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评 述

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岩溶湖库生产力的溶解无机碳施肥及碳增汇和富营养化缓解效应

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摘要 内陆水体在全球碳循环中的作用日益受到关注, 特别是喀斯特地表水体与水生光合作用有关的生物泵(biological pump, BP)将溶解无机碳(dissolved inorganic carbon, DIC)转化为有机碳沉积, 是形成长期稳定碳酸盐风化碳汇的关键. 富营养化作为BP的特殊阶段, 是地表水环境面临的主要环境问题之一. 然而, 通常认为富营养化的控制元素是磷(P)和氮(N), 而BP的控制元素还包括碳(C), 如喀斯特湖库尽管DIC浓度高, 但其碱性环境使得水中的CO_2很低, 因此BP效率受到C限制. 同时BP产生的碳酸钙促进了水中P的共沉淀, 缓解了水体向蓝藻型富营养化的发展, 可能促成水质安全和水体碳增汇的双赢. 未来需通过对不同气候(温度、降水差异)、不同土地利用(N-P营养输入差异)和不同岩性(碳酸盐岩-硅酸盐岩风化产生pH和DIC差异)条件下的喀斯特地表水体BP的DIC施肥及其碳增汇和富营养化缓解效应进行系统研究, 重点揭示以下关键科学问题: (1) DIC对BP施肥的机制及控制因素; (2) 水体C:N:P:Si与浮游-沉水植物群落结构/组成的耦合关系及机制; (3) DIC施肥下BP的碳增汇和富营养化缓解效应. 系统研究将为HCO_3-Ca型地表水体碳增汇和水质安全调控提供新的理论依据和科学支撑.

关键词 喀斯特, 地表水体, 生物泵, 溶解无机碳施肥, 碳增汇, 富营养化缓解

近年来由于人类活动的影响, 大气中CO_2含量大幅增加, 全球碳循环和全球气候发生显著变化. 现代碳循环研究表明, 在全球尺度上估算出的大气碳源量大于碳汇量, 碳源、汇收支不平衡, 此部分"遗失碳汇"去向成为近年研究关注的重点[1~4]. 随着研究的系统化和深入, 内陆水体(包括河流、湖泊和水库等)在全球碳循环中的作用得到越来越多的关注, 其在全球碳循环中的碳源汇作用显著[5,6], 特别是我们发现, 在喀斯特地表水生态系统中, 水生光合生物通过光合作用产生强烈的生物泵(biological pump, BP)效应, 可将部分碳酸盐风化碳汇固定下来, 形成稳定碳汇[3,7]:

$$Ca^{2+}+2HCO_3^- \overset{BP}{\Rightarrow} CaCO_3+x(CO_2+H_2O)+(1-x)(CH_2O(\text{碳汇})+O_2). \tag{1}$$

水体中溶解无机碳(dissolved inorganic carbon, DIC)浓度越高, 水生生产力越高, 存在"DIC施肥效应"[8~11]. 同时, 喀斯特地区BP具有改善水环境的作用[12]. 生物泵或水体富营养化都以水生光合作用形成有机质为机制. 通常认为, 氮(N)-磷(P)在富营养化过程中具有限制作用[13~17], 但生物在进行光合反应CO_2+H_2O=CH_2O+O_2时, 在满足光-热条件前提下, 陆地上CO_2或水都可能是光合固碳的限制性因子, 而水中则仅取决于CO_2[18]. 以往的研究认为, 水体可以源源不断地

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Liu Z H. DIC fertilization of primary production in karst lake-reservoirs and its effects on carbon sequestration and mitigation of eutrophication (in Chinese). Chin Sci Bull, 2023, 68: 915–926, doi: 10.1360/TB-2022-0640

从大气中获得CO_2，但事实上，水-大气间CO_2的交换是一个缓慢的过程(水中CO_2扩散速率仅为大气中的万分之一)[19]，藻类或沉水植物大多利用水中溶解CO_2进行光合作用[20,21]，而喀斯特水生生态系统中，由于其独特的水化学特性导致其碱性偏高，尤其是在pH>8的碱性水体中，$CO_{2(aq)}$不到溶解无机碳DIC的1%[11,22]，因此生物泵研究中碳的限制问题十分重要，而且越来越多的研究表明这一作用不容忽视[11,22~25].

此外，水体CO_2浓度高低也会对生物群落结构或组成造成影响，与富营养化直接相关的蓝藻相对于其他藻类更能适应较低的CO_2浓度[26~28]．近年来也有一些学者提出C、N和P对生产力的限制分为速率限制(rate-limiting)资源(如C、N)和产量限制(yield-limiting)资源(如P)两大类[27,29]．参与生物泵的水生植物既有沉水植物也有浮游植物．沉水植物可以利用其根系和茎叶吸收水体中的N、P，既满足了其自身的生长，又降低了水体中N、P等营养元素的含量，改善了水生生态系统环境[30,31]．Kragh和Sand-Jensen[32]对丹麦204个自然湖泊的对比研究不仅发现了硬水湖泊中浮游植物的生物量比软水湖泊中的高，而且还发现总磷(total phosphor, TP)和酸中和能力(acid neutralization capacity, ANC)的联合作用对叶绿素*a*的促进作用大于TP的单独促进作用，其生长共同受到C-P的限制．此外，生物泵效应利用水体中DIC形成内源有机质的过程中，由于喀斯特水体Ca^{2+}浓度高，方解石过饱和产生碳酸钙沉淀，该过程会将溶解性磷酸盐吸附在其表面，或是形成钙磷化合物(羟基磷灰石等)，将水体中的磷去除，对富营养化起到缓解作用[12,30,33~35].

无疑，揭示喀斯特水体生物泵DIC施肥的碳增汇和富营养化缓解效应能够为碳循环研究(有效应对气候变化)和富营养化防治(保证水质安全)取得双赢提供全新的科学支撑.

1 生物泵及其碳汇效应

生物泵是海洋科学家研究海洋碳循环时提出的概念，是指由有机物生产、消耗、传递、沉降和分解等一系列生物学过程构成的碳从表层向深层的转移[36~43]．生物体产生和持有的碳主要为溶解有机碳(dissolved organic carbon, DOC)和颗粒有机碳(particulate organic carbon, POC)，基本上都是通过初级生产过程实现的．基于海洋对大气CO_2的调节能力，海洋碳循环主要受两种机制调控：溶度积泵(solubility pump)和生物泵．溶度积泵是一个物理化学概念，是将大气CO_2溶解到海洋体系中形成溶解无机碳(DIC)的过程．而生物泵是以一系列生物为介质，通过光合作用将部分DIC转化为有机碳(organic carbon, OC)，之后在食物网内转化、物理混合、输送及沉降将碳从真光层传输到深层中的过程[36].

在早期碳循环研究中，溶度积泵受到极大的重视，但随着大气温度的持续增高，海洋表层的溶度积泵趋于饱和．此时，生物泵过程却在持续不断地工作．因此，海洋生物泵日益成为研究的热点[44~46]．研究者正在设想通过提高某些海区的初级生产力，加速生物泵的运转以提高海气界面碳通量.

总的来说，影响生物泵效率的因素除了温度和光照，主要还有以下两大方面：(1) 营养盐(C-N-P-Si-Fe等)的浓度[47~60]；(2) 生态系统或食物链结构[52,61~66].

海洋生物泵是全球碳循环的重要组成部分，调节上层海洋有机碳颗粒向下层海洋的传输，对维持大气CO_2浓度具有重要作用．生物泵的作用主要是通过CO_2的转化实现碳的向下转移和营养盐的消耗升高表层水的碱度，从而降低水中的CO_2分压，促进大气CO_2向海水中扩散.

生物泵的净效果是减少表层海水中的碳含量使得海水可以从大气中获取更多的CO_2以恢复表层平衡．海洋浮游植物通过光合作用吸收大气CO_2、释放出氧气，成为海洋食物链中其他各级生物的有机质食物来源，同时产生各种钙或硅质生物骨骼或壳体，死亡后的残骸逐渐沉降到洋底．这就犹如水泵那样，将上层海水中的CO_2最终被“抽提”输送到洋底沉积物之中，最终影响全球碳循环和气候[41,43,49].

2 陆地淡水生态系统在全球碳循环中的重要性

尽管淡水面积只占地球陆地的<2%[67]~3.7%[68]，但淡水生态系统，特别是河流、湖泊和水库在区域和全球碳循环中的重要性，近年来受到广泛的关注[5,6]．如据Cole等人[5]的估计，全球内陆水域每年从陆地景观获得的碳至少达到19亿吨，其中2亿吨被埋藏在水体沉积物中，8亿吨返回大气，其余9亿吨进入海洋．Tranvik等人[6]进一步指出，全球内陆水体向大气释放CO_2的量与海洋吸收的CO_2量相当，同时全球内陆水体沉积物埋藏的有机碳则超过海底有机碳汇．更为重要的是，Tranvik等人[6]的研究还指出，内陆水体碳循环由于水库建设等

人类活动以及气候变化的影响发生了重要的变化. 实际上, 早在20世纪80年代, Mulholland和Elwood[69]就指出, 水库累积了“遗失碳汇”中的重要部分, 达到每年2亿吨左右. Stallard[70]则指出, 陆地沉积埋藏的有机碳达到每年十亿吨的数量级. Dean和Gorham[67]也指出, 尽管湖泊、水库等的总面积不足地球表面积的2%, 但其沉积埋藏的有机碳(OC)可达到每年近3亿吨, 甚至超过了占地球表面积71%的海洋有机碳汇量(每年1亿吨左右), 这与湖库的高OC沉积速率和高保存度有关, 后者是海洋的50倍[71]. 特别是人类活动显著增加了(平均在3~4倍)湖库中有机碳的生产和保存, 因此湖库在抵消人类排放CO_2中的作用是不容忽视的[71].

2.1 湖-库的富营养化及其碳汇效应

Hanson等人[72]的研究表明, 温带湖泊大多数是净异养的, 其向大气碳排放超过了碳埋藏, 从而成为大气的净碳源. 只有DOC浓度较低, 且总磷含量高的湖泊是净自养的, 从而成为大气净碳汇. Downing等人[73]研究了过去百年因农业富营养化池塘中的OC埋藏, 发现仅世界农业池塘埋藏的碳就超过了海洋. Heathcote和Downing[74]进一步指出, 随着农业的开发, 湖泊中的碳埋藏在持续增加, 达到200 g C m^{-2} a^{-1}, 因此, 如果富营养化趋势继续, 湖泊碳埋藏的重要性未来将进一步增加. 此外, Brothers等人[75]研究了浅水湖泊富营养化致生物结构演替对碳埋藏的影响, 发现大型沉水植物向浮游植物的转变有利于碳的埋藏. 因为随着沉水植物的消失, 底水中溶解氧降低, 因此OC矿化速率降低, 从而碳埋藏效率增加[76]. 如果这种演替大面积发生, 无疑会改变浅水湖泊在全球碳循环中的作用, 即由湖泊向大气排放碳转向湖泊埋藏更多碳. Knoll等人[77]研究了美国两个喀斯特水库的碳循环过程, 发现库龄为50年左右的温带喀斯特水库是重要的有机碳汇. Pacheco等人[78]进一步指出, 富营养化通过增加碳埋藏和水中DOC浓度可逆转整个湖泊的碳收支, 即向大气排放CO_2减少, 而沉积碳埋藏和向下游的DOC浓度增加. Anderson等人[79]研究了欧洲湖泊富营养化在有机碳汇中的作用, 发现在20世纪100年中, 人类活动导致的富营养化使有机碳埋藏速率至少增加了4~5倍, 因此, 尽管富营养化对环境是不利的, 但从碳汇缓解气候暖化角度看是有利的. 另一方面, Davidson等人[80]的研究指出, 富营养化对浅水湖泊温室气体碳通量的影响超过了气候暖化的影响, 因此, 在未来全球变化情景下, 湖库在碳埋藏方面将变得越来越重要[81].

2.1.1 水体富营养化的N-P限制

通常认为, 富营养化湖泊中存在补偿N和C不足的天然机制, 如大气CO_2进入水体提供足够的C以支撑浮游植物的生长; 蓝藻能够固定大气中的N. 然而, P没有大气气相循环, 因此不存在补偿P的外在机制, 这是湖泊富营养化出现P限制的重要原因[82], 也是Schindler等人[83,84]认为湖泊富营养化不能通过降低N输入来加以控制的理论基础. 直到10余年前, 湖泊浮游植物营养控制的P范式受到挑战[29,56,85~90], 提出这些挑战的研究人员认为P和N在控制富营养化方面可能同等重要, 即存在所谓的P+N范式.

2.1.2 生物泵的碳限制

光合作用通过$CO_2+H_2O=CH_2O+O_2$反应实现, 因此, 在满足光-热条件前提下, 陆地CO_2或水都可能是光合固碳的限制性因子, 而水中则仅取决于CO_2[18]. 虽然N-P在富营养化过程中的作用已经进行了广泛的讨论和总结[82,91], 但研究者对藻类光合作用时C重要性的关注度远远不够, 原因已如前述. 事实上, 水-大气间CO_2的交换是一个很慢的过程, 据Stumm和Morgan[19], 水中CO_2扩散速率仅为大气中的万分之一, 因此, 藻类-植物大多利用水中溶解CO_2进行光合作用. 水生植物利用的碳主要是水中的DIC组分, 包括溶解CO_2、HCO_3^-和CO_3^{2-}. 这些组分的浓度比例取决于水的pH(图1). 水生生态系统中植物光合作用随CO_2浓度降低而减弱说明游离CO_2的可获得性是藻类光合作用的一个限制因子[20,21,27,50]. King[20]还发现, CO_2浓度对不同藻类的限制存在差异, 从高到低的顺序是: 硅藻、颗石藻、绿藻、

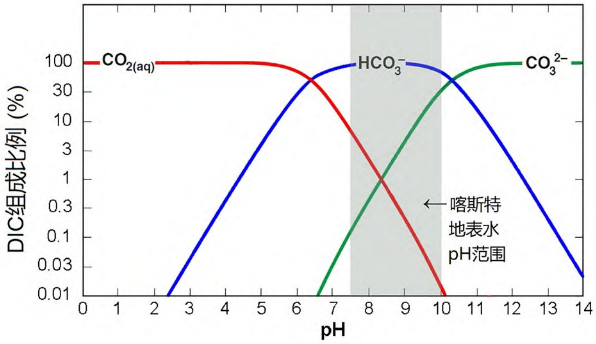

图 1 (网络版彩色)溶解无机碳组分($CO_{2(aq)}$、HCO_3^-和CO_3^{2-})比例与pH的关系(25°C, 淡水). 据文献[11]修改

Figure 1 (Color online) Proportions of dissolved inorganic carbon (DIC) species ($CO_{2(aq)}$, HCO_3^- and CO_3^{2-}) as a function of pH, for freshwater at a temperature of 25°C. Modified from Ref. [11]

蓝-绿藻[26,27]. 藻的生长需要N和P, 同样需要C. 有研究表明, 蓝藻的C:N:P=160:22:1, 而绿藻的C:N:P=375:23:1[20]. 由此可见, 藻类需要的碳比N-P更多, 而绿藻比蓝藻需要更多的C[92,93]. Aizawa和Miyachi[94]的研究进一步发现, 浮游植物-硅藻、绿藻在低pH高DIC环境生长, 而蓝藻在高pH低CO_2环境爆发, 因为后者细胞表面有碳酸酐酶[91~96], 既能利用CO_2也能利用HCO_3^-进行光合作用, 即具有CO_2浓集机制(CO_2-concentrating mechanism)[97~102]. 动力学研究表明, 大部分HCO_3^-是经细胞表面的碳酸酐酶(carbonic anhydrase, CA)转换为CO_2被利用的. 因此, 通过细胞膜时, 实际的分子组成是游离的CO_2. 而前者则主要利用CO_2进行光合作用[22,103].

另一方面, 许多生态系统中N和P的增加降低了它们对生产力的限制, 相应地提高了CO_2对生产力的限制, 至少在局地或短时间尺度上是如此[104]. Jansson等人[105]发现, CO_2过饱和湖泊(即使存在P限制的情况)的生产力甚至达到与大气CO_2平衡湖泊生产力的10倍. 为了区分C、N和P对生产力限制的差异, Low-Décarie等人[27]将营养区分为速率限制(rate-limiting)资源和产量限制(yield-limiting)资源两大类. Rate-limiting资源定义为其浓度影响生长速率, 如CO_2; 而yield-limiting资源定义为其总量限制系统潜在的最大生物量(承载力), 如P.

2.2 喀斯特(岩溶)碳汇研究的新进展

2.2.1 耦联生物泵的碳酸盐风化碳汇

传统喀斯特(岩溶)作用研究主要关注碳酸盐岩在CO_2-H_2O溶液中的溶解和沉积行为, 即水-岩-气相互作用过程及其环境效应. 其中, 重要的研究方向之一是岩溶水化学的成因和岩溶碳汇, 如早在20世纪90年代, Yuan[106](袁道先院士)专门以国际地质对比计划IGCP379项目“Karst processes and the carbon cycle”(岩溶作用与碳循环, 1995~1999年)开启了岩溶碳汇的研究, 并发表了“The carbon cycle in karst”一文, 得出全球岩溶作用碳汇(实际上是DIC通量)为6.08亿吨碳/年. 碳酸盐溶解能消耗大气和土壤中的CO_2, 但碳酸盐沉积时又可能将CO_2释放回大气, 所以岩溶作用能否真正产生碳汇一直存有质疑[107]. 为了解决这一问题, 也为全球“遗失碳汇”(missing carbon sink)之谜的解决找到新的研究内容, 我们提出了耦联水生光合作用(生物泵)的碳酸盐风化碳汇学说(图2)[3,7], 即耦合水生光合生物对DIC的利用及其形成的有机碳埋藏(或生物泵效应形成内源有机碳(autochthonous organic carbon, AOC)), 估算出耦合碳酸盐风化形成的大气CO_2汇达到约7亿吨碳(DIC+AOC)/年, 而且发现该碳汇对气候变化和土地利用变化响应敏感: 随着气候变暖和人类活动的增加, 耦合的碳酸盐风化碳汇显著增强, 体现其对全球变暖的负反馈机制. 因此, 耦合生物泵的碳酸盐风化碳汇不仅

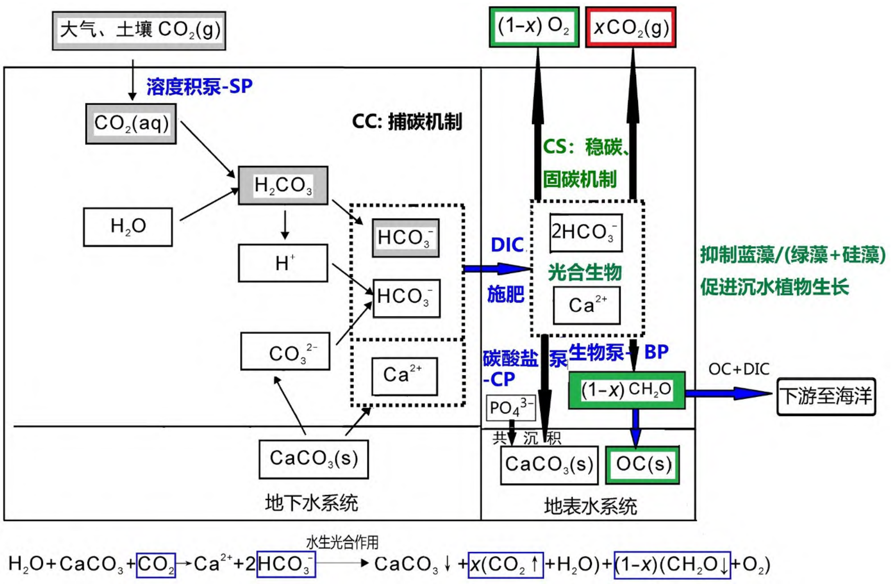

图 2 (网络版彩色)耦联水生光合作用(生物泵)的碳酸盐风化碳汇及其对蓝藻富营养化缓解机制图. 据文献[3]修改

Figure 2 (Color online) Carbon sink by carbonate weathering coupled with aquatic photosynthesis (biological pump, BP) and its mitigating cyanobacteria-type eutrophication. Modified from Ref. [3]

影响了短时间尺度的气候变化，而且在自水生光合生物出现以来的长时间尺度(百万年~亿年)气候变化控制上可能也是重要的，打破了只有硅酸盐风化碳汇才能控制长时间尺度气候变化的传统认识[108]．

2.2.2 生物泵效应与富营养化缓解问题

研究中我们还发现，高DIC浓度和高pH的喀斯特环境中，BP效应呈现显著的碳限制或DIC施肥效应[8~11]，因为水生光合作用主要或优先利用溶解CO_2进行光合作用，而后者取决于水的pH，如图1所示，在pH>8的喀斯特地表水环境中，溶解CO_2占DIC不足1%[11,22]．因此，尽管喀斯特水的DIC浓度通常较高，但能被水生光合生物有效利用的溶解CO_2仍然可能是不足的．已有研究[22,109]发现，高pH时，溶解CO_2不足成为海洋浮游植物生长和光合作用的限制因素．最新研究[110]也发现，CO_2升高和全球变暖有利于湖泊和水库(湖库)蓝藻的爆发．因此，BP效应的C限制应该作为湖库，特别是高pH喀斯特湖库富营养化机制及其控制是值得关注的研究方向，而不应受流行的P或N限制富营养化观点[13,14,16,85,111]的束缚．

另一方面，如图2所示的总化学反应，BP效应形成内源有机质AOC和碳酸盐沉积，其中碳酸盐沉积对P具有显著的去除功能[12,30,33,34,112~114](图3)，如Otsuki和Wetzel[33]的研究发现水中74%的PO_4^{3-}和碳酸盐共沉积；Hamilton等人[34]在美国密歇根湖的实验也发现P的去除率达50%以上，甚至全部的磷酸盐离子和碳酸盐一起沉积．由此推测硬水湖泊富营养化速率可能低于软水湖泊．有报道，意大利西西里水库曾有应急计划向水库撒石灰除P来阻止蓝藻的爆发，结果证明是有效的[115]．此外，对含有一定铁浓度的水体而言，高氧化还原电位使铁离子呈现高价态，高的pH有利于氢氧化铁胶体的形成，氢氧化铁胶体具有较大的比表面积，可以促使P在氧化铁/氢氧化铁上吸附，一同发生共沉淀[116,117]．而且，钙磷也可以转化为活性更低的铁磷，从而达到去P的目的(图3)[12]，但需要进一步系统深入地研究．

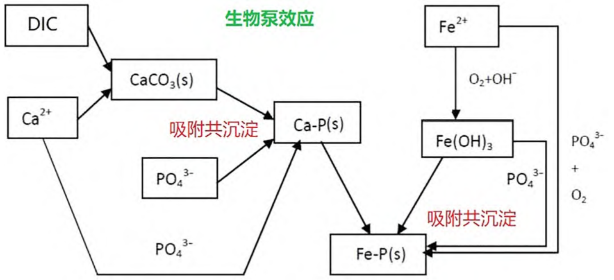

图 3 (网络版彩色)喀斯特地表水生态系统生物碳泵效应的去磷机制示意图．据文献[12]修改

Figure 3 (Color online) Sketch map showing the biological pump effect on phosphorus removal in karst aquatic ecosystems. Modified from Ref. [12]

3 喀斯特地表水体碳增汇和富营养化缓解研究典型案例

3.1 沙湾模拟实验场：喀斯特地表水体碳增汇和富营养化缓解的土地利用调控

人类活动改变了土地利用方式，从而也改变了流域的水化学特征(例如$CO_{2(aq)}$、NO_3^-和PO_4^{3-}浓度)，这些水化学特征的改变调节了地表水体水生光合生物的初级生产和内源有机碳(AOC)的形成，最终影响着内陆水体的碳循环和水体的富营养化状态．然而，在浮游植物与沉水植物共存的浅水环境中，C-N-P对水生生物初级生产(富营养化)的限制及其促进水体AOC形成(增汇)的机制尚不清楚．

针对以上科学问题，我们以贵州普定县沙湾喀斯特水-碳通量模拟试验场作为研究对象，在2018年9月~2019年8月的完整水文年期间，开展了大规模野外模拟试验，研究了C-N-P对浮游植物及其种类和沉水植物初级生产力的限制[118,119]．结果表明：

(1) 土地利用介导了水生生物生产力．地表水体浮游藻类生物量主要受不同土地利用方式介导的氮(N)和磷(P)输出浓度的共同限制，但以氮(N)限制为主，而沉水植物(布氏轮藻为优势种)生物量则主要受溶解无机碳浓度(DIC-$CO_{2(aq)}$)的限制．

(2) 土地利用同时介导了水生生物结构．在高DIC低N-P的水环境中(草地和灌丛对应的地表水体)，浮游藻类的生物量普遍较低，且绿藻和硅藻表现出了比蓝藻更强的竞争优势．

(3) 不同水生生物种类碳汇的形成存在季节性差异．浮游藻类和沉水植物对地表水体AOC形成的贡献存在季节差异，浮游藻类在春夏贡献较大，而沉水植物则在秋冬贡献较多．但从整个试验周期来看，浮游藻类贡献约为27%和沉水植物贡献约为28%(两者协同贡献则约为17%)，浮游藻类贡献与沉水植物贡献占比相近．

上述结果表明，自然恢复的植被(如草地和灌丛)可使相应地表水体DIC含量升高，N+P含量降低，从而促进沉水植物生长和抑制浮游藻类发育，并使硅藻和绿藻相对蓝藻更具竞争优势，从而有助于缓解水体富营

养化和增加地表水DIC的固定[119].

3.2 红枫湖-平寨水库: 喀斯特筑坝河-库富营养化缓解机制

生物泵将溶解无机碳转化为内源有机碳，是形成长期稳定碳酸盐风化碳汇的关键机制. DIC施肥效应可增加BP的强度. 富营养化作为BP的一个特殊阶段，是地表水环境的主要问题之一. 通常认为, 富营养化的控制元素是氮(N)和磷(P)，而BP的控制元素还包括碳(C). 由于碳酸盐的快速溶解动力学特性, 喀斯特水体的DIC浓度高于非喀斯特流域，但由于喀斯特水体的高pH特征，溶解态$CO_{2(aq)}$在pH>8.2的环境下不及总DIC的1%，因此BP受到C限制. 同时，BP通过磷(P)与方解石和Fe(Ⅲ)氢氧化物共沉淀去除P，降低了水体中P的含量，提高了水体中总氮(total nitrogen，TN)和总磷的比值，有可能缓解蓝藻型富营养化的发生.

我们以贵州的3个喀斯特河流-水库系统(平寨水库、普定水库和红枫湖水库)作为研究对象，利用水化学特征、DIC、总氮(TN)、总磷(TP)及叶绿素浓度(Chl-*a*), 同时结合沉降颗粒物中TP和P形态的沉降通量和浮游植物群落结构，系统研究了河流筑坝后BP的营养盐限制变化及其除P机制对蓝藻型富营养化的缓解情况[120]. 研究结果表明:

(1) 喀斯特河流筑坝后BP的营养盐限制由C限制向N或P限制转变. 利用Chl-*a*与营养盐化学计量比(DIC/TN、DIC/TP和TN/TP)的相关性分析发现, 在河流取样点Chl-*a*与DIC/TP的相关性高于Chl-*a*与DIC/TN和TN/TP的相关性, 表明河流中BP主要受C限制. 而河流筑坝后，在平寨水库和普定水库，BP主要受到N限制；而在红枫湖水库, BP主要受P限制.

(2) BP的除P降低了地表水体中TP浓度，提高了水体的TN/TP比. 通过对平寨水库和红枫湖水库悬浮颗粒物中TP通量和P形态的研究发现, 平寨水库和红枫湖水库TP沉降通量具有明显的时空变化，从水库上游到下游呈现逐渐降低的趋势. 平寨水库和红枫湖水库TP沉降通量的平均值分别为15.29、4.88 mg/(m^2 d)，平寨水库TP的沉降通量是红枫湖的3倍左右. 通过对P形态的分析发现，与BP有关的碳酸盐结合态P占TP的60%以上. BP除P导致水体中的TN/TP也呈现显著的空间变化, 从上游到下游, 水体中的TN/TP逐步升高.

(3) BP的除P降低了蓝藻相对丰度，缓解了蓝藻型富营养化的发展. Smith[82]发现，当水体中TN/TP(质量比)大于29:1时，水体中的蓝藻变得少见. 因此水体的TN/TP可以控制水体中的蓝藻比例. 我们的研究发现，在平寨水库，由于BP的除P导致水体的TN/TP从上游到下游逐渐升高，从而导致在某些取样点甚至没有蓝藻出现. 而红枫湖由于BP效应除P效果不及平寨水库，因此红枫湖水库蓝藻的比例明显高于平寨水库. 研究还发现, 当TN/TP(摩尔比)大于200时, 蓝藻丰度变得很少.

本研究可能对HCO_3-Ca型地表水，特别是对覆盖全球陆地表面15%喀斯特地区的富营养化控制(即通过DIC施肥强化BP效应)具有重要启示意义.

4 结论和展望

已有研究发现, 在喀斯特地表水生态系统中, 浮游-沉水植物通过光合作用产生强烈的生物泵效应可将部分碳酸盐风化碳汇固定下来, 形成稳定碳汇. 溶解无机碳浓度越高, 水生生产力越高, 存在“DIC施肥效应”. 同时，喀斯特地表水BP具有改善水环境的作用. BP或水体富营养化都以水生光合作用形成有机质为机制，通常认为，N-P在富营养化过程中具有限制作用，但生物在进行光合反应时, 在满足光-热条件前提下, CO_2或水都可能是光合固碳的限制性因子，而水中则仅取决于CO_2. 以往研究认为CO_2可以源源不断地从大气中获得, 但事实上, 水-大气间CO_2的交换是一个慢速过程, 植物利用水中溶解CO_2进行光合作用, 而喀斯特水生生态系统, 由于其独特的碱性环境, 尤其是在pH>8的碱性水体中溶解CO_2不到DIC的1%. 因此, 在对BP或生产力研究中, 碳限制问题同样重要. 同时, 水体CO_2高低也会对生物结构造成影响，蓝藻相对于其他藻类更能适应较低的CO_2浓度，而绿藻、硅藻和沉水植物更倾向于在富CO_2环境中生长[26]. 此外，BP在利用DIC形成内源有机质的过程中，由于喀斯特水体Ca^{2+}浓度高，方解石过饱和产生碳酸钙沉积，该过程促成P的共沉淀，将水体中的P去除, 对蓝藻型富营养化起到抑制作用. 因此, 喀斯特地表水体生产力或BP的DIC施肥及其对蓝藻富营养化的抑制作用可能为实现碳增汇和富营养化缓解双赢(新假说, 图4)提供新思路.

然而，为系统阐明全球尺度喀斯特地表水体生产力的DIC施肥及其碳增汇和富营养化缓解效应, 未来我们需要对不同气候(温度、降水差异)、不同土地利用(N-P营养输入差异)和不同岩性(碳酸盐岩-硅酸盐岩产生pH和DIC差异)条件进行综合地考虑，尤其是以下科学问题有待被进一步研究：(1) 喀斯特地表水体DIC对

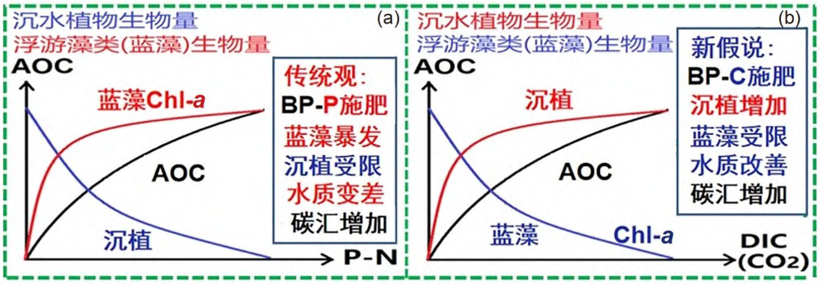

图 4 (网络版彩色)喀斯特地表水生产力(或者BP)的N-P限制(a)或DIC限制(b)及其碳汇和富营养化效应对比图
Figure 4 (Color online) Comparison of karst aquatic primary production (or BP) and its effects of carbon sequestration and eutrophication mitigation based on N-P limitation (a) and DIC limitation (b) paradigms of BP

BP施肥的机制及条件是怎样的? (2) 喀斯特地表水体C:N:P:Si与浮游-沉水植物群落结构的耦合关系及机制是什么? (3) 喀斯特地表水体DIC施肥下BP的碳增汇和富营养化缓解效应如何?

参考文献

1 Schindler D W. The mysterious missing sink. Nature, 1999, 398: 105–107

2 Houghton R A, Baccini A, Walker W S. Where is the residual terrestrial carbon sink? Glob Change Biol, 2018, 24: 3277–3279

3 Liu Z, Macpherson G L, Groves C, et al. Large and active CO_2 uptake by coupled carbonate weathering. Earth-Sci Rev, 2018, 182: 42–49

4 Kirschbaum M U F, Zeng G, Ximenes F, et al. Towards a more complete quantification of the global carbon cycle. Biogeosciences, 2019, 16: 831–846

5 Cole J J, Prairie Y T, Caraco N F, et al. Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget. Ecosystems, 2007, 10: 171–184

6 Tranvik L J, Downing J A, Cotner J B, et al. Lakes and reservoirs as regulators of carbon cycling and climate. Limnol Oceanogr, 2009, 54: 2298–2314

7 Liu Z H, Dreybrodt W, Wang H J. A possible important CO_2 sink by the global water cycle (in Chinese). Chin Sci Bull, 2008, 53: 402–407 [刘再华, Dreybrodt W, 王海静. 一种由全球水循环产生的可能重要的CO_2汇. 科学通报, 2007, 52: 2418–2422]

8 Liu H, Liu Z, Macpherson G L, et al. Diurnal hydrochemical variations in a karst spring and two ponds, Maolan karst experimental site, China: Biological pump effects. J Hydrol, 2015, 522: 407–417

9 Yang M, Liu Z, Sun H, et al. Organic carbon source tracing and DIC fertilization effect in the Pearl River: Insights from lipid biomarker and geochemical analysis. Appl Geochem, 2016, 73: 132–141

10 Chen B, Yang R, Liu Z, et al. Coupled control of land uses and aquatic biological processes on the diurnal hydrochemical variations in the five ponds at the Shawan Karst Test Site, China: Implications for the carbonate weathering-related carbon sink. Chem Geol, 2017, 456: 58–71

11 Zeng S, Liu H, Liu Z, et al. Seasonal and diurnal variations in DIC, NO_3^- and TOC concentrations in spring-pond ecosystems under different land-uses at the Shawan Karst Test Site, SW China: Carbon limitation of aquatic photosynthesis. J Hydrol, 2019, 574: 811–821

12 Chen C Y, Liu Z H. The role of biological carbon pump in the carbon sink and water environment improvement in karst surface aquatic ecosystems (in Chinese). Chin Sci Bull, 2017, 62: 3440–3450 [陈崇瑛, 刘再华. 喀斯特地表水生生态系统生物碳泵的碳汇和水环境改善效应. 科学通报, 2017, 62: 3440–3450]

13 Schindler D W. Evolution of phosphorus limitation in lakes. Science, 1977, 195: 260–262

14 Howarth R W, Marino R. Nitrogen as the limiting nutrient for eutrophication in coastal marine ecosystems: Evolving views over three decades. Limnol Oceanogr, 2006, 51: 364–376

15 Elser J J, Bracken M E S, Cleland E E, et al. Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. Ecol Lett, 2007, 10: 1135–1142

16 Paerl H W. Controlling eutrophication along the freshwater-marine continuum: Dual nutrient (N and P) reductions are essential. Estuaries Coasts, 2009, 32: 593–601

17 Abell J M, Özkundakci D, Hamilton D P. Nitrogen and phosphorus limitation of phytoplankton growth in New Zealand lakes: Implications for eutrophication control. Ecosystems, 2010, 13: 966–977

18 Field C B, Behrenfeld M J, Randerson J T, et al. Primary production of the biosphere: Integrating terrestrial and oceanic components. Science,

1998, 281: 237–240

19 Stumm W, Morgan J. Aquatic Chemistry: An Introduction Emphasizing Chemical Equilibria in Natural Waters. New York: John Wiley & Sons, 1981

20 King D L. The role of carbon in eutrophication. J Water Pollut Contr Fed, 1970, 42: 2035–2051

21 Burris J E, Wedge R, Lane A. Carbon dioxide limitation of photosynthesis of freshwater phytoplankton. J Freshw Ecol, 1981, 1: 81–96

22 Riebesell U, Wolf-Gladrow D A, Smetacek V. Carbon dioxide limitation of marine phytoplankton growth rates. Nature, 1993, 361: 249–251

23 Yang Y, Gao K. Effects of CO_2 concentrations on the freshwater microalgae, *Chlamydomonas reinhardtii*, *Chlorella pyrenoidosa*, and *Scenedesmus obliquus*, (Chlorophyta). J Appl Phycol, 2003, 15: 379–389

24 Zhang Y, Yin L, Jiang H S, et al. Biochemical and biophysical CO_2 concentrating mechanisms in two species of freshwater macrophyte within the genus Ottelia (Hydrocharitaceae). Photosynth Res, 2014, 121: 285–297

25 Hamdan M, Byström P, Hotchkiss E R, et al. Carbon dioxide stimulates lake primary production. Sci Rep, 2018, 8: 10878

26 Low-décarie E, Fussmann G F, Bell G. The effect of elevated CO_2 on growth and competition in experimental phytoplankton communities. Glob Change Biol, 2011, 17: 2525–2535

27 Low-Décarie E, Fussmann G F, Bell G. Aquatic primary production in a high-CO_2 world. Trends Ecol Evol, 2014, 29: 223–232

28 Low-Décarie E, Bell G, Fussmann G F. CO_2 alters community composition and response to nutrient enrichment of freshwater phytoplankton. Oecologia, 2015, 177: 875–883

29 Sterner R W. On the phosphorus limitation paradigm for lakes. Internat Rev Hydrobiol, 2008, 93: 433–445

30 Murphy T P, Hall K J, Yesaki I. Coprecipitation of phosphate with calcite in a naturally eutrophic lake. Limnol Oceanogr, 1983, 28: 58–69

31 Srivastava J, Gupta A, Chandra H. Managing water quality with aquatic macrophytes. Rev Environ Sci Biotechnol, 2008, 7: 255–266

32 Kragh T, Sand-Jensen K. Carbon limitation of lake productivity. Proc R Soc B-Biol Sci, 2018, 285: 20181415

33 Otsuki A, Wetzel R G. Coprecipitation of phosphate with carbonates in a marl-lake. Limnol Oceanogr, 1972, 17: 763–767

34 Hamilton S K, Bruesewitz D A, Horst G P, et al. Biogenic calcite-phosphorus precipitation as a negative feedback to lake eutrophication. Can J Fish Aquat Sci, 2009, 66: 343–350

35 Walsh J R, Corman J R, Munoz S E. Coupled long-term limnological data and sedimentary records reveal new control on water quality in a eutrophic lake. Limnol Oceanogr, 2019, 64: S34

36 Volk T, Hoffert M I. Ocean carbon pumps: Analysis of relative strengths and efficiencies in ocean-driven atmospheric CO_2 changes. In: Sundquist E T, Broecker W S, eds. The Carbon Cycle and Atmospheric CO_2: Natural Variations Archean to Present, Geophysical Monograph Series. Washington DC: American Geophysical Union, 1985, 32: 99–110

37 Wagener K, De Luca Rebello A. On the effectiveness of the ocean's biological pump in global CO_2 scenarios. Mar Chem, 1987, 22: 249–256

38 Longhurst A R, Glen Harrison W. The biological pump: Profiles of plankton production and consumption in the upper ocean. Prog Oceanogr, 1989, 22: 47–123

39 Sigman D M, Boyle E A. Glacial/interglacial variations in atmospheric carbon dioxide. Nature, 2000, 407: 859–869

40 Hain M P, Sigman D M, Haug G H. The biological pump in the past. In: Holland H D, Turekian K K, eds. The Oceans and Marine Geochemistry. 2nd ed. Amsterdam: Elsevier, 2014. 485–517

41 Ma Z, Gray E, Thomas E, et al. Carbon sequestration during the Palaeocene-Eocene Thermal Maximum by an efficient biological pump. Nat Geosci, 2014, 7: 382–388

42 Agusti S, González-Gordillo J I, Vaqué D, et al. Ubiquitous healthy diatoms in the deep sea confirm deep carbon injection by the biological pump. Nat Commun, 2018, 6: 7608

43 Shen J, Pearson A, Henkes G A, et al. Improved efficiency of the biological pump as a trigger for the Late Ordovician glaciation. Nat Geosci, 2018, 11: 510–514

44 Passow U, Carlson C A. The biological pump in a high CO_2 world. Mar Ecol Prog Ser, 2012, 470: 249–271

45 Rivero-Calle S, Gnanadesikan A, Del Castillo C E, et al. Multidecadal increase in North Atlantic coccolithophores and the potential role of rising CO_2. Science, 2015, 350: 1533–1537

46 Hauck J, Völker C, Wolf-Gladrow D A, et al. On the Southern Ocean CO_2 uptake and the role of the biological carbon pump in the 21st century. Glob Biogeochem Cycle, 2015, 29: 1451–1470

47 Martin J H, Fitzwater S E. Iron deficiency limits phytoplankton growth in the north-east Pacific subarctic. Nature, 1988, 331: 341–343

48 Martin J H, Gordon R M, Fitzwater S E. Iron in Antarctic waters. Nature, 1990, 345: 156–158

49 Martínez-García A, Sigman D M, Ren H, et al. Iron fertilization of the Subantarctic Ocean during the Last Ice Age. Science, 2014, 343: 1347–1350

50 Riebesell U, Schulz K G, Bellerby R G J, et al. Enhanced biological carbon consumption in a high CO_2 ocean. Nature, 2007, 450: 545–548

51 Krivtsov V, Bellinger E, Sigee D, et al. Interrelations between Si and P biogeochemical cycles—A new approach to the solution of the

eutrophication problem. Hydrol Process, 2000, 14: 283–295
52 Chen Y. Long-term dynamics of phytoplankton assemblages: Microcystis-domination in Lake Taihu, a large shallow lake in China. J Plankton Res, 2003, 25: 445–453
53 Blain S, Quéguiner B, Armand L, et al. Effect of natural iron fertilization on carbon sequestration in the Southern Ocean. Nature, 2007, 446: 1070–1074
54 Gao J, Xiong Z, Zhang J, et al. Phosphorus removal from water of eutrophic Lake Donghu by five submerged macrophytes. Desalination, 2009, 242: 193–204
55 Xu H, Paerl H W, Qin B, et al. Nitrogen and phosphorus inputs control phytoplankton growth in eutrophic Lake Taihu, China. Limnol Oceanogr, 2010, 55: 420–432
56 Lewis W M J, Wurtsbaugh W A. Control of lacustrine phytoplankton by nutrients: Erosion of the phosphorus paradigm. Internat Rev Hydrobiol, 2008, 93: 446–465
57 Paerl H W, Xu H, McCarthy M J, et al. Controlling harmful cyanobacterial blooms in a hyper-eutrophic lake (Lake Taihu, China): The need for a dual nutrient (N & P) management strategy. Water Res, 2011, 45: 1973–1983
58 Huisman J, Codd G A, Paerl H W, et al. Cyanobacterial blooms. Nat Rev Microbiol, 2018, 16: 471–483
59 Hillman A L, Abbott M B, Yu J Q. Climate and anthropogenic controls on the carbon cycle of Xingyun Lake, China. Palaeogeogr Palaeoclimatol Palaeoecol, 2018, 501: 70–81
60 Panizzo V N, Roberts S, Swann G E A, et al. Spatial differences in dissolved silicon utilization in Lake Baikal, Siberia: Examining the impact of high diatom biomass events and eutrophication. Limnol Oceanogr, 2018, 63: 1562–1578
61 Schindler D E, Carpenter S R, Cole J J, et al. Influence of food web structure on carbon exchange between lakes and the atmosphere. Science, 1997, 277: 248–251
62 Caraco N F, Cole J J, Strayer D L. Top down control from the bottom: Regulation of eutrophication in a large river by benthic grazing. Limnol Oceanogr, 2006, 51: 664–670
63 Xie D, Yu D, You W H, et al. Algae mediate submerged macrophyte response to nutrient and dissolved inorganic carbon loading: A mesocosm study on different species. Chemosphere, 2013, 93: 1301–1308
64 Cavan E L, Henson S A, Belcher A, et al. Role of zooplankton in determining the efficiency of the biological carbon pump. Biogeosciences, 2017, 14: 177–186
65 Gao H, Qian X, Wu H, et al. Combined effects of submerged macrophytes and aquatic animals on the restoration of a eutrophic water body—A case study of Gonghu Bay, Lake Taihu. Ecol Eng, 2017, 102: 15–23
66 Spilling K, Olli K, Lehtoranta J, et al. Shifting diatom-dinoflagellate dominance during spring bloom in the Baltic Sea and its potential effects on biogeochemical cycling. Front Mar Sci, 2018, 5: 327
67 Dean W E, Gorham E. Magnitude and significance of carbon burial in lakes, reservoirs, and peatlands. Geology, 1998, 26: 535–538
68 Verpoorter C, Kutser T, Seekell D A, et al. A global inventory of lakes based on high-resolution satellite imagery. Geophys Res Lett, 2014, 41: 6396–6402
69 Mulholland P J, Elwood J W. The role of lake and reservoir sediments as sinks in the perturbed global carbon-cycle. Tellus, 1982, 34: 490–499
70 Stallard R F. Terrestrial sedimentation and the carbon cycle: Coupling weathering and erosion to carbon burial. Glob Biogeochem Cycle, 1998, 12: 231–257
71 Einsele G. Atmospheric carbon burial in modern lake basins and its significance for the global carbon budget. Glob Planet Change, 2001, 30: 167–195
72 Hanson P C, Pollard A I, Bade D L, et al. A model of carbon evasion and sedimentation in temperate lakes. Glob Change Biol, 2004, 10: 1285–1298
73 Downing J A, Cole J J, Middelburg J J, et al. Sediment organic carbon burial in agriculturally eutrophic impoundments over the last century. Glob Biogeochem Cycle, 2008, 22: GB1018
74 Heathcote A J, Downing J A. Impacts of eutrophication on carbon burial in freshwater lakes in an intensively agricultural landscape. Ecosystems, 2012, 15: 60–70
75 Brothers S M, Hilt S, Attermeyer K, et al. A regime shift from macrophyte to phytoplankton dominance enhances carbon burial in a shallow, eutrophic lake. Ecosphere, 2013, 4: UNSP 137
76 Katsev S, Crowe S A. Organic carbon burial efficiencies in sediments: The power law of mineralization revisited. Geology, 2015, 43: 607–610
77 Knoll L B, Vanni M J, Renwick W H, et al. Temperate reservoirs are large carbon sinks and small CO_2 sources: Results from high-resolution carbon budgets. Glob Biogeochem Cycle, 2013, 27: 52–64
78 Pacheco F, Roland F, Downing J. Eutrophication reverses whole-lake carbon budgets. Inland Waters, 2014, 4: 41–48
79 Anderson N J, Bennion H, Lotter A F. Lake eutrophication and its implications for organic carbon sequestration in Europe. Glob Change Biol,

2014, 20: 2741–2751

80 Davidson T A, Audet J, Svenning J C, et al. Eutrophication effects on greenhouse gas fluxes from shallow-lake mesocosms override those of climate warming. Glob Change Biol, 2015, 21: 4449–4463

81 Heathcote A J, Anderson N J, Prairie Y T, et al. Large increases in carbon burial in northern lakes during the Anthropocene. Nat Commun, 2015, 6: 10016

82 Smith V H. Low nitrogen to phosphorus ratios favor dominance by blue-green algae in lake phytoplankton. Science, 1983, 221: 669–671

83 Schindler D W, Hecky R E, Findlay D L, et al. Eutrophication of lakes cannot be controlled by reducing nitrogen input: Results of a 37-year whole-ecosystem experiment. Proc Natl Acad Sci USA, 2008, 105: 11254–11258

84 Schindler D W. The dilemma of controlling cultural eutrophication of lakes. Proc R Soc B, 2012, 279: 4322–4333

85 Conley D J, Paerl H W, Howarth R W, et al. Controlling eutrophication: Nitrogen and phosphorus. Science, 2009, 323: 1014–1015

86 Paerl H W, Hall N S, Peierls B L, et al. Evolving paradigms and challenges in estuarine and coastal eutrophication dynamics in a culturally and climatically stressed world. Estuaries Coasts, 2014, 37: 243–258

87 Paerl H W, Xu H, Hall N S, et al. Nutrient limitation dynamics examined on a multi-annual scale in Lake Taihu, China: Implications for controlling eutrophication and harmful algal blooms. J Freshw Ecol, 2015, 30: 5–24

88 Paerl H W, Scott J T, McCarthy M J, et al. It takes two to Tango: When and where dual nutrient (N & P) reductions are needed to protect lakes and downstream ecosystems. Environ Sci Technol, 2016, 50: 10805–10813

89 Dodds W, Smith V. Nitrogen, phosphorus, and eutrophication in streams. Inland Waters, 2016, 6: 155–164

90 Smith V, Wood S, McBride C, et al. Phosphorus and nitrogen loading restraints are essential for successful eutrophication control of Lake Rotorua, New Zealand. Inland Waters, 2016, 6: 273–283

91 Gerloff G C, Skoog F. Nitrogen as a limiting factor for the growth of microcystis aeruginosa in southern Wisconsin Lakes. Ecology, 1957, 38: 556–561

92 Weiss C M. Relation of phosphates to eutrophication. J Am Water Works Assoc, 1969, 61: 387–391

93 Shapiro J. Blue-green algae: Why they become dominant. Science, 1973, 179: 382–384

94 Aizawa K, Miyachi S. Carbonic anhydrase and CO_2 concentrating mechanisms in microalgae and cyanobacteria. FEMS Microbiol Lett, 1986, 39: 215–233

95 Badger M R, Price G D. The role of carbonic anhydrase in photosynthesis. Annu Rev Plant Physiol Plant Mol Biol, 1994, 45: 369–392

96 Mercado J M, Ramírez T, Cortés D, et al. Effect of carbonic anhydrase inhibitors on the inorganic carbon uptake by phytoplankton natural assemblages. J Phycol, 2009, 45: 8–15

97 Kaplan A, Reinhold L. CO_2 concentrating mechanisms in photosynthetic microorganisms. Annu Rev Plant Physiol Plant Mol Biol, 1999, 50: 539–570

98 Badger M R, Price G D. CO_2 concentrating mechanisms in cyanobacteria: Molecular components, their diversity and evolution. J Exp Bot, 2003, 54: 609–622

99 Cassar N, Laws E A, Bidigare R R, et al. Bicarbonate uptake by Southern Ocean phytoplankton. Glob Biogeochem Cycle, 2004, 18: GB2003

100 Giordano M, Beardall J, Raven J A. CO_2 concentrating mechanisms in algae: Mechanisms, environmental modulation, and evolution. Annu Rev Plant Biol, 2005, 56: 99–131

101 Wu Y, Li P, Wang B, et al. Composition and activity of external carbonic anhydrase of microalgae from karst lakes in China. Phycol Res, 2008, 56: 76–82

102 Van Dam B R, Tobias C, Holbach A, et al. CO_2 limited conditions favor cyanobacteria in a hypereutrophic lake: An empirical and theoretical stable isotope study. Limnol Oceanogr, 2018, 63: 1643–1659

103 Taucher J, Jones J, James A, et al. Combined effects of CO_2 and temperature on carbon uptake and partitioning by the marine diatoms *Thalassiosira weissflogii* and *Dactyliosolen fragilissimus*. Limnol Oceanogr, 2015, 60: 901–919

104 Schindler D W, Fee E J. Diurnal variation of dissolved inorganic carbon and its use in estimating primary production and CO_2 invasion in lake 227. J Fish Res Bd Can, 1973, 30: 1501–1510

105 Jansson M, Karlsson J, Jonsson A. Carbon dioxide supersaturation promotes primary production in lakes. Ecol Lett, 2012, 15: 527–532

106 Yuan D X. The carbon cycle in karst. Z Geomorphol, 1997, 108: 91–102

107 Curl R L. Carbon shifted but not sequestered. Science, 2012, 335: 655

108 Liu Z, Dreybrodt W, Liu H. Atmospheric CO_2 sink: Silicate weathering or carbonate weathering? Appl Geochem, 2011, 26: 292–294

109 Chen C Y, Durbin E G. Effects of pH on the growth and carbon uptake of marine phytoplankton. Mar Ecol Prog Ser, 1994, 109: 83–94

110 Visser P M, Verspagen J M H, Sandrini G, et al. How rising CO_2 and global warming may stimulate harmful cyanobacterial blooms. Harmful Algae, 2016, 54: 145–159

111 Ryther J H, Dunstan W M. Nitrogen, phosphorus, and eutrophication in the coastal marine environment. Science, 1971, 171: 1008–1013

112 Dittrich M, Dittrich T, Sieber I, et al. A balance analysis of phosphorus elimination by artificial calcite precipitation in a stratified hardwater lake. Water Res, 1997, 31: 237–248

113 Robertson D M, Garn H S, Rose W J. Response of calcareous Nagawicka Lake, Wisconsin, to changes in phosphorus loading. Lake Reserv Manag, 2007, 23: 298–312

114 Zhu D W, Zhu H, Ni L S, et al. Relationship between calcium pump driven by submerged macrophytes and phosphorus cycle in water (in Chinese). Sci Limnol Sin, 2012, 24: 355–361 [朱端卫, 朱红, 倪玲珊, 等. 沉水植物驱动的水环境钙泵与水体磷循环的关系. 湖泊科学, 2012, 24: 355–361]

115 Naselli-Flores L, Barone R, Mosello R. Eutrophication control by lime addition: A preliminary approach in Sicilian reservoirs. Hydrobiologia, 2003, 504: 297–303

116 Fytianos K, Voudrias E, Raikos N. Modelling of phosphorus removal from aqueous and wastewater samples using ferric iron. Environ Pollut, 1998, 101: 123–130

117 Hoffman A R, Armstrong D E, Lathrop R C. Influence of phosphorus scavenging by iron in contrasting dimictic lake. Can J Fish Aquat Sci, 2013, 70: 941–952

118 Bao Q, Liu Z, Zhao M, et al. Role of carbon and nutrient exports from different land uses in the aquatic carbon sequestration and eutrophication process. Sci Total Environ, 2022, 813: 151917

119 Bao Q, Liu Z, Zhao M, et al. Primary productivity and seasonal dynamics of planktonic algae species composition in karst surface waters under different land uses. J Hydrol, 2020, 591: 125295

120 Sun H, Han C, Liu Z, et al. The nutrient limitation on primary productivity and phosphorus removal by biological pump in river-dammed reservoirs: Implications for carbon sink and eutrophication control. J Hydrol, 2022, 607: 127480

Summary for “岩溶湖库生产力的溶解无机碳施肥及碳增汇和富营养化缓解效应”

DIC fertilization of primary production in karst lake-reservoirs and its effects on carbon sequestration and mitigation of eutrophication

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The role of inland water bodies in the global carbon cycle is receiving more and more attention. It was found that in karst surface water ecosystems, phytoplankton and/or submerged plants can fix some of the carbonate weathering-related carbon and form stable carbon sinks. The higher the concentration of dissolved inorganic carbon (DIC), the higher the aquatic productivity, showing a “DIC fertilization effect” on the biological pump (BP) that improves the environment. Both BP and aqueous eutrophication are based on the formation of organic matter by aquatic photosynthesis. It is usually believed that N-P plays the limiting role in eutrophication, but both CO_2 and water may be limiting factors in photosynthetic reactions on land, while abundance of CO_2 is the only constraint in water. Previous studies have supposed that CO_2 can be obtained continuously from the atmosphere but, in fact, air-water atmospheric CO_2 exchange is a slow process and in alkaline karst aquatic ecosystems, (especially at pH>8), the limited CO_2 is important. Aqueous CO_2 concentrations also affect the biological composition in water bodies. Cyanobacteria can adapt to lower CO_2 concentrations than other algae, while green algae, diatoms and submerged plants tend to demand CO_2-rich water environments. In addition, when the BP utilizes DIC to build autochthonous organic matter, the precipitation of calcium carbonate due to high concentrations of Ca^{2+} also induces co-precipitation of phosphorus, removing the latter from the water and thus suppressing eutrophication of cyanobacteria. In short, the DIC fertilization effect on the biological pump and its inhibition of cyanobacterial eutrophication provides a new perspective on the climate-change win-win case of increased carbon sequestration plus reduced eutrophication. Future studies should try to focus on the following key scientific issues through integrated investigation on DIC fertilization, carbon sequestration enhancement and eutrophication mitigation effects of karst lake and reservoir BP in different nutrient states by combining with control experiments: (1) Mechanisms and controlling factors of DIC fertilization on BP; (2) coupling relationship and mechanism between water body C:N:P:Si and phytoplankton-submerged plant community structure/compositions; (3) effects of BP on carbon sink increase and eutrophication mitigation under DIC fertilization.

karst, surface aquatic ecosystem, biological pump, dissolved inorganic carbon fertilization, carbon sequestration, mitigating eutrophication

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