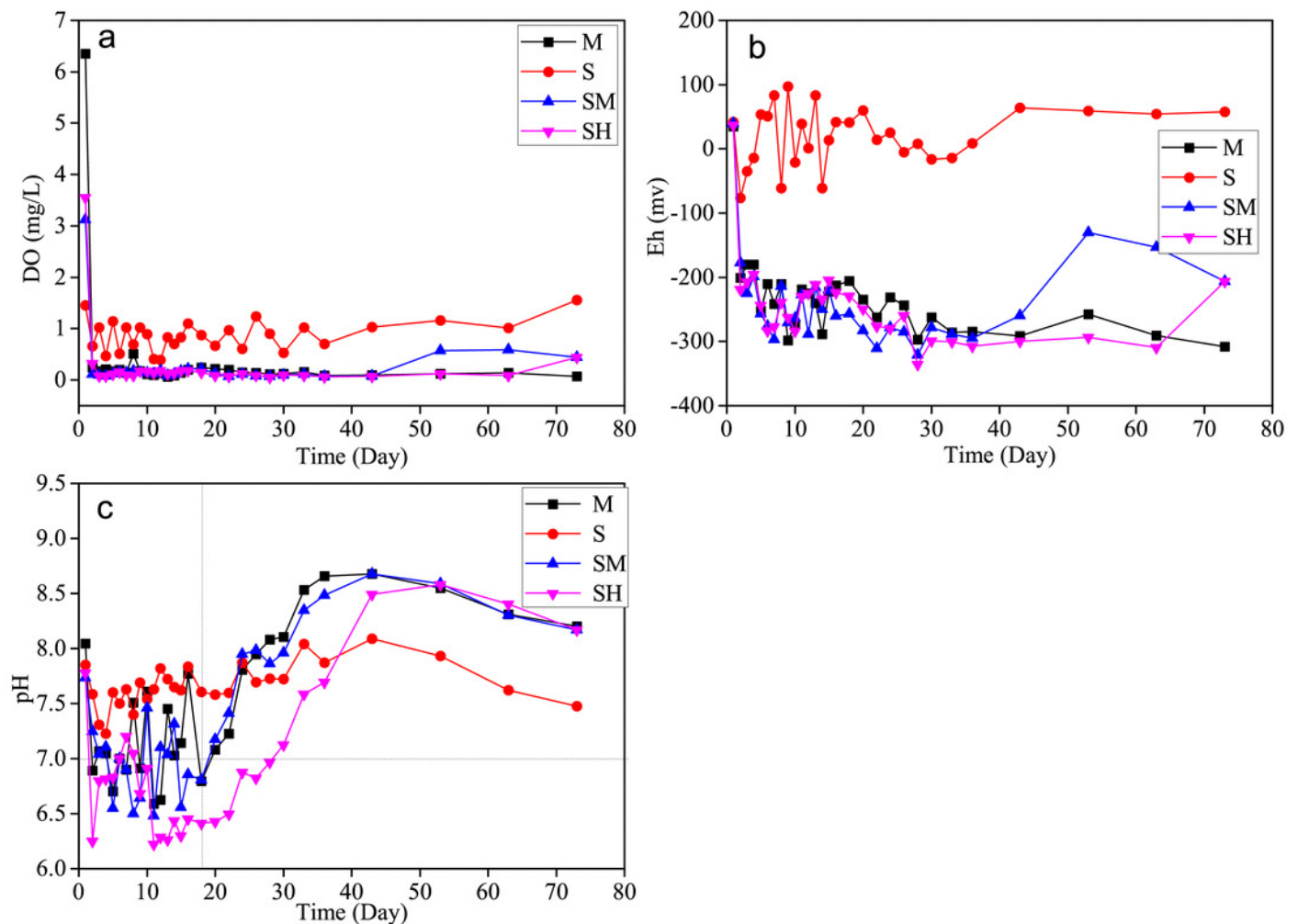
Figure 5

Variations of TDC, DOC, DIC and DOC/TDC ratios during incubation in overlying water of each treatment including the influence of cyanobacteria biomass and absence or presence of sediments.

TDC (a, b), DOC (c, d), DIC (e, f) and DOC/TDC ratios(g, h). The influence of added cyanobacteria biomass (a, c, e, g). The influence for absence or presence of sediments (b, d, f, h).
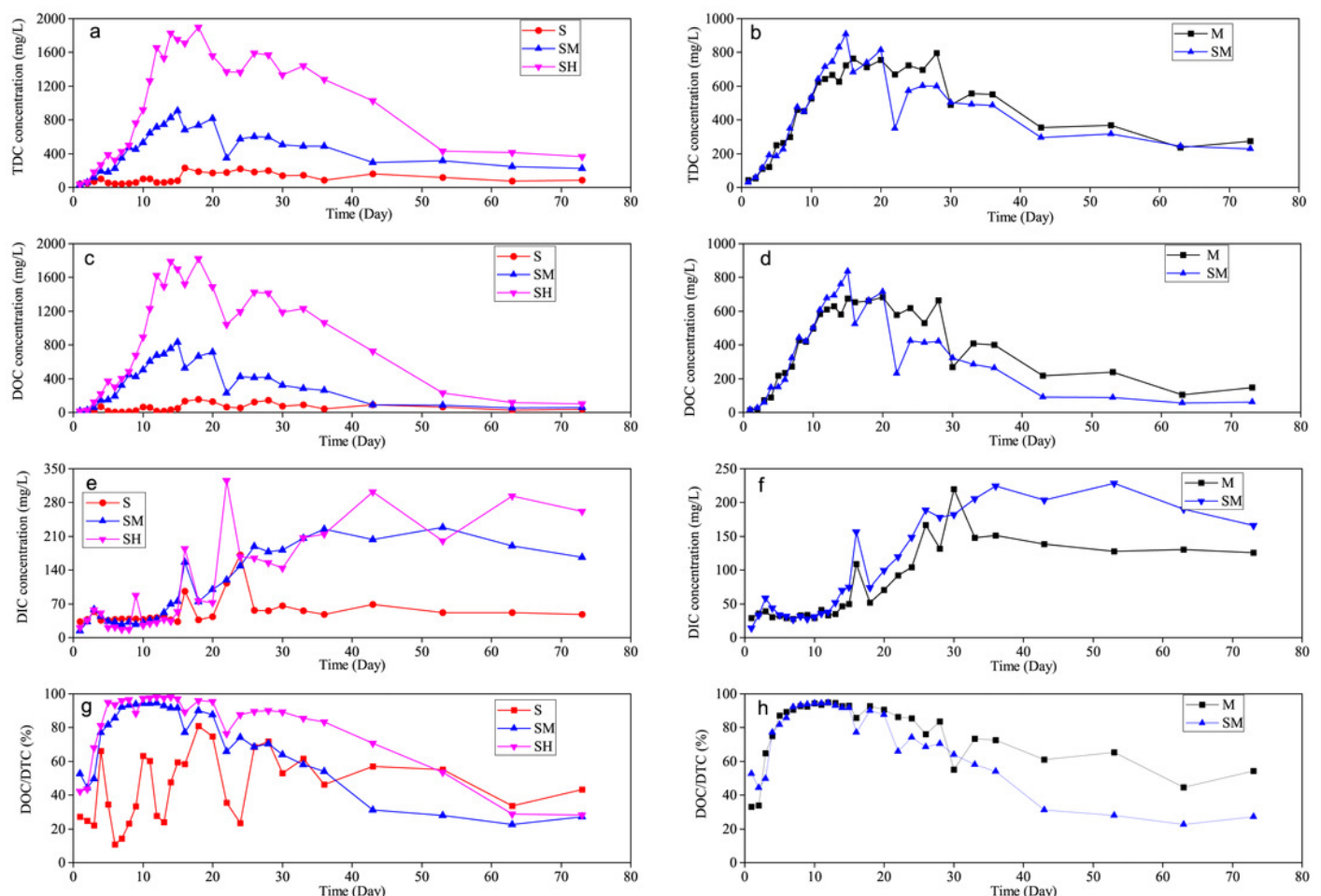
Figure 6

Statistical box-plots of TDC, DOC and DIC and comparison of D-values in treatments added different cyanobacterial biomasses.

TDC (a), DOC (b) and DIC (c) and comparison of D-values (d). D-value means the max TDC concentration in incubation subtracts the sum of DOC and DIC values in final stage in each treatment.
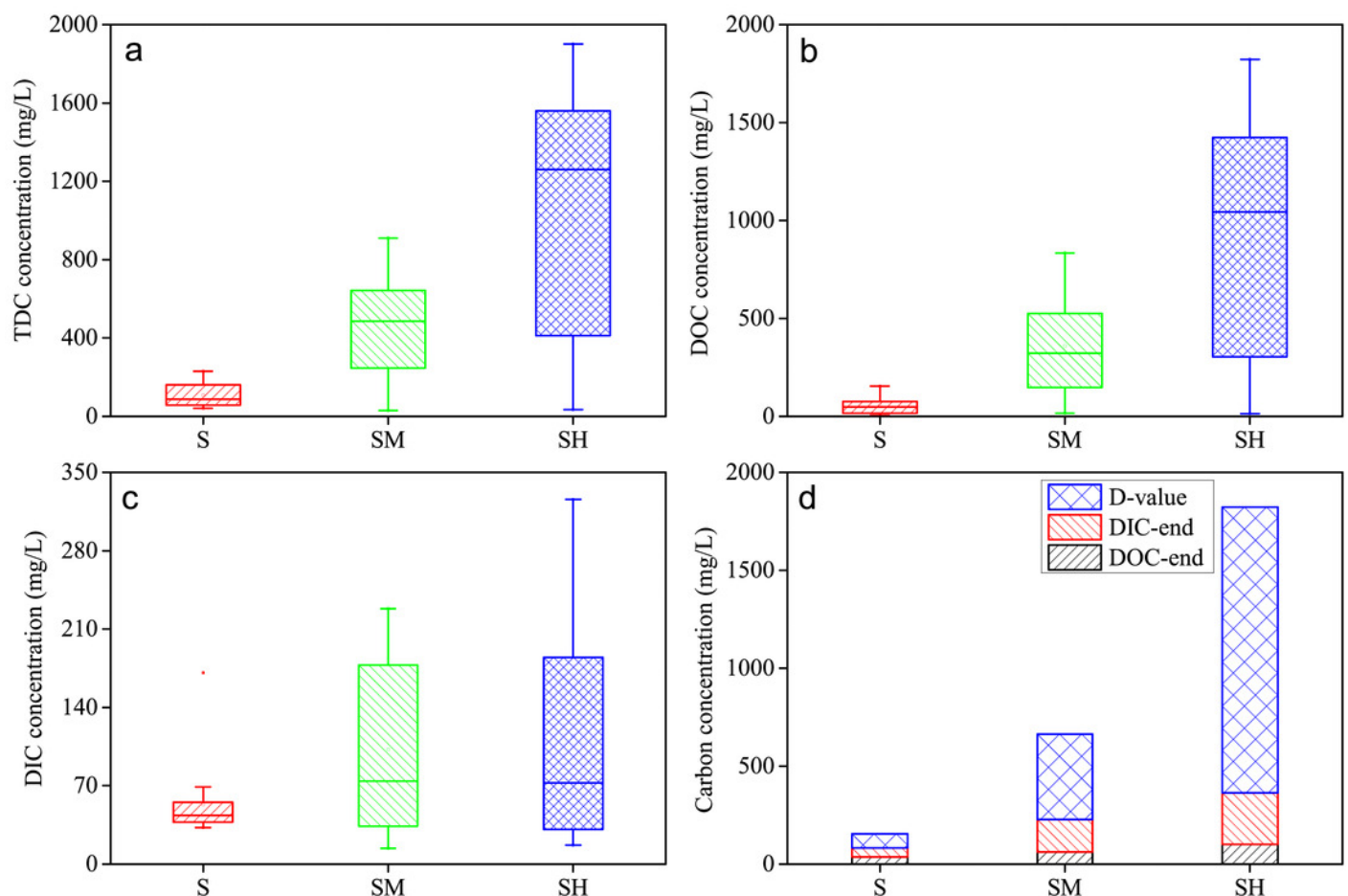
Figure 7

Variations of TDC, DIC, DOC and diffusive fluxes of DOC at the sediment-water interface with incubation time in each treatment added different cyanobacteria biomass.

TDC (a, b and c), DIC (e, f and g), DOC (g, h and i) and diffusive fluxes of DOC (j).
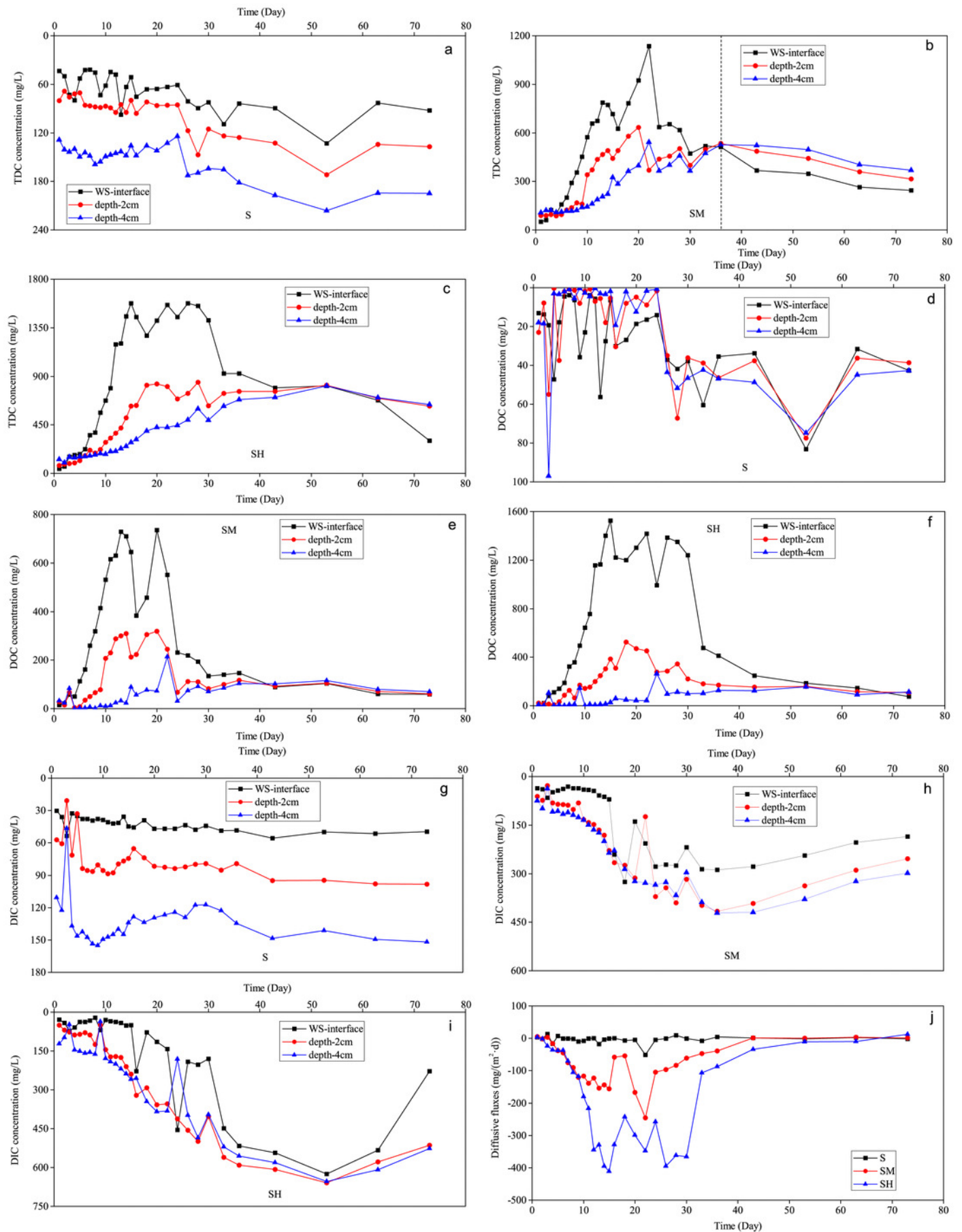
Figure 8

Statistical box-plot of the diffusive fluxes of DOC at the sediment-water interface in each experimental group.
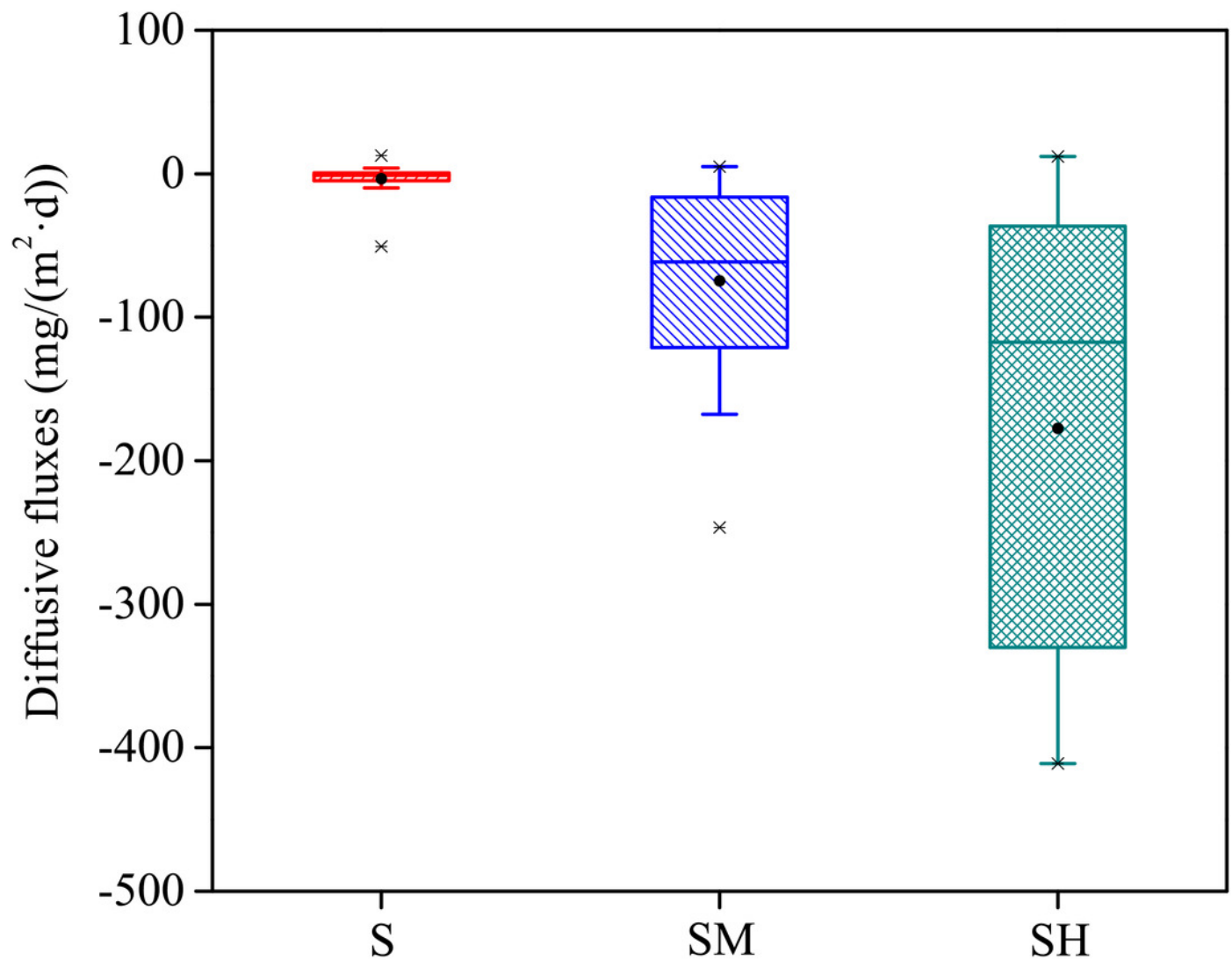
Figure 9

Migration and transformation of DC generated by accumulated cyanobacteria in aquatic plant-belts and trenches of Taihu Lake, China.

Solid arrow and dotted arrow represent the implications of this study and the previous studies, respectively. Cyanobacteria-derived POC was biologically degraded into DOC, and may result in the decrease of pH values and anoxic state in lake water (a). A little Cyanobacteria-derived POC decomposed into DOC (b). Cyanobacteria-derived POC were transformed into gaseous carbon (Smith et al., 2008; Liu et al., 2017; Huang et al., 2018) (c). Cyanobacteria-derived POC deposited into organic matter at the top of sediment and contribute to humification and carbon burial (Hu et al., 2011; Kuntz et al., 2015; Marie et al., 2015) (d). DOC diffused from overlying water to pore water (e). A little DOC volatilized into Atmosphere (Yu et al., 2016; Liu et al., 2017; Huang et al., 2018) (f). DOC mineralization (g). Organic matter decomposition (h). Organic matter mineralization (i). Organic matter methanogenesis produced CO_2 and CH_4 (Clayer et al., 2016; Yan et al., 2017) (j). DIC diffusion at the water-sediment interface causing the increase of pH value (k). CO_2 diffusion at the water-air interface (Yan et al., 2017) (l). Some DOC may be also assimilated by bacteria thus transformed to POC (Bo et al., 1995; Khodse et al., 2011; Yang et al., 2016) (m).