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上海城市河网附着硅藻群落特征及其对溶解性总氮总磷的指示作用

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摘要: 附着硅藻群落结构能快速、综合地反映水环境变化, 然而目前有关超大型城市河网附着硅藻群落特征及相关环境因子的研究, 还相对匮乏。以上海城市河网为例, 选取16条中小河道, 利用人工基质采集附着硅藻, 使用加权营养状态指数法(TSI)综合评估水质情况, 分析附着硅藻群落特征并量化附着硅藻群落响应溶解性氮、磷营养盐的阈值。结果显示: 调查水体中除宝山区束家湾2个位点外, 大部分位点均处于富营养状态; 硅藻群落中相对丰度超过10%的类群主要为舟形藻属(*Navicula*)、肘形藻属(*Ulnaria*)、菱形藻属(*Nitzschia*)、直链藻属(*Melosira*)和异极藻属(*Gomphonema*)等; 相对丰度超过1%的物种共计28种, 其中丰度最高的为变异直链藻(*Melosira varians*)。RDA分析显示, 水体溶解性总氮(DTN)、溶解性总磷(DTP)、氨氮(NH₄⁺-N)、二氧化硅(SiO₂)以及高锰酸盐指数(COD_{Mn})是影响附着硅藻群落差异的关键因子。另外, 临界指示物种分析(TITAN)显示附着硅藻群落会在DTN和DTP达到阈值时发生较大变化, 附着硅藻群落的DTN正响应阈值为2.26 mg/L, 正响应物种共14种, 其中指示种中纤细异极藻(*Gomphonema gracile*)的阈值最高, 为3.30 mg/L; DTP正、负响应阈值分别为0.12、0.16 mg/L, 正响应指示种共15种, 其中尖突异极藻(*Gomphonema acuminatu*)和纤细异极藻的阈值最高均为0.24 mg/L; 负响应指示种仅2种, 分别为橄榄绿异极藻(*Gomphonella olivacea*, 阈值为0.14 mg/L)和隐柔弱舟形藻(*Navicula cryptotenella*, 阈值为0.17 mg/L)。结论表明: 上海中小河道水体的关键水化学参数能显著影响硅藻群落结构; 纤细异极藻等物种可作为水体可溶性总氮总磷的指示物种。本研究为上海河网的生态监测和科学管理提供了基础数据和技术支撑。

关键词: 附着硅藻; 指示作用; 富营养化; 超大型城市; 临界指示物种分析

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藻类是水体中重要的初级生产者, 是水体地球化学循环的重要组分^[1]。附着藻类是一类可以生长在人工或天然基质上的微藻, 其多样性和群落组成特征可较好地反映水环境变化和水体受干扰程度^[2-3]; 其中附着硅藻对水体环境变化(如pH、温度和营养盐浓度等)非常敏感^[4]; 因此, 在河流以及一些水力扰动较大的湖泊中, 附着硅藻是非常关键的水质监测指示物^[5-6]。早在20世纪90年代, 国外就有学者使用“营养硅藻指数”(TDI)来评价欧洲河流的富营养化程度^[7]。近些年, 国内科研团队使用附着硅藻群落及各类指标对我国多条河流开展了水质评价研究^[8-11]; 近期,

刘心怡等^[12]又以深圳市的河道为例, 探究了硅藻群落功能多样性对城市化进程的响应。

附着硅藻群落在水体中受到多种环境因子的综合影响, 而在外界环境的影响下, 其群落也会在多种状态(稳态)间转换, 而不同状态存在“突变点”, 即: 当某个环境或多个环境因子的变化会引起硅藻群落结构和功能的快速巨变, 这个环境因子或者某几个环境因子所对应的点, 即为生态阈值^[13]。生态阈值观点的提出为研究水体环境胁迫因子, 筛选出关键指示性物种奠定了基础。目前, 常见的研究方法包括: 非参数突变点分析(nonparametric Change-point analysis,

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nCPA)、随机森林树分析(Random forest)以及临界指示物种分析(Thresholds indicator taxa analysis, TITAN)。目前,TITAN分析方法在三峡水库支流的氮磷阈值评估中开展了应用,筛选出了重要的附石硅藻指示种^[14]。杨璐等^[15]利用TITAN分析,对太子河着生藻类群落与氮、磷营养盐的定量关系进行研究,确定了多种指示性附着硅藻,为该流域氮磷污染控制提供了基础数据。不过,尽管国内外在河湖附着硅藻生态和水质评价方面开展了不少研究,但目前为止,有关超大型城市的河网附着硅藻群落特征和指示作用的研究还鲜有报道。

城市是以人为主体,由自然环境、社会经济和文化科学技术共同组成的综合系;强烈的人类活动干扰着城市水体,并深刻地改变着城市水生生态系统^[16-17]。重金属、营养物质(N、P等)以及新型污染物(如抗生素、微塑料和内分泌干扰物)等在城市水体中层出不穷^[18-19],对水体生态健康和功能造成严重危害。研究显示,由于污染物处理和水消费引起的城市水体问题已成为制约城市发展关键因素^[20]。因此,近年来水生态健康引起了人们的广泛关注;科学、准确的生态监测和城市水体生态恢复措施是扭转城市河流的污染和退化趋势的重要前提和保障。上海是典型的超大城市,水网密布,城市化水平高;其河流状态直接关系到2 000多万居民的生活。目前,上海仍然有很多水体正处于富营养化状态^[21];尽管已有研究从不同角度分析了富营养化对上海河道生物群影响,如:许志^[22]对上海河道浮游生物群落结构夏季的空间分布特征进行研究,并对其进行水质评价;顾国权^[23]分析了两种挺水植物在上海农村水体中的氮磷吸收情况,然而,关于上海城市河网中附着硅藻群落特征及其指示作用的研究极少。

本研究对上海典型中小河道进行生态调查,分析引起硅藻群落变化的关键因子和阈值,并获得对水体溶解性总氮(DTN)和溶解性总磷(DTP)具指示作用的特征性物种,旨在了解上海超大城市河网附着生物多样性和水生态状况,探究影响其群落结构差异的关键因子,为超大型城市河网水系水生态监测和科学管理提供理论基础。

1 材料与方法

1.1 研究区域和位点

在上海市中心、城郊以及崇明岛等8个不同区域,共选取16条中小河道,设置32个采样点(图1),包含了城市河道、乡村河道和城乡结合地区的河道类型;考虑到低温季节较适宜附着硅藻生长,于2015年12月—2016年1月(冬季)开展调查,利用人工附着基采集附着硅藻,并同步开展对应的生境要素调查。

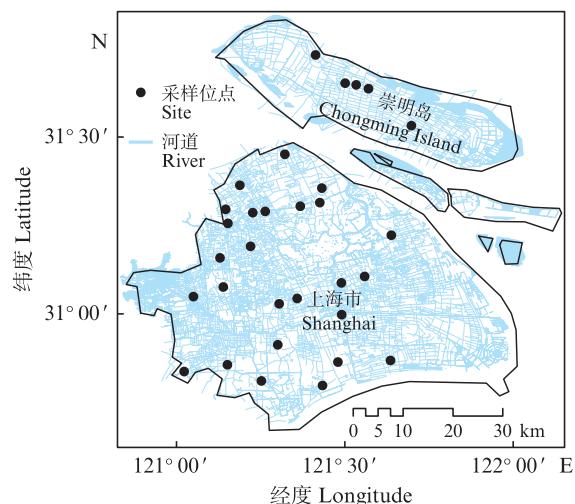


图1 上海中小河道附着硅藻采样位点
Fig. 1 Sampling locations for diatoms attached to small and medium-sized rivers in Shanghai

1.2 附着硅藻的采集和鉴定

附着硅藻采样:将自制附着基(10 cm×10 cm玻片架,安插10张标准载玻片)置于采样点1/2透明度左右的水深处,悬挂30 d,回收装置。从装置中随机取出2片载玻片,用软毛刷将藻类刷入培养皿中,用去离子水润洗刷子和培养皿,洗涤液和样品共同收集到血清瓶中,浓缩至50 mL,并加入鲁哥试剂和甲醛溶液进行固定,最后置于暗处保存,待进一步处理和鉴定。

硅藻定性鉴定:取10 mL样品,利用“盐酸+双氧水法”^[24]去除杂质,采用Naphrax[®]硅藻胶制作封片,硅藻的鉴定在1 000倍油镜(奥林巴斯BX51)下进行,每个封片至少计数400个壳体。硅藻物种鉴定主要参考LANGE-BERTALOT^[25]、KRAMMER等^[26]、胡鸿钧^[27]等的硅藻分类学著作。附着硅藻定量计数:依据下面的公式,计算定

量计数的各种类的个体数,并换算为1 cm²基质上藻类个体数量。

$$N_i = (C_1 \cdot L \cdot n_i) / (C_2 \cdot R \cdot h \cdot S) \quad (1)$$

式中:N_i为单位面积*i*种藻类的个体数,个/cm²;C₁为标本定容水量数,mL;C₂为实际计数的标本水量,mL;L为藻类计数框每边的长度,μm;h为视野中平行线间的距离,μm;R为计数的行数;n_i为实际计数所得*i*种藻类个体数;S为刮取基质的总面积,cm²。

1.3 理化指标测定

每个采样点分别在水深0.5 m和1.5 m处采集5 L混合水样,水深不足1.5 m的采集水深1/2处水样,并在4 h内送至实验室测定总磷(TP)、总氮(TN)、化学需氧量(COD_{Mn})、叶绿素a(*Chl.a*)、溶解总氮(DTN)、铵态氮(NH₄⁺-N)、亚硝酸盐氮(NO₂⁻-N)、硝酸盐氮(NO₃⁻-N)、溶解总磷(DTP)、磷酸盐(PO₄³⁻-P)和二氧化硅(SiO₂)等指标,测定方法参考《水与废水测定(第四版)》。溶解性有机碳(DOC)的测量采用总有机碳分析仪(TOC-VCPN,岛津,日本),重复水样所有参数的重现性均为>90%。使用YSI Pro Plus(USA)现场测定水中的pH、电导率(Spc)、盐度(Sal)和饱和溶解氧(DO);水体透明度(SD)使用赛氏盘现场测量。因附着藻类群落特征反映的是一段时间内水体总体的环境变化,本研究在挂片初期、中期和回收挂片时,分别采集水样进行水质测定,最后求3次的平均值,用于探究硅藻群落与环境因子之间关系。使用加权营养状态指数法(TSI)计算水体富营养化程度:

$$TSI(\Sigma) = \sum_{j=1}^m W_j (TSI)_j \quad (2)$$

式中:W_j为第*j*个参数的相关权重系数;TSI_j为第*j*个参数的营养状态指数。

1.4 统计方法

使用Origin 2021软件对各位点水体富营养化指数以及相对丰度>1%的物种进行展示。使用R语言中的vegan包对附着硅藻群落的丰度以及环境因子进行标准化转化。对硅藻数据采用自上而下的层级聚类(Agglomerative hierarchical clustering)进行聚类,根据欧几里得距离(Euclidean metric)对硅藻群落进行分组。采用主坐标分析法(Principal coordinates analysis, PCoA)研究群落分组情况,并使用相似性分析(Analysis of similarities, ANOSIM)来确定3组硅

藻的组成差异。此外通过相似性百分比(SIMPER)分析对群落差异的贡献物种。

环境因子采用单因素方差分析(ANOVA)检验组间差异的显著性。采用Fisher's Least significant difference(LSD)检验对环境数据的差异和方差的齐性进行检验(Levene's检验),或者采用事后多重比较Tamhane检验显著性。在选择合适的模型之前,利用DCA对4个排序轴的梯度长度进行了分析,对于附着硅藻类群,最长的排序轴(1)的渐变长度(Axis lengths)为2.369 6。因此,采用线性排序(冗余分析,RDA)来显示标准化环境变量与硅藻类群分布之间的关系。利用方差膨胀因子分析去除共线性环境因子,然后通过db-RDA进行分析。

当一个或多个环境变量低于或高于某个值时,可能在生态系统或特定组分中产生较大的响应,这就是生态阈值^[28-29];探明生态阈值是防止生物多样性和生态系统功能丧失的重要基础^[30]。使用R语言中TITAN包对附着藻群落组成的DTN和DTP的阈值进行TITAN分析,其主要方法为利用Bray-Curtis相异度来度量生物群落对营养盐浓度变化的响应。在数据分析前,对数据进行lg(a+1)数据分析以降低罕见种的影响,并排除出现频数低于3的物种。筛选后对符合要求的109种物种进行重抽样自举分析,次数为500次^[31]。最后以不确定性(*P*<0.05)、可靠度(reliability≥0.90)和纯度(purity≥0.95)为依据确定DTN、DTP的指示物种。

2 结果

2.1 上海中小河道富营养化状态及其硅藻群落特征

在32个采样位点中,仅宝山区束家湾2个位点处于中营养状态,占比6.25%,其他位点均处于富营养状态,其中轻度富营养状态水体占15.63%,中度富营养状态水体占75.00%,重度富营养水体占3.13%。共鉴定出了硅藻43属162种。在所有点位中,有5个属的相对丰度超过10%,分别为舟形藻属(*Navicula*)、肘形藻属(*Ulnaria*)、菱形藻属(*Nitzschia*)、直链藻属(*Melosira*)和异极藻属(*Gomphonema*);共计28个物种的相对丰度超过1%,其中丰度最高的是变异直链藻(*Melosira varians*),其次为谷皮菱形藻(*Nitzschia palea*)。

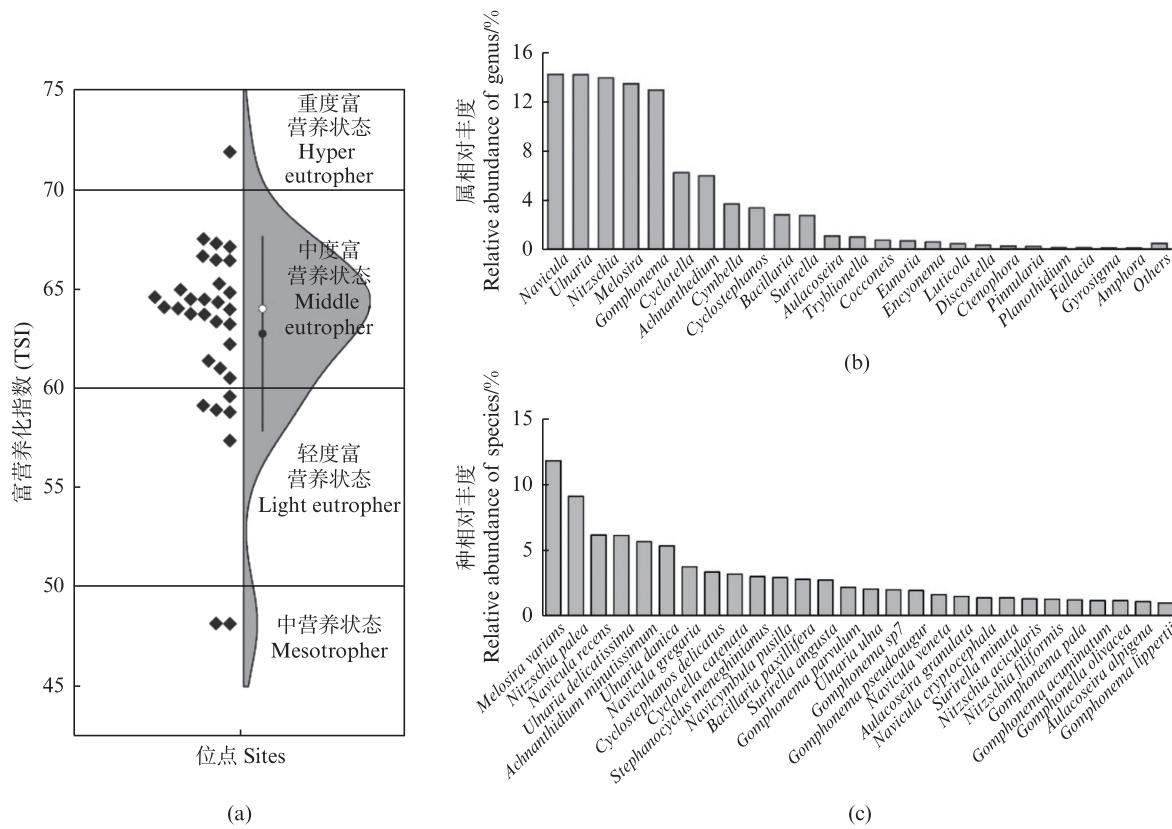


图2 上海中小河道富营养化状态及其附着硅藻种属相对丰度
Fig. 2 Eutrophication status of medium and small rivers in Shanghai and the relative abundance of periphytic diatom genus and species

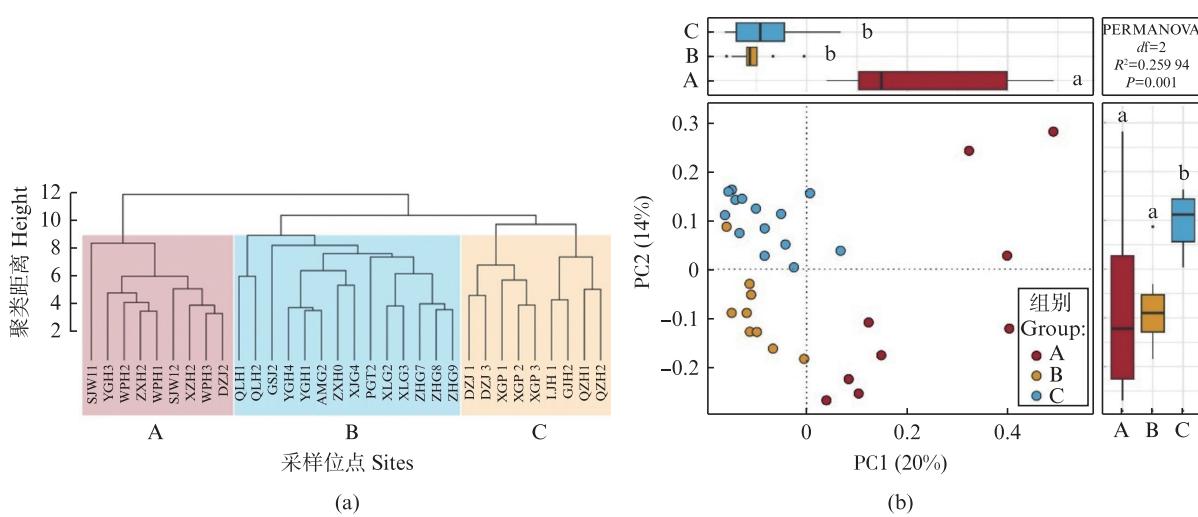


图3 附着硅藻群落聚类分析及群落组成差异
Fig. 3 Differences in periphytic diatom communities and species composition

根据欧几里得距离,层级聚类(AHC)分析将32个硅藻群落分成3大类(A-C组)(图3a)。A组,B组和C组硅藻的物种丰富度分别为93、137和117种,共有物种为77种。PCoA和ANOSIM分析,显示3组的硅藻群落存在显著差异($P<0.05$)。

A组水体优势物种有6种,其中优势度最高的为极小曲丝藻(*Achnanthidium minutissimum*)；B组中优势物种有12种,其中优势度最高的为变异直链藻(*Melosira varians*),该组特征物种(指示种)为谷皮菱形藻(*Nitzschia palea*)、颗粒沟链藻(*Aulacoseira granulata*)、微小双菱藻(*Surirella*)

minuta)以及丝状菱形藻(*Nitzschia filiformis*);C组有优势种15种,其中能表征该类水体的指示性

物种为:谷皮菱形藻和柔弱肘形藻(*Ulnaria delicatissima*),以及颗粒沟链藻(表1)。

表1 不同分组附着硅藻优势种及指示种
Tab. 1 Dominant and indicator species of periphytic diatoms in different groups

拉丁名 Latin names	组 A Group A	组 B Group B	组 C Group C
变异直链藻 <i>Melosira varians</i>	0.035 ⁺	0.249 ⁺ *	0.026 ⁺
谷皮菱形藻 <i>Nitzschia palea</i>	0.035 ⁺	0.081 ^{++*}	0.111 ^{++*}
新近舟形藻 <i>Navicula recens</i>	0.001	0.139 ⁺ *	0.009
柔弱肘形藻 <i>Ulnaria delicatissima</i>	0.004	0.004	0.121 ^{++*}
极小曲丝藻 <i>Achnanthidium minutissimum</i>	0.505 ⁺	0.006	0.001
丹尼卡肘形藻 <i>Ulnaria danica</i>	0.026	0.004	0.100 ⁺
群生舟形藻 <i>Navicula gregaria</i>	0.019	0.083 ⁺ *	0.003
精致环冠藻 <i>Cyclostephanos delicatus</i>	0.002	0.004	0.064 ⁺
链形小环藻 <i>Cyclotella catenata</i>	0.018	0	0.061 ⁺
梅尼冠盘藻 <i>Stephanocyclus meneghinianus</i>	0.008	0.023 ⁺ *	0.040 ^{++*}
小舟形桥弯藻 <i>Navicymbula pusilla</i>	0.023 ⁺	0.043 ^{++*}	0.019
奇异棍形藻 <i>Bacillaria paxillifera</i>	0.016	0.036 ⁺	0.024 ⁺
窄双菱藻 <i>Surirella angusta</i>	0.002	0.021 ⁺	0.037 ⁺
小型异极藻 <i>Gomphonema parvulum</i>	0.002	0.013	0.033 ⁺
肘状肘形藻 <i>Ulnaria ulna</i>	0.028 ⁺	0.019	0.020
异极藻 <i>Gomphonema</i> sp7.	0.001	0.001	0.040 ⁺
假尖顶异极藻 <i>Gomphonema pseudoaugur</i>	0.004	0.001	0.038 ⁺
威蓝色舟形藻 <i>Navicula veneta</i>	0.017	0.023 ⁺ *	0.010
颗粒沟链藻 <i>Aulacoseira granulata</i>	0	0.013 ^{**}	0.019 ^{**}
隐头舟形藻 <i>Navicula cryptocephala</i>	0.017	0.002	0.022 ^{++*}
微小双菱藻 <i>Surirella minuta</i>	0.007	0.025 ^{++*}	0.005
针形菱形藻 <i>Nitzschia acicularis</i>	0.004	0.006	0.020 [*]
丝状菱形藻 <i>Nitzschia filiformis</i>	0.004	0.020 ^{++*}	0.008
铲形异极藻 <i>Gomphonema pala</i>	0.011	0.008	0.016
尖异极藻 <i>Gomphonema acuminatum</i>	0.001	0.001	0.023 ^{++*}
橄榄绿异极藻 <i>Gomphonella olivacea</i>	0.001	0.028 [*]	-
高山沟链藻 <i>Aulacoseira alpigena</i>	0.001	0.011 [*]	0.013 [*]
利珀蒂异极藻 <i>Gomphonema lippertii</i>	0.002	0.002	0.017

注:“+”.优势种;“*”&“**”.指示种;“***” $P<0.001$;“**” $P<0.01$;“*” $P<0.05$;“-”.未检测到。

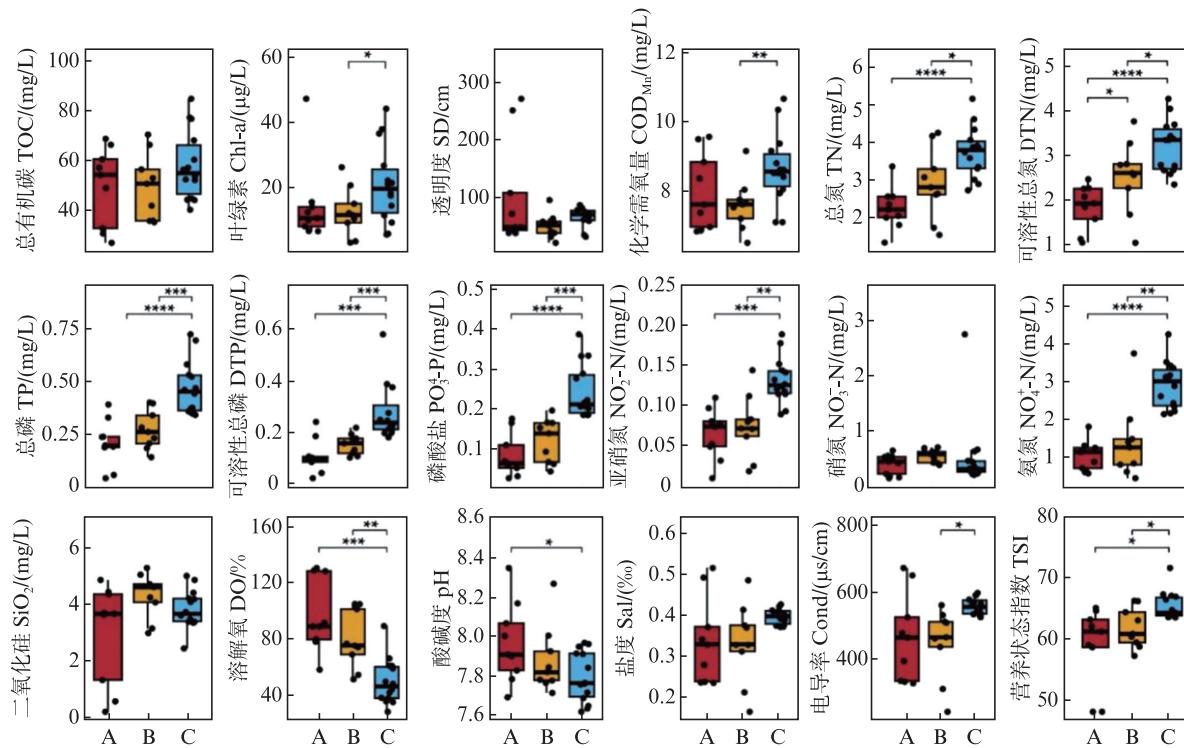
Notes: “+”. dominant taxa; “*”&“**”. indicator taxa; “***” $P < 0.001$; “**” $P < 0.01$; “*” $P < 0.05$; “-”. Not detected.

2.2 环境参数

本研究中,调查水体的TN浓度为1.32~5.14 mg/L,DTN浓度为1.04~4.25 mg/L,TP浓度为0.04~0.72 mg/L,DTP浓度为0.02~0.58 mg/L,*Chl.a*浓度为2.88~47.13 $\mu\text{g}/\text{L}$ 。A-C组3类水体的营养盐(除NO₃⁻-N外)、电导率以及盐度等环境因子,总体呈现为C组最高,B组次之,A组最低;3组营养盐存在显著差异,尤其是DTN浓度($P<0.05$)。*pH*和DO则呈现相反趋势。此外,TOC、SD、NO₃⁻-N、SiO₂和盐度等指标,3组未见显著差异($P>0.05$,图4)。

2.3 环境因子与硅藻群落的关系

RDA分析显示,前两个RDA轴的特征值分别解释了物种-环境因子关系的12.90%和8.53%(图5)。SiO₂、COD_{Mn}、DTN、DTP和NH₄⁺-N浓度与3组间的RDA得分呈现显著的相关性($P<0.005$),为关键性环境变量,其中DTN和NH₄⁺-N之间具有正相关关系($R^2=0.68$),其余环境变量(TOC、NO₃⁻-N、NO₂⁻-N、WT、pH以及Sal)与3组间的RDA得分呈现一定的相关性($P<0.01$)。变差分解后发现关键环境变量共解释了16.9%的群落变化。



显著性由*表示,其中**** $P<0.0001$,*** $P<0.001$,** $P<0.01$,* $P<0.05$ 。

The significance of the regression coefficients is indicated by *** $P<0.001$, ** $P<0.01$, * $P<0.05$.

图4 三组理化指标比较分析

Fig. 4 Comparison and analysis of physicochemical parameters among three types water bodies

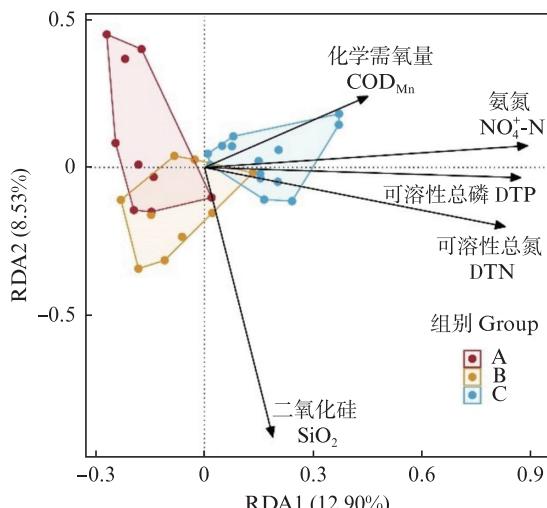


图5 环境变量与硅藻群落分布之间的冗余分析

Fig. 5 Redundancy analysis of environmental variables and diatom community distribution

2.4 临界指示物种分析

根据RDA(图5)和分组差异性分析(图4)的结果,选取DTN和DTP作为主要环境指标,用于结合硅藻群落数据,进一步开展TITAN分析。结果表明,DTN阈值浓度分别为0.12和0.16 mg/L时,硅藻群落会分别发生显著正、负响应变化;

DTN阈值为2.26 mg/L时,硅藻群落发生显著正响应(即响应变量随环境因子梯度增加而增加)(图6)。

TITAN分析获得DTP指示物种17种,其中正响应物种15种,DTP正响应指示种中,谷皮菱形藻(*Nitzschia palea*)出现频数最高,为31次,此外突细异极藻(*Gomphonema acuminatum*)和纤细异极藻(*G. gracile*)的阈值较高,为0.24 mg/L。DTP负响应指示橄榄绿异极藻(*Gomphonella olivacea*)和隐柔弱舟形藻(*Navicula cryptotenella*)出现频次较低,分别为7和11次;隐柔弱舟形藻的阈值较高,为0.17 mg/L。对DTN变化的指示性物种14种,均为正响应物种,其中谷皮菱形藻出现的频次最高,为31次,其次是梅尼冠盘藻(*Stephanocyclus meneghinianus*),为30次;纤细异极藻的阈值最高,为3.30 mg/L。

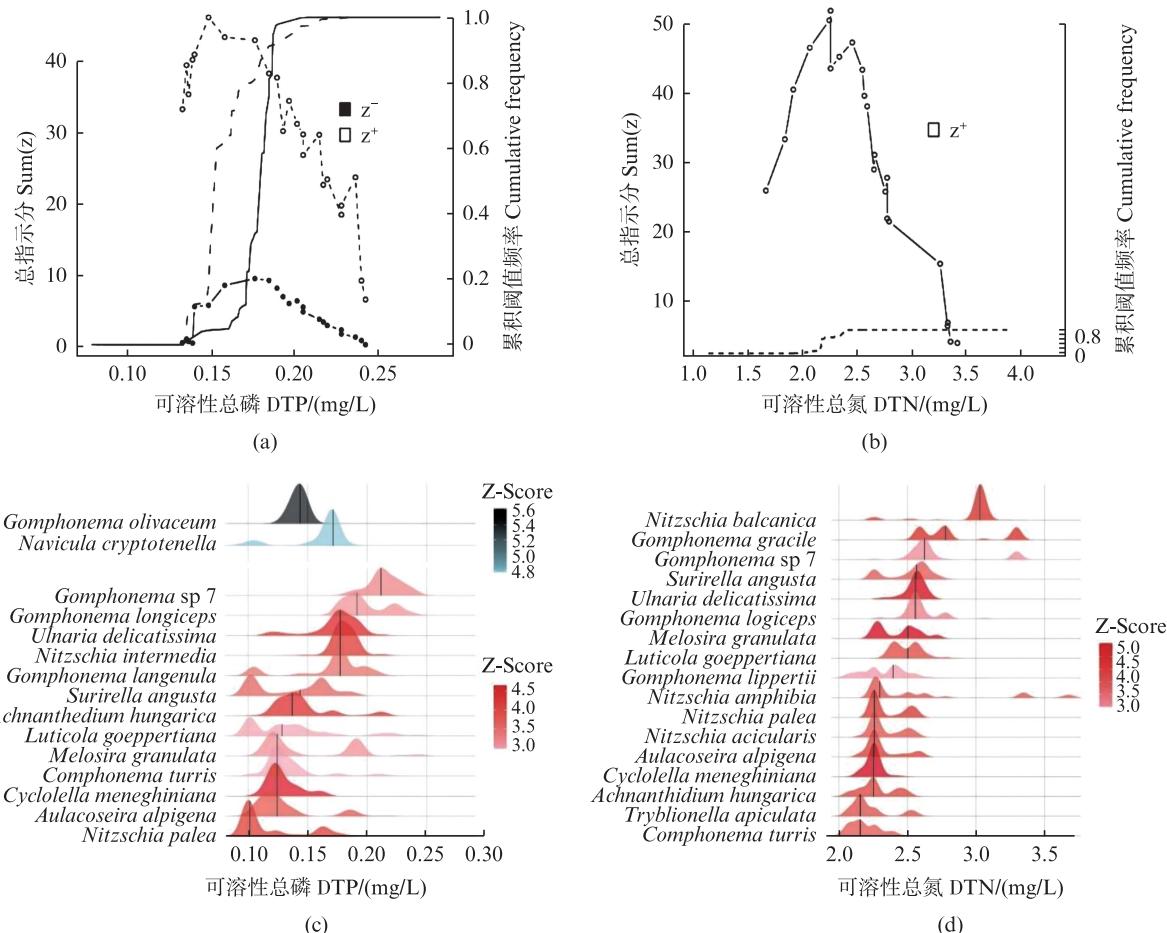
3 讨论

3.1 上海中小河道附着硅藻群落特征及环境驱动因子

本研究发现,上海中小河道水体的附着硅

藻,以舟形藻属、肘形藻属、菱形藻属、异极藻属和直链藻属等类群占优势,其中直链藻属的变异直链藻出现频率和相对丰度最高,这可能是因为该硅藻的生态幅较宽,是水体常见的泛化种^[32];该物种常常在低温季节富营养化程度高的河流中占据优势地位^[33-34],这和本研究调查的水质数据共同反映出上海中小河道总体处于富营养化状态^[21]。富营养化会驱动水体优势种群和指示类群更迭。而群落的优势类群和指示类群指示物种,能够综合地反映整体群落情况以及栖息地特征^[35]。本研究中上海中小河道附着硅藻群落总体分成3大类(组);不同的组别相对应的优势种、指示类群具有显著差别(图3,表1)。在组A中优势度最高的物种为极小曲丝藻,该物种对营养盐污染较为敏感,通常在水质相对较好的生境中出现^[36],常被用作水质良好的指示物种,同时

水质数据也显示A组的氮、磷浓度显著低于其他两组(图4)。在组B中变异直链藻的优势度远超其他物种,并且占比也远超其他两组,该物种喜欢富营养化,并略含有有机污染物的水体^[37]。附着硅藻对氨氮变化会产生快速的响应^[38],比如在组C中占据优势地位的谷皮菱形藻和尖肘形藻;而C组的营养盐水平特别是氨氮浓度显著高于其他组别。研究表明,谷皮菱形藻还是一种高氮磷环境的耐受物种^[39],在营养循环中也具有关键作用^[40];尖肘形藻的丰度常与水体中的营养盐水平呈正相关关系^[41]。三组的优势物种各有不同,但是B组和C组的指示种有所重合,均有谷皮菱形藻和颗粒沟链藻,可能与这两种指示物种的耐污性较强有关,而颗粒沟链藻占优也说明水体存在一定的扰动性^[42],这与上海位于长江口存在往复流有关。



z^- : 负响应物种; z^+ : 正响应物种。黑色和灰色虚线分别表示负响应种和正响应种沿环境阈值的响应,虚线表示累积频率。
 z^- : Negative responding species; z^+ : Positive responding species. Black and grey dotted lines respectively represented responses of negative responding species and positive responding species along nutrient gradients, and broken lines represented the cumulative frequency.

图6 附着硅藻群落对DTP和DTN的响应阈值

Fig. 6 The response thresholds of periphytic diatom communities to DTP and DTN in water columns

表2 TITAN 分析 DTP 指示物种及其阈值
Tab. 2 Indicating species and thresholds of DTP by TITAN analysis

物种 Species	阈值 Env.cp/(mg/L)	频数 Freq	方向 Maxgrp	显著性 Obsiv.prob	纯度 Purity	可靠性 Reliability
尖细异极藻 <i>Gomphonema acuminatum</i>	0.24	21	+	0.009	1	1
纤细异极藻 <i>Gomphonema gracile</i>	0.24	16	+	0.004	0.99	0.94
异极藻 <i>Gomphonema</i> sp.7	0.23	19	+	0.001	1	1
中型菱形藻 <i>Nitzschia intermedia</i>	0.18	13	+	0.002	1	1
双头菱形藻 <i>Nitzschia amphibia</i>	0.16	15	+	0.009	0.99	0.94
具领异极藻 <i>Gomphonema lagenula</i>	0.14	22	+	0.003	1	0.97
柔弱肘形藻 <i>Ulnaria delicatissima</i>	0.13	26	+	0.001	1	1
窄双菱藻 <i>Surirella angusta</i>	0.13	27	+	0.001	1	1
匈牙利雷曼尼卡藻 <i>Lemnicola hungarica</i>	0.12	25	+	0.001	1	1
塔形异极藻 <i>Gomphonema turris</i>	0.12	28	+	0.002	0.99	0.97
梅尼冠盘藻 <i>Stephanocycrus meneghinianus</i>	0.11	30	+	0.001	1	1
高山沟链藻 <i>Aulacoseira alpigena</i>	0.11	21	+	0.003	0.99	0.98
颗粒沟链藻 <i>Aulacoseira granulata</i>	0.11	21	+	0.007	0.99	0.95
桥佩蒂泥栖藻 <i>Luticola goeppertiana</i>	0.11	25	+	0.004	0.98	0.96
谷皮菱形藻 <i>Nitzschia palea</i>	0.10	31	+	0.001	1	0.99
橄榄绿异极藻 <i>Gomphonella olivacea</i>	0.14	7	-	0.001	1	0.99
隐头舟形藻 <i>Navicula cryptotenella</i>	0.17	11	-	0.001	1	0.99

注: 阈值表示各物种的响应阈值; 频数表示物种出现的频数; 方向表示响应的方向, 其中“-”表示负响应, “+”表示正响应; 显著性表示从数据中获得相等或较大的 IndVal 分数的可能性; 纯度表示自举重抽样中突变点的响应方向与所观察到响应方向一致的比例; 可靠性表示在 0.05 的显著性水平下自举抽样的可靠概率。下同。

Notes: Env. cp represents environment change point for each taxon based on IndVal maximum; Freq represents number of non-zero abundance values per taxon; Maxgrp represents the direction of responses, “-” means negative response and “+” means positive response; Obsiv. prob represents the possibility of obtaining an equal or large IndVal score from random data; Purity represents the proportion of correct assignments as a threshold indicator among bootstrap replicates; Reliability represents the proportion of obsiv. prob replicates <0.05. The same as the following table.

表3 TITAN 分析 DTN 指示物种及其阈值
Tab. 3 Indicating species and thresholds of DTN by TITAN analysis

物种 Species	阈值 Env.cp/(mg/L)	频数 Freq	方向 Maxgrp	显著性 Obsiv.prob	纯度 Purity	可靠性 Reliability
纤细异极藻 <i>Gomphonema gracile</i>	3.3	16	+	0.001	1	1
巴尔干菱形藻 <i>Nitzschia balcanica</i>	3.03	19	+	0.001	1	1
柔弱肘形藻 <i>Ulnaria delicatissima</i>	2.56	26	+	0.001	1	1
尖细异极藻 <i>Gomphonema acuminatum</i>	2.56	21	+	0.002	1	0.97
桥佩蒂泥栖藻 <i>Luticola goeppertiana</i>	2.48	25	+	0.003	0.99	0.97
窄双菱藻 <i>Surirella angusta</i>	2.42	27	+	0.001	1	1
颗粒沟链藻 <i>Aulacoseira granulata</i>	2.28	21	+	0.001	1	1
谷皮菱形藻 <i>Nitzschia palea</i>	2.26	31	+	0.001	0.99	1
双头菱形藻 <i>Nitzschia amphibia</i>	2.26	15	+	0.004	1	0.99
梅尼冠盘藻 <i>Stephanocycrus meneghinianus</i>	2.25	30	+	0.001	1	1
高山沟链藻 <i>Aulacoseira alpigena</i>	2.25	21	+	0.003	1	0.99
尖顶盘杆藻 <i>Tryblionella apiculata</i>	2.16	24	+	0.002	0.98	0.98
匈牙利雷曼尼卡藻 <i>Lemnicola hungarica</i>	2.12	25	+	0.002	0.99	0.99
塔形异极藻 <i>Gomphonema turris</i>	2.07	28	+	0.002	1	0.98

冗余分析显示, $\text{NH}_4^+ \text{-N}$ 、DTN、DTP、 SiO_2 和 COD_{Mn} 与硅藻群落变化显著相关。上海是一座超大型城市, 2015年末常住人口总数为达到了

2 415.27万人。有研究显示, 水体的营养元素, 各种离子含量、电导率和pH等都与人类活动强度成正比^[43]。水体的pH以及营养元素会改变附着

硅藻的群落结构。而在本研究中pH并非是上海中小河道附着硅藻群落的关键因子,这可能是由于上海整体区域人类活动较高,pH对附着硅藻群落的影响通常发生在低人类活动强度时^[43]。水体富营养化的风险。氮、磷等物质,尤其是溶解性氮磷物质的增加,会极大地促进耐受高营养微藻的生长,导致藻类群落结构的变化^[44-45]。此外,水体中溶解性氮、磷元素的浓度变化,还会改变硅藻代谢过程^[46]。河道中COD_{Mn}浓度既与人类活动的排放有关,也与高密度浮游植物分解释放有机物有关^[47],会通过形成低氧环境间接地影响附着硅藻的生长^[48]。而硅(Si)元素是硅藻生长发育过程中硅质外壳的必要元素,同时也会影响硅藻细胞中光合色素和蛋白质的合成^[49];研究表明,在富营养化水体中,硅酸盐浓度的增加会显著提高浮游硅藻的生物量占比,从而导致水体藻类群落结构的变化^[50]。

3.2 附着硅藻对中小河道氮磷的指示阈值

TITAN分析发现,上海中小河道附着硅藻对DTN的响应阈值与A组和B组DTN浓度的界限相近,从侧面验证可能是DTN的浓度变化导致A组和B组的群落差异。而硅藻群落对DTP的响应阈值与A、B组和C组DTP浓度有关,因此A、B两组和C组的群落差异可能是由DTP的浓度变化导致。氮、磷是富营养水体中最主要的污染物,硅藻群落对其的响应已有不少研究。通常而言,氮磷元素的增加对硅藻群落丰富度以及群落稳定性具有“低促高抑”的现象^[51-52]。近期美国俄亥俄州的一项DNA宏条形码的研究发现,硅藻群落对N元素的负响应阈值在0.280~0.525 mg/L之间^[53],响应阈值与本研究相近,这也从某种程度上解释了本研究DTN负响应物种缺失的原因,即:上海中小河道中DTN浓度过高,可能已经超过了硅藻群落DTN负响应阈值。

TITAN分析还可识别出敏感类群(负响应物种)和耐受类群(正响应物种),以及它们对不同干扰的个体反应^[54]。本研究中DTP指示物种和DTN指示物种具有重合部分,这是因为氮磷之间存在一定的协同作用^[55]。其中,谷皮菱形藻和梅尼小环藻出现的频数最高,且对DTP和DTN均为正响应物种。谷皮菱形藻是一种常见的环境耐受物种,在3.1节已有论述;梅尼小环藻具有很宽的生态位,在氮和磷等营养盐含量较高的情况

下甚至会出现水华现象^[56],长江和丹江口水库的相关研究也显示梅尼小环藻是富营养水体的指示物种^[57-58]。DTP的正响应物种中尖突异极藻(*G. acuminatum*)和纤细异极藻的响应阈值高于其他指示种,并且DTN的正响应物种中响应阈值最高的物种也是纤细异极藻。尖突异极藻是广布性物种,在淡水生境中喜欢中等电解质的水体,可以在富营养化水体中成为优势种^[59]。纤细异极藻(*G. gracile*)的过往研究显示其能耐受重金属以及除草剂等有毒物质^[60-61],但其对氮磷的响应的相关研究存在争议:巴西富营养化水体的研究认为纤细异极藻是环境耐受种,而土耳其奥赫里德湖和南非普马兰加高地地区的研究显示纤细异极藻是寡营养环境指示种^[62-63]。这种争议在不同的研究中并不罕见;不同研究之间研究手段、区域间气候特征、环境变量协同作用等的差异都会导致同一物种在不同区域呈现不同的指示特征^[64]。在本研究中得到的DTP和DTN耐受物种,中型菱形藻(*Nitzschia intermedia*)^[58]和柔弱肘形藻(*Ulnaria delicatissima*)^[65]在其他研究中被认为是寡营养指示种;除此之外,本研究中其他的耐受物种,如具领异极藻(*Gomphonema lagenula*)^[66]、窄双菱藻(*Surirella angusta*)^[67]、高山沟链藻(*Aulacoseira alpigena*)、颗粒沟链藻(*Aulacoseira granulata*)以及两栖菱形藻(*Nitzschia amphibia*)等和与他人研究相近,均能指示高氮磷的富营养化环境;另有研究显示,环境敏感物种橄榄绿异极藻和隐柔弱舟形藻为贫营养水体的指示种,对氮磷的耐受能力较弱^[68],这与本研究结果一致。

4 结论

上海中小河道冬季附着硅藻群落中主要为舟形藻属、肘形藻属、菱形藻属、直链藻属、异极藻属优势,水体总体呈富营养化状态;NH₄⁺-N、DTN、DTP、SiO₂和COD_{Mn}驱动附着硅藻群落变化的显著性因子。附着硅藻对DTP的正响应阈值为0.12 mg/L,负响应阈值为0.16 mg/L,对DTN的正响应阈值为2.26 mg/L。谷皮菱形藻、尖突异极藻和纤细异极藻等对DTP和DTN具有正向指示作用,而橄榄绿异极藻和隐柔弱舟形藻对DTP具有负向指示作用;对DTN起负向指示作用的物种存在缺失,可能是由于水体富营养化程度过高导致。

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Characteristics of periphytic diatoms communities to the urban river network in Shanghai and their indicative role for dissolved total nitrogen and total phosphorus

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Abstract: The characteristics of periphytic diatoms serve as effective indicators of changes in aquatic environments. However, research on the characteristics of periphytic diatom communities and their associated environmental factors in large urban river networks remains limited. Our study focuses on the urban river network of Shanghai City, selecting 16 medium and small rivers to investigate periphytic diatoms by using artificial substrates. The Trophic State Index (TSI) method was employed to comprehensively assess water quality. The characteristics of the periphytic diatoms communities were analyzed, and the threshold response of these communities to soluble nitrogen and phosphorus nutrients was quantified. Our results indicate that, with the exception of two sites in Shujiawan River, Baoshan District, most locations are eutrophic. The main genera with a relative abundance exceeding 10% include *Navicula*, *Ulnaria*, *Nitzschia*, *Melosira*, and *Gomphonema*. A total of 28 species with relative abundances greater than 1% were identified, with *Melosira varians* being the most dominant. Redundancy analysis (RDA) revealed that the primary factors influencing differences in periphytic diatom communities are dissolved total nitrogen (DTN), dissolved total phosphorus (DTP), ammonia nitrogen ($\text{NH}_4^+ \text{-N}$), silica (SiO_2), and chemical oxygen demand (COD_{Mn}). Furthermore, threshold indicator taxa analysis (TITAN) indicated that the periphytic diatom communities undergo significant changes when the thresholds of DTN and DTP are reached. The positive response threshold for DTN is 2.26 mg/L, while the thresholds for DTP are 0.12 mg/L (positive response) and 0.16 mg/L (negative response). Fourteen species exhibited a positive response to DTN, with *Gomphonema angustatum* showing the highest threshold at 3.30 mg/L. Fifteen indicator species responded positively to DTP, with *Gomphonema acuminatum* and *Gomphonema gracile* both displaying a threshold of 0.24 mg/L. Only two species showed negative responses: *Gomphonella olivacea* (threshold 0.14 mg/L) and *Navicula cryptotenella* (threshold 0.17 mg/L), while *Nitzschia palea* was the most frequently observed species, occurring 31 times. The results demonstrate that key water chemical parameters in small and medium rivers of Shanghai significantly influence the structure of diatom communities. Species such as *Gomphonema gracile* can serve as bioindicators for dissolved total nitrogen (DTN) and dissolved total phosphorus (DTP) levels in water bodies. This study provides foundational data and technical support for ecological monitoring and scientific management of Shanghai's river network.

Key words: periphytic diatoms; indicative role; eutrophication; megacity; threshold indicator taxa analysis