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长三角典型城郊流域生物可降解性有机质的分布及影响因素

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摘要: 快速城镇化改变了流域水体中碳的生物地球化学循环过程, 生物可利用性的溶解性有机质组分是其中最为关键的一环, 辨识生物可降解性有机质 (BDOM) 的时空分布特征及其影响因素对流域水质管控具有重要意义和应用价值. 以长三角地区典型城郊流域漳溪为研究对象, 根据流域地形特征、土地利用及人类活动强度布设监测点位, 于 2019 年分别在雨季和旱季采样, 利用三维荧光平行因子 (EEM-PARAFAC) 方法结合源汇景观模型研究流域水体 BDOM 的时空分布特征. 结果表明, 流域中生物可降解性有机碳浓度范围在 $0.57 \sim 6.80 \text{ mg} \cdot \text{L}^{-1}$, 且具有较高的时空异质性, 人类活动强度较高的区域水体中 BDOM 的浓度也相对较高, 且雨季显著高于旱季. EEM-PARAFAC 分析结果表明, 流域 BDOM 主要包括陆源腐殖质 (C1) 和类蛋白质类 (C2) 这 2 种荧光组分. 流域 BDOM 及其陆源腐殖质荧光组分主要受土地利用和人类活动的影响, 其浓度与农业及城镇用地比例和源汇景观负荷比 (LWLI) 关系密切, 表明城镇化过程中人类活动是影响 BDOM 分布的重要因素.

关键词: 城郊流域; 溶解性有机质 (DOM); 生物可降解性有机质 (BDOM); 土地利用格局; 平行因子分析

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Distribution of Biodegradable Dissolved Organic Matter and Its Affecting Factors in a Typical Peri-urban Watershed in Yangtze River Delta

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Abstract: Dissolved organic matter (DOM) plays key roles in the carbon biogeochemical cycle, and biodegradable dissolved organic matter (BDOM) is one of the key fractions of DOM. Rapid urbanization and intensive human activities substantially influence the distribution of DOM at the watershed scale. Identifying the spatial and temporal variability in BDOM has become an important and urgent issue of water quality control in rapid urbanization areas. However, limited studies have been conducted to explore the role of human activities on the occurrence and distribution of BDOM in peri-urban watersheds. In this study, the spatial and temporal distribution of BDOM and related affecting factors were investigated in a typical peri-urban watershed (Zhangxi watershed) located at Ningbo City in Yangtze River Delta. Water samples were collected in wet and dry seasons in 2019 based on topographic features, land use, and intensity of human activities. The BDOM were characterized by fluorescence excitation-emission matrix and parallel factor analysis (EEM-PARAFAC), and land use patterns were analyzed using the Source-Sink Landscape Model. The results of this study showed that the BDOM concentrations ranged from 0.57 to $6.80 \text{ mg} \cdot \text{L}^{-1}$. Obvious spatial and temporal heterogeneities of BDOM were found at the watershed scale, and significantly higher concentrations of BDOM were observed in the wet season than those in the dry season. Furthermore, relatively high concentrations of BDOM were found in areas with relatively higher intensive human activities. Two fluorescent components (a terrestrial humic-like substance and protein-like substance) were observed using the PARAFAC model. The results of spatial analysis showed that terrestrial humic-like fluorescent components were closely positively correlated with anthropogenic parameters (percentages of agricultural and urban land and ratio of source and sink landscapes). The results showed that the occurrence and distribution of BDOM were strongly influenced by human activities, which could provide scientific guidance for water quality control and related land management in peri-urban aquatic ecosystems.

Key words: peri-urban watershed; dissolved organic matter (DOM); biodegradable dissolved organic matter (BDOM); land use pattern; parallel factor analysis

城郊是连接城镇与乡村的关键过渡地带, 城郊地区土地利用多样、景观结构复杂、生态系统结构和功能独特^[1]. 城镇化梯度的三元结构(城镇核心区、城镇郊区和乡村/自然地区)的边界及其承载的环境过程也随城镇扩张不断改变^[2,3]. 一方面, 城郊为城镇提供关键的原材料、能源和农产品等, 使得城郊成为生态系统服务功能冲突最为强烈的. 另一方面, 大量的城市工业污染和废弃物进入城郊, 使得城郊地区生态系统服务的供需冲突最为强烈^[4,5].

溶解性有机质 (dissolved organic matter, DOM) 是一类结构复杂的有机混合物且极其不稳定, 是无机碳和生命形态碳的关键纽带^[6]. 生物可降解性有机质 (biodegradable dissolved organic matter, BDOM) 是指水体中可被细菌降解成 CO_2 或用于维持自身生长

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繁殖的有机物,为微生物提供碳源和能源,是 DOM 重要的组成部分^[7]. 环境中的细菌群落结构与功能也与 DOM 的生物降解性密切相关^[8,9]. 具有不同生物降解性的 DOM 会引起细菌多样性,群落结构和代谢的不同反应,反映在碳消耗、生长和呼吸速率和酶的降解方面^[10-12]. 不稳定的蛋白质和脂肪族化合物能够被细菌快速利用,而稳定的材料只能被特定的基团降解^[10-12]. 以生物可降解溶解性有机碳 (biodegradable dissolved organic carbon, BDOC) 可作为饮用水生物稳定性指标来衡量 BDOM,其代表异养微生物降解的溶解性有机碳^[13]. BDOC 已广泛应用于地表水有机物^[14]、天然有机物^[15]和海水^[16]的生物降解性和转化研究,但目前对于实际水体中 BDOM 的特点和组成分析报道较少,探索生物可降解性的过程,可以更好地理解 DOM 动力学以及生态系统中能量和物质循环^[17].

人类活动对城郊生态系统 DOM 的含量和性质造成了剧烈影响,打破了原有的碳循环过程^[18]. 有研究表明,植被类型和土地利用类型可对流域内 DOM 和 BDOC 造成重要影响^[7]. Zhou 等^[19]的研究发现,人为的干扰、经济发展水平的提高以及城市和农业土地使用加剧,会增加流域中有机碳的负荷或改变其组成和生物可利用性. 近年来,随着我国快速的城镇化过程,城郊地区已成为生态系统服务功能冲突最激烈的区域^[5]. 不同的人类活动会造成独特的 DOM 组成,城郊剧烈的人类活动直接改变了 DOM 的含量和性质,Zhang 等^[20]对嘉陵江南充段的研究发现,其有色可溶性有机物 (colored dissolved organic matter, CDOM) 的来源和组成主要受城市化发展的影响;对于东北吉林省水域的研究表明,城镇化发展过程中的人为活动促进了 DOM 数量的增加,导致 DOM 组分向类蛋白质成分转化^[21]. 源汇景观格局分析方法将景观格局与生态过程有机结合,

可定量表征不同景观类型及其空间配置对特定生态过程的影响^[22],已广泛应用于生态环境领域. 例如,周添惠等^[23]利用源汇景观格局分析方法研究了黄土高原渭河源流域径流及泥沙特征,结果表明在长时间尺度上源汇景观格局演变改变了流域径流及泥沙特征. 在海河流域的研究中也表明,源汇景观格局指数与总氮的空间变异特征密切相关^[24]. 李敏等^[25]在樟溪流域中的研究也显示,源汇景观负荷比指数 (LWLI) 与水体抗生素浓度呈正相关关系,流域 LWLI 越大其水体抗生素浓度越高.

然而现有的研究多致力于流域 DOM 的分布及影响因素,对城郊流域 BDOM 的分布特性及其与源汇景观格局的关系的研究还很薄弱. 因此,本文以宁波城郊关键带樟溪流域为研究区域,通过对流域水体的采样分析,分析不同城镇化梯度下流域水体 BDOM 的分布特性,揭示城郊流域 BDOM 浓度变化的驱动因子,以期快速城镇化背景下城郊流域的水环境质量和安全保障提供科学支撑.

1 材料与方法

1.1 研究区概况

樟溪流域 (29°44' ~ 29°51' N, 121°13' ~ 121°21' E) 位于浙江省宁波市 (图 1), 总面积 89.7 km². 该流域属亚热带季风气候,有明显的雨季和旱季,雨季一般在 4 ~ 9 月,累计降雨量为 1 035 mm,旱季一般在 10 ~ 12 月和 1 ~ 3 月,累计降水量为 782 mm^[4]. 研究区内樟溪为奉化江支流,全长 14.5 km,上游为饮用水源地皎口水库,流经章水、龙观和鄞江这 3 个乡镇. 研究区位于四明山区向宁绍平原的过渡地带,主要土地利用类型有城镇建设用地、农田、园地、林地和水库等,其土地利用格局受城镇化影响较大. 农田主要以贝母、花生和蔬菜种植为主,林地主要为亚热带常绿阔叶林,园地主要为经济林木苗圃^[26].

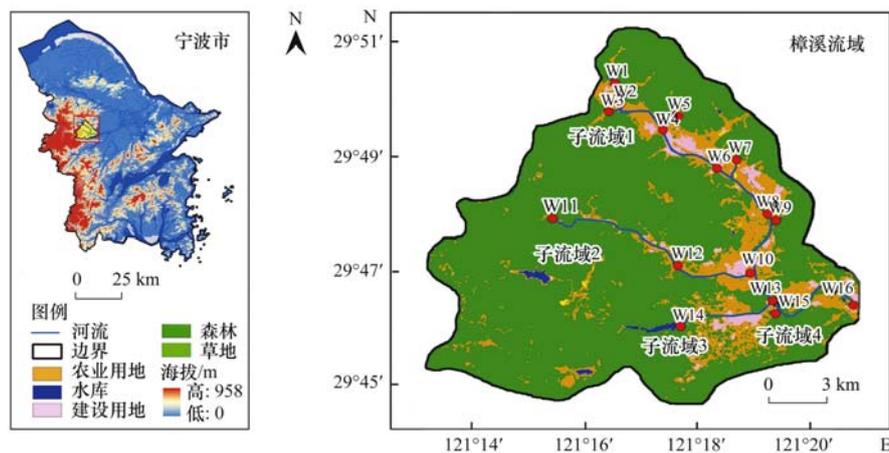


图 1 研究区土地利用和采样点分布示意

Fig. 1 Land use and water sampling sites of study area

基于流域的土地利用特征、水文路径和地形因素,根据人为干扰程度,将研究区划分为4个城市化梯度明显的子流域:子流域4 > 子流域1 > 子流域2 > 子流域3,设置了16个监测断面用于地表水的长期定位监测,其中采样点W1~W9属于子流域1,W11~W12属于子流域2,W14属于子流域3,流域点位靠近水库,为森林覆盖率较高的自然生态系统(96.3%),W10、W13、W15和W16属于子流域4,相比其它子流域其农业用地和建设用地比例较高,为耕地(35.8%)和城镇(10.3%)^[5].

1.2 样品采集

样品采集于2019年6月(雨季)和12月(旱季).使用pH < 2的硫酸处理过的5 L棕色玻璃瓶,在每个河流采样点中间水面30 cm深处收集3个平行水样(样瓶用水样预冲洗3次),在密封无气泡状态下4℃低温黑暗保存运回,并在1 d之内完成实验培养^[7].

1.3 实验室培养测定BDOC

参照文献^[7,27]进行DOM的培养.首先加入3 mL过1.2 μm GF/F滤膜作为接种微生物到血清瓶中,然后移取30 mL过0.45 μm GF/F滤膜的水样到血清瓶中进行培养,再分别加入100 μL的NH₄NO₃和K₂HPO₄溶液,以降低营养盐对微生物活性的限制,用等体积去离子水加营养盐设置空白对照实验.所有样品放入恒温培养箱25℃条件黑暗培养,每24 h打开瓶盖并摇晃一次,以确保有氧条件;分别在第0、2、7、14、21和28 d取样,用0.45 μm GF/F滤膜(预先在马弗炉中450℃灼烧5 h除去有机质)过滤,并立即测定DOC的浓度,最终结果取3个平行水样的平均值.由于0.45 μm滤膜重新过滤几乎可以过滤掉全部的微生物量,所以最后测得DOC降解程度包括了微生物矿化作用和同化作用两部分的量,以上所有操作均在无菌超净台完成.DOC浓度采用总有机碳(TOC V-CPH, Elementar, Germany)进行.

1.4 DOM的光谱特性

DOM的光谱表征包括紫外-可见光光谱和荧光光谱,采用紫外分光光度计(UV3600, Shimadzu, Japan)扫描200~600 nm吸光度,采用荧光分光光度计(F-4600, Hitachi, Japan)进行水体DOM的三维荧光光谱测定,配以1 cm石英比色皿.以超纯水为实验空白,对水样进行三维荧光扫描.仪器光源为150 W氙灯,光电倍增电压为800 V,激发和发射狭缝宽度均设置为5 nm,相应时间0.1 s,激发波长(E_x)为220~450 nm,扫描间隔5 nm;发射波长(E_m)为260~600 nm,扫描间隔1 nm;扫描速度为2 400 nm·min⁻¹.所有水样的三维荧光均需减去空

白光谱,以消除拉曼散射的影响^[28,29];并将发射波长等于激发波长和发射波长等于2倍激发波长包围外的区域光谱值赋值为零,以修正瑞利散射的影响^[30].使用MATLAB 2014a(Math Works, Natick, USA)和DOMFluor工具箱执行平行因子分析(parallel factor analysis, PARAFAC)^[31,32],使用OpenFluor网站(<http://www.openfluor.org>)的在线光谱库来验证PARAFAC的结果^[4].

1.5 源汇景观模型

源汇景观模型(source-sink landscape model, SSLM)是中国科学院生态环境研究中心城市与区域生态国家重点实验室开发的分布式评价模型^[26],是基于ArcGIS开发的toolbox模型插件.SSLM根据研究区的土地利用特征和DOM的排放性质,将建设用地、农田和林地划分为“源”景观,将河流和水库划分为“汇”景观.通过SSLM可以快捷地进行流域范围划分,提取汇水区范围内的DEM和土地利用,输出距流域出水口距离、流域坡度并通过海拔、坡度和距离等参数绘制不同源和汇景观的洛伦兹曲线,并计算出源汇景观负荷比指数(LWLI).对于海拔高程和距离要素,LWLI越大,景观在高程或距离要素上的分布越有助于推动子流域出口点的环境效应,而对于坡度要素,LWLI越大,景观在坡度要素上的分布越有助于阻碍子流域出口点的环境效应^[25].

1.6 数据处理

本文对实验室培养测定BDOC用到的两种关系见式(1)和式(2)^[7]:

$$\text{BDOC}_t = \text{DOC}_{t_0} - \text{DOC}_t \quad (1)$$

$$\text{BDOC}_A = \frac{\text{DOC}_{t_0} - \text{DOC}_t}{\text{DOC}_{t_0}} \times 100\% \quad (2)$$

式中,BDOC_t为t时刻的微生物可降解溶解性有机碳浓度(mg·L⁻¹),DOC_{t₀}为样品初始时刻溶解性有机碳浓度(mg·L⁻¹),DOC_t为t时刻的溶解性有机碳浓度(mg·L⁻¹),BDOC_A为BDOC的降解率(%).本文研究利用SPSS 25.0和EXCEL 2017对数据进行处理和描述性统计,采用Origin 2017处理土地利用与DOC、BDOC的相关关系;使用ArcGIS 10.5对研究区土地利用数据进行处理,源汇景观负荷比指数由SSLM进行计算;使用R语言Corrplot对DOC和BDOC和源汇景观负荷比指数以及土地利用进行矩阵相关分析.

2 结果与分析

2.1 BDOM的生物利用时间动力学

DOM浓度经常用溶解性有机碳(dissolved

organic carbon, DOC) 浓度来进行量化, 所以利用 DOC 浓度变化情况来解释 BDOM 的降解动力学过程^[33]. 樟溪流域水样的 DOM 降解动力学过程如图 2 所示, 在培养过程中, 水样的 DOC 浓度逐渐下降直至达到平衡. 整个降解动力学过程可用一级降解动力学方程拟合.

基于一级降解动力学理论, 拟合典型土地利用样本数据随时间的变化, 采用生物降解动力学模型, 表述如式(3)^[34]:

$$C_{\text{DOC},t} = C_{\text{DOC,eq}}(1 - e^{-kt}) \quad (3)$$

式中, t 为降解时间(d), $C_{\text{DOC},t}$ 为 t 时刻 DOC 生物降解率(%), $C_{\text{DOC,eq}}$ 为达到平衡时 DOC 生物降解所占的质量分数(%), k 为降解系数(d^{-1}). 对不同典型土地利用样本 DOC 生物降解所占的质量分数随时间变化进行曲线拟合, 得到降解系数 k 和达到平衡时 $C_{\text{DOC,eq}}$ 的浓度, 动力学模型结果显示所有样品在 28 d 之内均已达到平衡^[19], 因此本研究以最终培养 28 d 降解后损失的 DOM 为 BDOM.

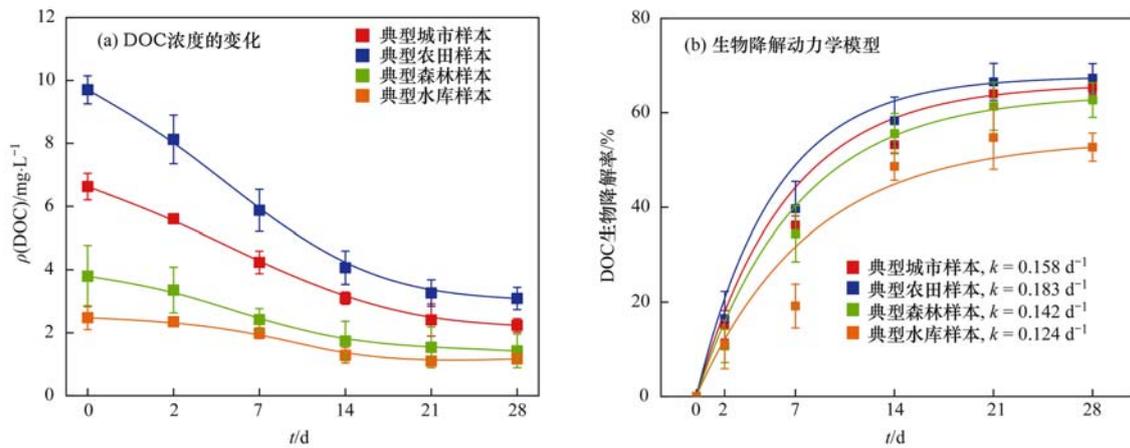


图 2 典型样本 DOC 浓度的变化和生物降解动力学模型

Fig. 2 Variation in DOC concentration and biodegradation kinetic model for a typical sample

2.2 樟溪流域 BDOC 的区域分布特征

结果表明, 培养完成后樟溪流域的 $\rho(\text{DOC})$ 在 $0.87 \sim 3.29 \text{ mg} \cdot \text{L}^{-1}$ 之间, 其中雨季 $\rho(\text{DOC})$ 为 $0.98 \sim 3.29 \text{ mg} \cdot \text{L}^{-1}$, 平均值为 $(1.85 \pm 0.66) \text{ mg} \cdot \text{L}^{-1}$, 旱季 $\rho(\text{DOC})$ 为 $0.87 \sim 2.13 \text{ mg} \cdot \text{L}^{-1}$, 平均值为 $(1.51 \pm 0.36) \text{ mg} \cdot \text{L}^{-1}$, 雨季浓度显著高于旱季 ($P < 0.001$). $\rho(\text{BDOC})$ 在 $0.57 \sim 6.80 \text{ mg} \cdot \text{L}^{-1}$ 之间, 雨季 $\rho(\text{BDOC})$ 范围为 $1.12 \sim 6.80 \text{ mg} \cdot \text{L}^{-1}$, 平均值为 $(3.69 \pm 1.70) \text{ mg} \cdot \text{L}^{-1}$, 在旱季 $\rho(\text{BDOC})$ 范围为 $0.57 \sim 2.17 \text{ mg} \cdot \text{L}^{-1}$, 平均值为 $(1.41 \pm 0.49) \text{ mg} \cdot \text{L}^{-1}$, BDOC 浓度在旱、雨季存在极显著性差异

($P < 0.001$). 在各子流域之间 BDOC 浓度也存在极显著的差异 ($P = 0.001$), 旱雨季中 BDOC 浓度在各子流域中的分布趋势保持一致, 中位值由高到低依次为: 子流域 4 > 子流域 1 > 子流域 2 > 子流域 3 [图 3(a)].

樟溪水样的 BDOC_A 年增长率平均值为 $(56.2 \pm 12.4)\%$, 其中雨季样品的 BDOC_A 增长率平均值为 $(65.1 \pm 6.6)\%$, 旱季增长相对较低 [$(47.3 \pm 10.3)\%$], 雨季和旱季存在极显著差异 ($P < 0.001$), 这是因为水温对水样的影响, 旱季多低温 ($< 5^\circ\text{C}$) 会降低水样中的微生物活性, 减缓 DOC

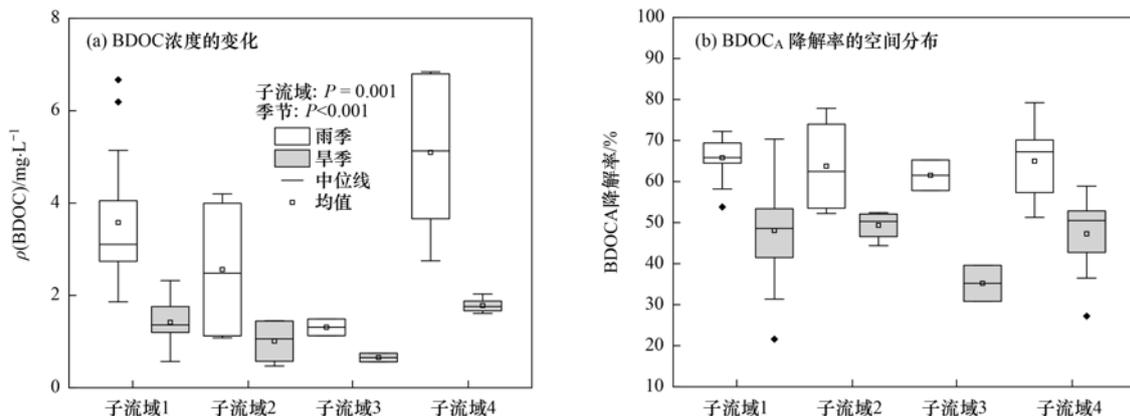


图 3 旱雨季 BDOC 浓度和 BDOC 降解率的空间分布

Fig. 3 Spatial distribution of BDOC concentrations and BDOC degradation rate in dry and rainy seasons

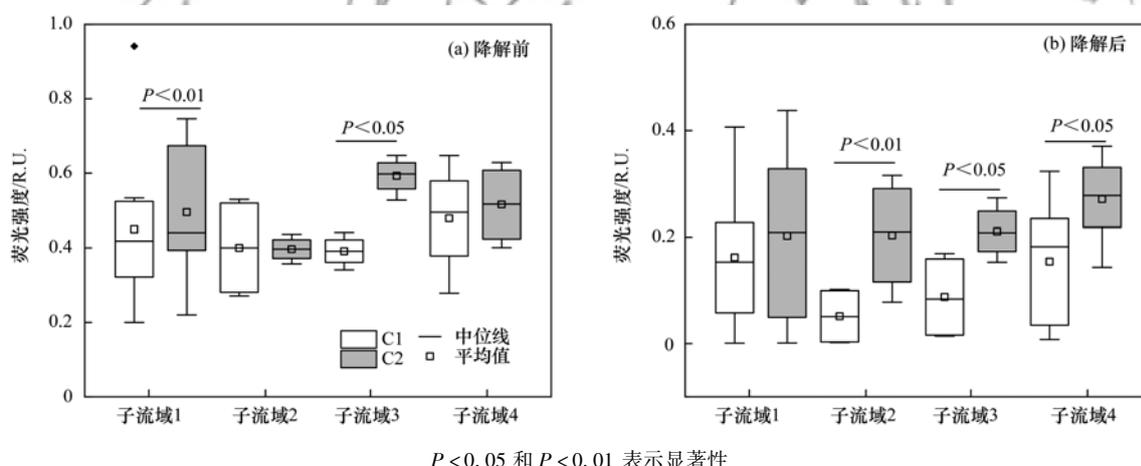
的降解,而雨季温度相对较高($>20^{\circ}\text{C}$)促进了水样中的细菌生长与活动,更易造成 DOC 的损失与降解^[35];各子流域之间 BDOC_A 值也存在极显著差异[图 3(b)],其中子流域 4 的 BDOC_A 值最高,雨季和旱季分别为 $(65.0 \pm 9.3)\%$ 和 $(47.3 \pm 10.3)\%$;子流域 3 则最低,雨季和旱季分别为 61.5% 和 35.2% . 同时,各流域 BDOC_A 值与 BDOC 浓度在子流域中的分布趋势一致,随着人类活动程度增加而升高^[36,37],表明溶解有机质的可利用性越强.

2.3 DOM 的荧光特性

利用三维荧光-平行因子模型分析得到 2 个组分:陆源腐殖质组分 C1 ($E_x = 230$, $E_m = 425$ nm)^[38,39],蛋白质类组分 C2 ($E_x = 225$ (275), $E_m = 332$ nm)^[40]. 本研究结果与 EEM-PARAFAC 模型数据库 OpenFluor 有很好的匹配(相似性 $>95\%$).

培养前后樟溪水样的陆源腐殖质 C1 无显著差异($P > 0.05$),且 C1 组分的 F_{\max} 值(0.45 ± 0.18)略低于蛋白质类 C2 组分(0.49 ± 0.15);C2 组分反而

平均降低了 0.17 ± 0.2 ,各样点之间具有显著差异性($P < 0.05$).4 个子流域中组分 C1 的荧光强度与 BDOC_A 分布一致:子流域 4 $>$ 子流域 1 $>$ 子流域 2 $>$ 子流域 3;组分 C2 的荧光强度分布为:子流域 3 $>$ 子流域 4 $>$ 子流域 1 $>$ 子流域 2 [图 4(a)];这可能是因为夏季垂钓事件频繁发生,水库人为影响因素较大,所以蛋白质类 C2 组分相对较高^[41];而以森林为主的子流域 2 荧光强度最低,Tang 等^[4]的研究结果表明,森林等自然流域所含的荧光组分相较于城区等强度较低.培养后各子流域陆源腐殖质 C1 和蛋白质类 C2 分布与培养前 C1 组分一致[图 4(b)].而组分 C2 的降解幅度显著高于 C1,相较于其它子流域,子流域 4 的组分 C2 降解量最高.该结果与樟溪流域整体变化趋势一致,表明在培养过程中,腐殖质类物质含量相对较低且相对稳定^[42],而微生物活动也会优先与类蛋白质发生反应^[19,43],同时 C1 和 C2 组分在不同子流域内的分布情况表示人为活动和土地利用比例会影响河流 DOM 的化学组成和浓度变化^[44].



$P < 0.05$ 和 $P < 0.01$ 表示显著性

图 4 PARAFAC 降解前与降解后荧光组分箱形图比较

Fig. 4 Comparison of box diagrams of fluorescent fractions before and after PARAFAC degradation

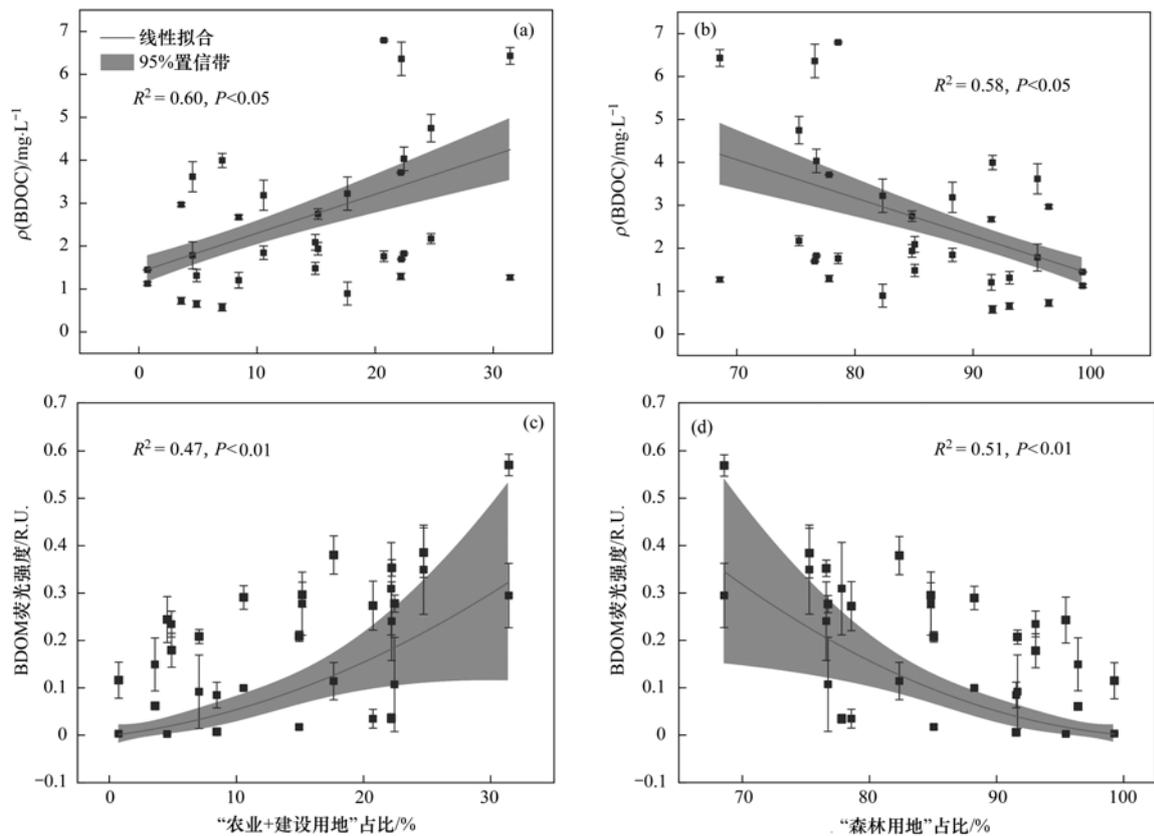
3 讨论

源汇景观模型通过输入流域数字高程模型(digital elevation model, DEM)数据、土地利用数据和流域出口位置计算得出基于距离的景观负荷比指数(LWLI. D),基于坡度的景观负荷比指数(LWLI. S),源汇景观负荷比指数(LWLI),基于海拔的景观负荷比指数(LWLI. E)等指标.然后进一步通过源汇模型指数,将源汇土地利用比例和景观负荷比指数与其流域水文过程结合起来,可描述 BDOM 在流域内的时空分布规律.利用源汇景观计算樟溪流域的土地利用格局可间接表征流域内人类活动强度.结果表明樟溪流域培养 28 d 后的 BDOC 浓度与源汇模型中“农

业 + 建设用地”占比有显著正相关关系 [$R^2 = 0.60$, $P < 0.05$,图 5(a)],与林地用地占比显著负相关 [$R^2 = 0.58$, $P < 0.05$,图 5(b)].在城市化梯度的研究中也发现,城镇流域中 BDOC 浓度显著高于森林溪流 ($P < 0.001$)^[45];这表明随着流域内人类活动强度(农业和城镇用地)的增加,流域水体中 BDOC 浓度有明显的上升趋势^[46].土地利用方式与人类活动关系密切,而人为干扰较少的林地中 BDOC 浓度则较低^[47].樟溪流域 DOM 浓度分布的结果也表明,流域内未进行充分处理的生活污水等进入水体也可能增加 BDOC 浓度^[5].这些发现说明,流域城市化导致河流 DOM 浓度变化影响河流生态系统的新陈代谢,并最终影响河流中有机碳的命运^[45].

BDOM 与土地利用的相关性和 BDOC 浓度一致,与源汇模型中“农业 + 建设用地”占比有显著正相关关系 [$R^2 = 0.47, P < 0.01$, 图 5(c)],与林地用地占比显著负相关 [$R^2 = 0.51, P < 0.01$, 图 5(d)].这是因为在林地中腐殖质的来源主要为陆源植物的凋落;而在农业和建设用地中,人为活动会影响水体中的 DOM 组成,这在一定程度上会促成微生物的生长^[25],在内源微生物的降解和部分陆源输入的情况下^[48],导致 BDOM 荧光强度随着“农业 + 建设用地”占比的增加而上升.

由图 5(c)和图 5(d)可知,BDOM 与“农业 + 建设用地”占比和 BDOC 浓度相一致,也存在着显著正相关 ($R^2 = 0.47, P < 0.01$),且 BDOM 与森林用地占比存在显著负相关 ($R^2 = 0.51, P < 0.01$).由此也可表明人类活动强的土地利用类型是水体 BDOM 和 BDOC 的重要来源.这是因为与城镇相邻的河流,其沿岸分布了一定面积的农田,由人类活动产生的 DOM 会随地表径流进入水体,这在一定程度上会造成微生物的生长,容易发生藻类暴发等,严重污染水体环境^[30].



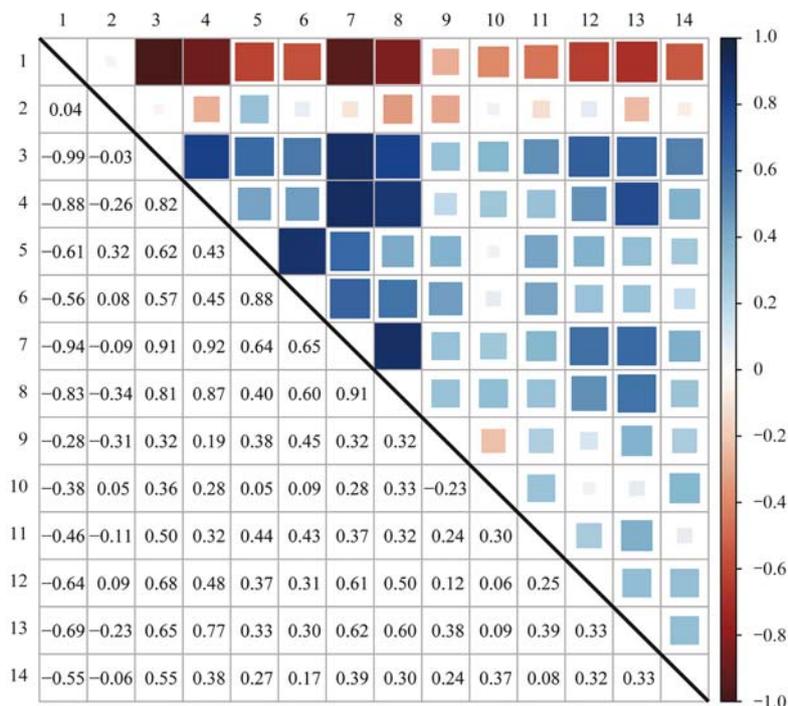
(a)和(b)分别表示 BDOC 浓度与“农业 + 建设用地”和森林用地占比的相关性分析;
(c)和(d)分别表示 BDOM 荧光强度 (BDOM_C)与“农业 + 建设用地”和森林用地占比的相关性分析

图 5 BDOC 浓度和 BDOM 与不同土地利用类型比例的相关性分析

Fig. 5 Correlation analysis of BDOC concentrations and BDOM to different land use percentages

BDOC 和 BDOM 与源汇景观格局特征的相关矩阵分析结果显示 (图 6),林地和水库用地占比与 BDOC_A 和 BDOM 均呈负相关,农业用地占比与 BDOC_{28(雨季)} 和 BDOM_{C1} 有较高的正相关 ($R^2 = 0.68$ 和 $R^2 = 0.65$),建设用地占比与 BDOM_{C1} 来源密切相关 ($R^2 = 0.77$).此外,BDOC_A、BDOC₂₈ 和 BDOM 均与源汇景观负荷比指数呈正相关关系,表明源汇景观负荷比指数越大的流域,水体 BDOM 的浓度越高,但景观负荷比指数和土地利用比例对 BDOM、BDOC 雨季和旱季变化的影响程度也各有不同. BDOM_{C1} 相比 BDOM_{C2} 与源汇景观负荷比指数

(LWLI) 关系更密切, BDOM_{C1} 受距离景观负荷比指数 (LWLI.D) 和坡度景观负荷比指数 (LWLI.S) 影响较大,而 BDOM_{C2} 受源汇景观负荷比指数影响较小,这可能与蛋白质类组分 C2 排放主要来自于下游人口密集活动相关,从上游到下游“源”景观 (城镇和农田) 面积逐渐增大,而“汇” (林地和水库) 景观面积逐渐减小,在地理空间上,也影响了 BDOM 在上下游区域的可降解性浓度.除此之外, BDOC_{A(雨季)}} 和 BDOC_{28(雨季)}} 与景观负荷比指数 (LWLI) 的正相关性较高,表明雨季相比旱季于景观格局分布上更容易影响流域 BDOC 和 BDOM 的迁



蓝色方块表示正相关性,红色方块表示负相关性,大小和颜色深浅表示相关性的强弱;1. 林地用地占比,2. 水库用地占比,3. 农业用地占比,4. 建设用地占比,5. LWLI,6. LWLI. E,7. LWLI. D,8. LWLI. S,9. BDOC_{A(旱季)},10. BDOC_{28(旱季)},11. BDOC_{A(雨季)},12. BDOC_{28(雨季)},13. BDOM_{C1},14. BDOM_{C2}

图6 不同季节下BDOC、BDOM与源汇土地利用比例和景观负荷比指数相关矩阵分析

Fig. 6 Correlation matrix analysis of BDOC, BDOM, and source-sink land use ratio and landscape load ratio index in different seasons

移转化.这可能因为雨季流域地表水和土壤各物质发生更复杂的相互交换过程要较旱季更为强烈^[7].

综上,可利用源汇景观模型探究景观格局对BDOM的影响,通过合理的景观分布和格局优化来预防水体生态环境污染和控制水体污染物,有助于城郊流域土地利用格局对BDOM生物可利用性影响研究,对降低城乡复合生态系统水体水质污染、提升水质净化等多种生态系统服务功能具有重要意义.

4 结论

(1)流域 ρ (BDOC)为0.57~6.80 mg·L⁻¹,在空间上BDOC浓度分布为:子流域4>子流域1>子流域2>子流域3,在时间上BDOC浓度在旱雨季存在极显著差异($P < 0.001$).

(2)流域中BDOM的荧光组分通过EEM-PARAFAC得到2个组分,蛋白质类C2组分略高于陆源腐殖质类C1的 F_{max} 值,C1组分与BDOC空间分布一致.

(3)流域内土地利用类型与BDOC和组分C1的BDOM的分布密切相关,人类活动强度越大的区域其浓度越高.

(4)流域源汇景观格局特征与BDOC和BDOM

显著相关,“源”景观(城镇和农田)影响了BDOM在流域内的空间分布,源汇景观格局影响了流域碳的环境行为和过程.

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