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封面图说:大蟾蜍蝌蚪群——大蟾蜍别名癞蛤蟆,体长达10cm以上,身体肥胖,四肢短,步态及齐足跳的姿势具特征性。其背部皮肤厚而干燥,通常有疣,呈黑绿色,常有褐色花斑,趾间具蹼。毒腺在背部的疣内,受惊后毒腺分泌或射出毒液。大蟾蜍早春在水中繁殖,可迁移至1.5km外或更远的适合繁殖的池塘,产卵量很大,产卵数天后蝌蚪即可孵出,1—3个月后发育为蟾。大蟾蜍常作为实验动物或药用动物,其耳后腺和皮肤腺的白色分泌物可制成“蟾酥”,可治疗多种疾病。研究表明,大蟾蜍蝌蚪最高逃避温度和最高致死温度比最适温度产生的影响要大。

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叶琳琳,孔繁翔,史小丽,阳振,闫德智,张民.富营养化湖泊溶解性有机碳生物可利用性研究进展.生态学报,2014,34(4):779-788.

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富营养化湖泊溶解性有机碳生物可利用性研究进展

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摘要:富营养化湖泊溶解性有机碳(DOC)包括内源和外源性碳源,不同来源碳源在物质化学结构组成和分子量级等方面具有显著差异,进而影响到对细菌的生物可利用性和碳素在食物网中的传递效率。根据国内外文献,综述了内外源 DOC 在碳稳定同位素值域上的显著差异,建议通过对 DOC 碳稳定同位素的分析来识别富营养化湖泊中 DOC 的主要来源;通过对比内外源 DOC 在碳水化合物、结合态中性糖和腐殖质含量上的差异,并结合细菌生长参数如细菌二级生产力、细菌呼吸作用及细菌生长效率来分析内外源 DOC 对细菌的生物可利用性。从富营养化湖泊 DOC 来源的角度探讨其生物可利用性和碳素传递效率,有助于了解富营养化湖泊食物网中碳素循环特征,加强对湖泊生态学的认识,为湖泊环境治理与保护提供科学依据。

关键词:富营养化湖泊; 溶解性有机碳; 来源; 生物可利用性; 综述

The bioavailability of dissolved organic carbon in the eutrophic lakes

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Abstract: The dissolved organic carbon (DOC) pool is composed of both autochthonous and allochthonous DOC, and its concentration in lakes generally increases with the trophic status. Accumulation of the autochthonous DOC was observed in the eutrophic lake, and the allochthonous DOC was highest in the dystrophic lake. Carbohydrates constitute a large component of the DOC, the consumption of DOC by heterotrophic bacteria is one of the largest fluxes of carbon in most aquatic ecosystems, but the bioavailability and the efficiency of carbon transfer in lakes food web is affected by the distribution of molecular weight and chemical composition. The DOC can be separated into high and low molecular weight DOC fractions by cross-flow ultrafiltration, but which fraction is more bioreactive is still in dispute.

Stable carbon isotope can be used to trace the origins of organic carbon, and the approach depends on the fact that DOC from different origins has different stable isotopic compositions. The riverine DOC has a $\delta^{13}C$ value of −27‰, which is different from freshwater phytoplankton, with a range from −35‰ to −25‰. This paper reviewed the researches on the stable carbon isotope ratio of the autochthonous and allochthonous DOC, suggesting that the main sources of DOC in eutrophic lakes can be identified by using natural stable carbon isotope ratio of DOC; the difference on the total dissolved carbohydrates (TCHO) and dissolved combined neutral sugar (DCNS) concentrations, as well as the humic substances (HS) was compared between the autochthonous and allochthonous DOC. Net increases in TCHO and DCNS were observed in the autochthonous DOC during phytoplankton blooms, whereas the HS fraction was quantitatively important in the allochthonous DOC. Many studies have reported the bacterial availability of TCHO and DCNS, and the ratio of TCHO/DOC

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is used to characterize the bioavailability of DOC, whereas HS can also increase bacterial secondary production and support bacterial growth if labile substrates are abundant.

Furthermore, to elucidate the bioavailability of the two sources of DOC, the bacterial secondary production, bacterial respiration and bacteria growth efficiency (BGE) was analyzed together. The DOC can be either transformed to bacterial secondary production or respired to inorganic carbon. BGE is the fraction of assimilated organic carbon that supports growth. The source of DOC and its chemical composition could be a key regulator of BGE. Traditionally, the autochthonous DOC has been considered to be the main source for bacterial as well as other secondary production, the allochthonous DOC was long considered relatively recalcitrant to bacterial degradation. However, in lakes which are both humic-rich and oligotrophic, the ecosystem respiration exceeds gross primary production, suggesting that the allochthonous DOC can be incorporated into the bacteria biomass and makes a significant carbon and energy subsidy for lakes food web, but little of the allochthonous carbon assimilated by bacteria is likely to reach higher consumers. Recent studies suggest that bacterial BGE increases with the concentration of the low molecular weight DOC in allochthonous DOC.

Discussing the bioavailability and efficiency of carbon transfer in the food web from the sources of DOC, will be helpful to investigate the characterization of carbon cycling in the eutrophic lakes, enhance our understanding of the lake ecology and to provide scientific references for the lake management and protection.

Key Words: eutrophic lake; dissolved organic carbon; source; bioavailability; review

溶解性有机碳(DOC)在水体中主要以溶解性有机物(DOM)形式存在,是浮游细菌生长的重要碳源。通过细菌的呼吸作用(BR),部分 DOC 以二氧化碳的形式被释放。另一部分 DOC 通过细菌吸收利用合成二级生产力(BP),所形成的细胞颗粒通过浮游动物的摄食再进入传统食物链[1-2]。研究人员用细菌生长效率(BGE=BP/[BP+BR])来表征 DOC 中碳源通过浮游细菌传递到更高营养级别的效率[3-4]。但是,DOC 的来源、生物化学结构组成及形态存在显著差异,进而影响其降解程度及细菌对其吸收利用途径[5]。

DOC 的生物可利用性一直是生态系统研究的重点与热点。Søndergaard 和 Middelboe[6]系统总结了湖泊,河流和海洋中 126 项 DOC 的研究表明,DOC 中可利用组分与 DOC 总浓度显著正相关,其中湖泊中 DOC 可利用组分所占比例为 14%。Yokokawa 和 Nagata[7-8]在日本 Otsuchi 湾研究发现,DOC 到浮游细菌的碳通量为 23μg C L^{-1} d^{-1},所形成的细菌二级生产力再被浮游动物摄食,产生的碳通量为 7μg C L^{-1} d^{-1}。Carpenter 等[9]对不同营养级别的湖泊研究发现,在贫营养湖泊中,DOC 来源以外源输入为主,外源性 DOC 在湖泊中的降解常数为 0.0001—0.01/d[10]。在亚马逊河 Batata 湖研究发现,高水位期间,水体 DOC 以外源性为主,低水位期间,DOC 以内源性为主,而低水位期间细菌 BGE 值要高于高水位期间[11]。但是,外源性 DOC 对细菌二级生产力的贡献率,DOC 分子量级的高低及腐殖质含量对其生物可利用性的影响至今还存在分歧[12-15]。因此,本文从 DOC 来源的角度综述了内外源 DOC 生物可利用性及其在碳素代谢途径和效率方面的显著差异,为今后深入研究富营养化湖泊生态系统中碳素循环机理和湖泊环境保护提供参考依据。

1 溶解性有机碳的来源与区分

利用碳稳定同位素技术可以追溯有机物的来源,但目前的溯源研究主要集中在颗粒态有机物(POM)方面[16-18]。Gu 等[19]对 32 个淡水湖泊 $\delta^{13}C_{POM}$进行统计分析,研究结果表明,$\delta^{13}C_{POM}$年变化值域中最大值与湖泊富营养化参数(总氮、总磷、叶绿素)显著正相关。Heligings 等[16]在比利时 Scheldt 河口研究发现,夏季 POM 的主要来源为浮游植物,而冬季以陆源输入为主。曾庆飞[20]在太湖研究发现,夏季 POM 的主要来源为蓝藻,并且 $\delta^{13}C_{浮游动物}$与 $\delta^{13}C_{POM}$大量重叠,表明浮游动物摄食了部分蓝藻。但是以碳稳定同位素特征值为工具对富营养化湖泊 DOC 进行溯源,继而深入研究其生物可利用性的研究还较少。

DOC 按其来源可分为内源性和外源性 DOC。

内源性 DOC 主要来源于浮游植物光合作用产物的释放以及内源性碎屑物质的分解[21]。研究发现，淡水湖泊藻类的碳稳定同位素 $\delta^{13}C$ 在 −35‰—−25‰[22]。外源性 DOC 主要来源于陆源的流域输入，而多数陆生植物的光合作用主要通过 C3 途径把大气中 CO_2（$\delta^{13}C \approx -7‰$）合成有机物，其 $\delta^{13}C$ 为 −27‰[23]。因此，不同来源有机物 $\delta^{13}C$ 存在差异且值域重叠少，通过碳稳定同位素特征值可以追溯有机物的来源，这为区分内外碳源对有机物的贡献提供了有力保障[24-25]。

在日本富营养化浅水湖泊霞浦湖研究发现，$\delta^{13}C_{DOM}$变化范围为−25.9‰—−24.2‰，并且春季 $\delta^{13}C_{DOM}$值高于秋季，表明 DOC 来源存在季节性变化规律，春季藻类水华期间 DOC 主要来源是内源性碳[26]。在美国威斯康辛州 Northern Highland 湖区的 32 个湖泊研究发现，$\delta^{13}C_{DOM}$变化范围为−22.9‰—−29.3‰，部分湖泊 $\delta^{13}C_{DOM}$与陆源 C3 植物碳稳定同位素特征值（−27‰）相似，表明其 DOC 主要来源为外源输入，内源性 DOC 所占比例低于 25%，而在 $\delta^{13}C_{DOM}$与 $\delta^{13}C_{POM(颗粒态有机物)}$值域接近的湖泊中，内源性碳对 DOC 的贡献较高[27-28]。但是也有研究发现有无藻类水华，法国 Rohemel 水库 $\delta^{13}C_{DOM}$（−28.1‰—−28.6‰）与外源性 $\delta^{13}C_{DOM}$（−28.6‰）相似，DOC 来源以外源性碳为主[29]。在苏格兰 Loch Lomond 湖泊研究发现，内源性 DOC 的形成不足以改变水体中 DOC 的碳稳定同位素特征值，虽然 $\delta^{13}C_{DOM}$在 6—9 月期间有显著增长趋势，变化范围为−29.0‰—−28.4‰，但是仍然属于外源性 DOC 碳稳定同位素值域，表明外源性 DOC 是水体中 DOC 的主要来源[30]。因此，通过 DOC 碳稳定同位素特征值的变化特征，可以区分水体中 DOC 的主要来源途径。

2　溶解性有机碳的化学结构组成对其生物可利用性的影响

2.1　溶解性有机碳中碳水化合物含量对其生物可利用性的影响

DOC 物质结构组成复杂，研究人员对其中部分物质的化学结构还不清楚，但溶解性总碳水化合物（TCHO）在目前可识别的 DOC 组分中所占比例最高，是细菌生长代谢的重要物质基础，与显色剂 2,4,6-反式 2-吡啶基三嗪（2,4,6-tripyridyl-s-triazine，TPTZ）可生成紫色络合产物，通过紫外分光光度计在 595nm 处测定[31-34]。在匈牙利富营养化湖泊，TCHO 在 DOC 中比例为 15%—20%[35]。有研究发现，TCHO/DOC 可以表征 DOC 生物可利用性[36-37]。在印度 Mandovi 河口，细菌数量与 TCHO/DOC 显著负相关，表明细菌通过分解碳水化合物来提供其物质代谢的主要碳源[38]。而有研究发现，在浮游植物水华过程中，溶解性结合态中性糖（DCNS）在碳水化合物中比例高达 54%，能为细菌生长提供重要碳源[39-40]。

2.2　溶解性有机碳的分子量级对其生物可利用性的影响

DOC 按其分子量级可分为高分子溶解性有机碳（HMWDOC）和低分子量溶解性有机碳（LMWDOC）。但对于不同量级组分生物利用性的认识，还一直存在争议。Amon 和 Benner[14,41] 认为 HMWDOC 生物可利用性要高于 LMWDOC。在墨西哥湾 Saint Louis 河口，研究发现 HMWDOC 组分容易被细菌分解利用，TCHO 在 HMWDOC 所占比例（53%—73%）要显著高于在 DOC 中比例（10%—31%）[42]。但也有研究认为 LMWDOC 具有较高生物活性，细菌对 LMWDOC 组分中 TCHO 利用效率（76%）要显著高于 HMWDOC 组分（46%）[33,43-44]。

2.3　溶解性有机碳中腐殖质含量对其生物可利用性的影响

腐殖质（HS）也是 DOC 中重要的物质组成，其所占比例可高达 80%[45]。在匈牙利 Balaton 湖的入湖河流 River Zala 和湖区东部，HS 在 DOC 中所占比例分别为 75%和 50%[46]。一般认为，腐殖质物质不容易被细菌分解利用[15,47]。美国卡罗来纳 L 湖，HS 在 DOC 所占比例为 50%，对细菌生产力的贡献为 22%[48]。在挪威 Kjelsåsputten 湖，细菌对 DOC 中的 HS 吸收利用效率低于 10%[49]。研究发现在德国富含腐殖质的湖泊（Schwarze kuhle）和清水湖（Schöhsee），DOC 中生物活性组分的含量没有显著差异，约为 15%—22%[50]。但近来有研究发现，HS 浓度对其生物可利用性具有重要影响[51-52]，在匈牙利 Balaton 湖，HS 浓度与 DOC 中生物活性组分浓度之间显著正相关[53]。在波兰富营养化湖泊 Jeziorak，添加 HS 浓度为 25 mg/L 时细菌数量达到最大值[54]。James[55] 也研究发现，在富含 HS 的湖泊中，

HS 浓度不超过 20 mg/L,其对细菌生长具有促进作用。

3 内源性溶解性有机碳生物可利用性及其对浮游植物水华生消的响应

有研究认为,富营养化湖泊比寡营养和中度富营养化湖泊中 DOC 含量高[56-59],其原因是富营养化湖泊中,浮游植物水华过程会导致 DOC 浓度显著升高。在日本富营养化湖泊 Nakanuma 春季水华暴发期间,DOC 的产生速率是 2.8 μmol L^{-1} d^{-1}[60]。在丹麦富营养化湖泊 Frederiksborq Slotssø 春季硅藻水华消亡期间,DOC 的产生速率是 9 μ L^{-1} d^{-1}[61]。德国中富营养化湖泊康士坦茨湖硅藻水华暴发时 DOC 浓度达到峰值,表明有新的 DOC 形成[62]。有研究发现在超富营养化湖泊太湖的贡湖湾湖区,春夏季蓝藻水华期间,DOC 浓度升高,并与叶绿素浓度显著正相关[63]。以上研究结果表明,浮游植物水华生消过程中,DOC 浓度会显著增加,并且主要是来源于内源性 DOC 的形成。

有研究发现,浮游植物细胞内碳水化合物含量为 13%—35%,在浮游植物水华过程中,由于藻细胞的胞外释放、被浮游动物摄食和细胞自然裂解,细胞内碳水化合物会释放到水体中从而改变 DOC 中碳水化合物含量[64-65]。在富营养化湖泊巢湖夏季蓝藻水华期间,TCHO 在 DOC 中比例为 26%[66]。在围格内模拟硅藻水华,新产生的 DOC 中有 16% 是由 DCNS 组成[67]。在美国 Delaware 河口春季水华过后的 4—5 月间,DCNS 浓度在 DOC 中所占比例为 4%—12%[68]。

此外,浮游植物水华过程会对 DOC 的分子量级产生影响[63,69-70]。Gobler 和 Sañudo-Wilhelmy[71] 在美国 Pecomic 河口研究发现浮游植物暴发期间,HMWDOC 含量显著增加,LMWDOC 含量基本保持不变,而在水华消亡过程中,LMWDOC 成为水体中有机碳主要组分。孙小静等[72] 通过室内模拟实验研究发现,蓝藻水华在降解的过程中会释放大量的 HMWDOC。Hama 等[73] 通过碳稳定同位素示踪研究发现,浮游植物经过光合作用后,在黑暗中释放的 DOC 产物主要以 HMWDOC 为主。

相对于外源性 DOC 来说,新产生的内源性 DOC 富含碳水化合物,因此转化周期短,可以很快被细菌分解利用,从而参与到微食物网中碳素传递过程[74-77]。TCHO 和 DCNS 都是细菌生长代谢的重要碳源,在德国中富营养化康士坦茨湖研究发现,春季水华暴发和消亡期,细菌对 TCHO 的利用效率最高[78]。此外,实验模拟的水华产生的 DCNS 有 70%—80%能在 35d 内被降解[79]。另有研究发现,浮游植物水华产生的 DCNS 有 91%能在 15 d 内被降解[80]。在罗斯海,浮游植物水华暴发期间,DCNS 浓度增加了 3 倍,在 DOC 易降解组分中所占比例达到 50%[40]。在内源性 DOM 的降解实验中发现,30%的 DOC 被细菌分解利用,DCNS 在 DOC 中比例从实验初期的 14%降低到实验结束后的 5%[81]。此外,有研究发现,浮游植物水华过程中产生的内源性 HMWDOC 生物可利用性高,比 LMWDOC 转化速率快[71,73]。综上所述,浮游植物水华生消过程会改变 DOC 浓度、物质结构组成及分子量级,进而改变其生物可利用性。

在比利时富营养化浅水湖泊 Blankaart,浮游细菌生长主要以内源性 DOC 为主[82]。有研究发现 13%的内源性 DOC 支持了 30%—65%的细菌生长代谢活动[79]。在太湖研究发现,浮游植物降解产生的内源性 DOC 可能是细菌生长的重要碳源[83]。在波兰马祖里湖区,对深水的中度富营养化湖泊 Kuc、富营养化湖泊 Ryńskie 和超富营养化浅水湖泊 Szymon 进行调查,研究发现 DOC 主要来源于内源性 DOC,细菌生产力和叶绿素浓度显著正相关(表 1),结果表明细菌生长的碳源主要来源于内源性 DOC[84]。有研究发现,进行营养盐添加增大湖泊初级生产力,有利于提高微生物对内源性 DOC 的利用份额。在添加了氮磷营养盐的 Peter 湖,内源性 DOC 对异养生物呼吸的贡献从 60%增大到 88%[85]。在芬兰中腐殖质湖泊 Pääjärvi,夏季浮游植物水华过程中释放的内源性 DOC 含有较高生物可利用性组分,细菌 BGE 达到 26%[86]。综上所述,浮游植物水华过程中产生的内源性 DOC 富含碳水化合物,结合态中性糖,具有较高生物可利用性,在湖泊微食物网碳素循环中具有重要作用。

但内源性 DOC 中也有部分组分不易降解[52,87]。在日本富营养化浅水湖泊霞浦湖湖心区域,内源性 DOC 中不易降解组分浓度从秋季到冬季有所增长[88]。有研究发现,部分内源性 DOC 能在水里保留 1a 以上不降解[89]。在添加了营养盐进行的围格实

验中,研究发现实验 46d 后,新产生的内源性 DOC 中有 32%难以降解[80]。实验模拟产生的水华形成的内源性 DOC 中有 25%—30%在 2.5a 后,仍难以被矿化和利用[87]。研究还发现在淡水围格中,硅藻水华形成阶段,难降解 DOC 组分含量较高[77]。此外,浮游植物水华在消亡过程中受到磷元素的限制作用,也会产生大量难降解的 DOC 组分[90]。

表 1　不同营养级别湖泊中叶绿素,溶解性有机碳和细菌生产力的变化

Table 1　The variation of Chl a, dissolved organic carbon and bacteria production in different trophic lakes

湖泊 Lake	营养水平 The eutrophication level	叶绿素/(μg/L) (Chlorophyll a, Ch a)	溶解性有机碳/(mg C/L) (Dissolved organic carbon, DOC)	细菌生产力/(μg C L^{-1} d^{-1}) (Bacterial production, BP)
Lake Kuc Kuc 湖	贫/中度富营养	2.8—4.5(3.6)	5.9—6.8(6.4)	24.6—88.2(51.5)
Lake Ryńskie Ryńskie 湖	富营养化	28.4—34.2(31.3)	10.8—10.9(10.8)	177.1—294.5(254.6)
Lake Szymon Szymon 湖	超富营养化	102.8—149.4(126.1)	13.4—13.6 (13.5)	216.7—795.8(435.6)

4　外源性溶解性有机碳的生物可利用性

在贫营养的湖泊中,外源性 DOC 含量要显著高于内源性 DOC[9,91]。Carpenter 等[9] 在 2001 年和 2002 年选取威斯康辛州 Paul、Peter 和 Tutesday 湖为研究对象,研究结果见表 2。Bade[28] 也发现没有进行营养盐添加的湖泊,80%—90%的 DOC 来源于外源性 DOC。Cole 等[92]通过 C13 示踪,发现在富含腐殖质的美国 East Long 湖泊中,外源性 DOC 在总有机碳中所占比例高达 90%。综上所述,在贫营养和富含腐殖质的湖泊中,外源性 DOC 所占比例高。

表 2　不同营养级别湖泊中外源性 DOC 贡献率

Table 2　The contribution of allochthonous DOC in lakes of different trophic status

湖泊 Lake	Lake Paul	Lake Peter	Lake Peter	Lake Tuesday
采样时间 Sampling time/a	2001	2001	2002	2002
叶绿素 Chlorophyll a, Ch a/(μg/L)	4.21	3.55	42.1	6.8
溶解性有机碳 Dissolved organic carbon, DOC/(mg C/L)	304	376	483	700
外源性 DOC 所占比例 The contribution of allochthonous DOC/%	53—85	69—87	43—70	92—96

2001 年没有对 Paul 和 Peter 湖添加营养盐;2002 年对 Peter 湖添加营养盐;Tuesday 湖为贫营养湖泊

以往的研究认为外源性 DOC 主要以腐殖质物质存在,分子量高,氮磷比低,具有芳香性,不易被微生物所利用[93-94]。有研究发现,在德国贫营养湖泊 Groβe Fuchskuhle 西部湖区,DOC 以外源性为主,其中 HS 所占比例达到 58%[95]。在日本富营养化浅水湖泊霞浦湖湖心,外源性 DOC 是 DOC 中不易降解组分的主要来源[88]。在芬兰富含腐殖质的 Mekkojärvi 湖研究发现 95% 的外源性 DOC 不能被细菌分解利用[86]。

但近来有研究发现,很多湖泊属于异养型,整个湖泊生态系统的呼吸作用(R)大于总初级生产力(GPP)。因此,外源性有机碳是湖泊物质代谢过程中的重要补充[96-98]。有研究发现,在未添加营养盐的湖泊中,外源性有机碳对浮游动物碳源的贡献率为 22%—75%[8]。在营养不良的 Tuesday 湖,外源性 DOC 对异养生物呼吸的贡献率达到 68%[86]。在挪威中腐殖质湖泊 Kjelsåsputten[49] 和瑞典 Örträsket 湖[99],90%的细菌生产力来源于外源性 DOC。在瑞典 12 个湖泊中研究发现,细菌二级生产力和呼吸作用均与外源性 DOC 显著正相关(图 1),但其中 90% 的 DOC 是用于细菌呼吸作用,因此 BGE 较低[100]。在 East Long 湖研究发现 DOC 以外源性为主,细菌 BGE 仅为 4%[92]。有研究发现,内源性 DOC 营养价值高,碳氮比值约为 12:1,而外源性 DOC 碳氮比值约为 50:1[101],不同来源 DOC 营养价值的差异会影响细菌的生长效率 BGE, 有研究表明 BGE 与生长基质中碳氮比值具有负相关性[102]。因此,以外源性 DOC 为碳源, 细菌生长效率低[11-12,17]。Kritzberg

等[12]研究发现在异养型湖泊中,细菌的二级生产力和内源性 DOC 具有显著相关性,表明被细菌吸收的外源性 DOC 不可能被传递到上一层消费者,在食物网中碳素传递效率低。

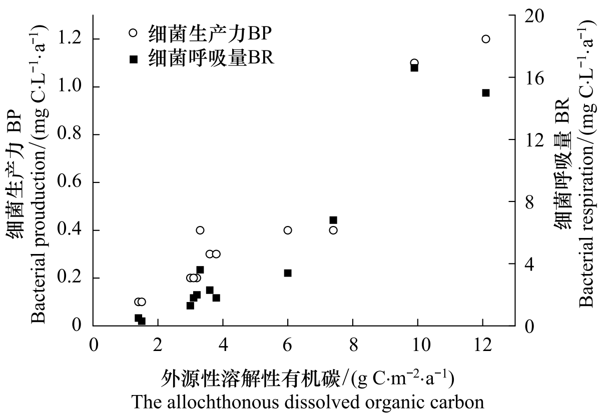

图 1 瑞典 12 个湖泊中细菌二级生产力 BP、呼吸量 BR 与外源性溶解性有机碳的变化趋势

Fig.1 The variation of bacteria production, bacteria respiration and allochthonous dissolved organic carbon in twelve lakes in Sweden

此外有研究发现,外源性 DOC 分子量级组成对 BGE 具有显著影响[103-104]。Berggren 等[13]研究发现,外源性 DOC 中 LMWDOC 对细菌、原生动物和后生动物二级生产力的贡献分别为 80%、54%和 23%,通过摄食浮游细菌,这部分碳源可被有效地传递到更高营养级别。在瑞典的溪流和湖泊中,研究发现细菌 BGE 随着外源性 DOC 中 LMWDOC 浓度的升高而增大[105]。新的外源性 DOC 中,细菌的 BGE 高达 50%,陈年的外源性 DOC 中 BGE 只有 10%,可能是其中 LMWDOC 组分耗竭所致[106-108]。但在芬兰富含腐殖质的 Mekkojärvi Lake,细菌吸收利用了外源性 DOC 中 30%的 LMWDOC,BGE 只有 3%,而吸收利用 4%的 HMWDOC,BGE 达到 26%,表明外源性 DOC 中 HMWDOC 组分比 LMWDOC 组分营养价值高[86]。综上所述,外源性 DOC 也是湖泊食物网中碳循环的重要补充,但其分子量级对其生物可利用性具有重要影响。

5 结论与展望

DOC 是湖泊生态系统食物网的重要做成部分。目前,国内就富营养化湖泊中浮游植物水华过程对 DOC 浓度和形态等方面开展了大量的工作[69,109],张运林等利用三维荧光对太湖溶解性有机碳的来源也进行了分析[110-111],并取得了丰富的研究成果。但从 DOC 来源的角度,探索其生物可利用性、碳素代谢途径和效率以及 DOC-细菌-浮游植物相互关系的研究较少。

随着人们对湖泊生态系统中碳循环机理的深入研究,有关 DOC 来源及生物可利用性对浮游植物水华过程的响应急需得到进一步加强。通过碳稳定同位素技术,可以明确富营养化湖泊中 DOC 的主要来源。通过对不同来源 DOC 中碳水化合物、溶解性结合态中性糖、分子量级和腐殖质的分析,并结合细菌生长参数,可以明确不同来源 DOC 生物可利用性的显著差异,及其在湖泊食物网碳循环中作用和碳传递效率,为今后深入研究湖泊生态系统碳素循环机制和生态系统稳定性提供参考依据。

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