2017 年 11 月 地 球 学 报 Nov. 2017
第 38 卷 增刊 1: 51-54 Acta Geoscientica Sinica Vol.38 Supp.1: 51-54
www.cagsbulletin.com

典型水生植物对岩溶水生生态系统无机碳稳定性影响研究

王 培[1, 2)], 曹建华[1)*], 邵景力[2)]

1)中国地质科学院岩溶地质研究所, 广西桂林 541004; 2)中国地质大学(北京), 北京 100083

碳循环研究是全球变化科学中的研究重点, 其平衡问题已成为全球变化与地球科学领域的研究前沿和热点。“遗失汇”是全球碳收支研究的重点, 寻找和揭示其存在机理对研究全球碳循环具有重要意义。在全球碳循环研究中, 仅考虑海洋碳库和陆地生态系统碳库对全球碳循环的贡献, 然并未对地球岩石圈中碳酸盐岩碳库作充分评估。以袁道先院士为首的研究团队, 利用石灰岩溶蚀试片法(Carbonate-rock-tablet-test method)、水化学法(Hydrogen-discharge method)和扩散边界法(Diffusion Boundary Layer Model, DBL)首次估算了全球每年因碳酸盐岩溶蚀作用产生的碳汇量其约占当前碳循环模型中“遗失汇”的约 1/3。现代岩溶学研究成果表明, 岩溶作用积极参与全球碳循环。但有学者对岩溶作用产生碳汇的稳定性提出质疑, 认为“碳酸盐岩的溶蚀作用只是碳迁移的过程并没有产生碳汇”。然而水生植物是水生生态系统的重要组成部分, 占据着水域生态系统的关键界面, 水生植物光合作用对河流和湖泊初级生产力及碳元素的生物地球化学循环具有举足轻重的作用。本研究建立在水-岩-气-生相互作用的岩溶动力系统新模型基础之上, 选取典型岩溶区地表河为研究对象, 利用随机样方法开展流域尺度的水生植物群落调查, 确定岩溶水生生态系统中水生植物的优势种; 以岩溶水生生态系统中优势种为生物材料, 通过对比研究岩溶水与非岩溶水对水生植物生长的影响、pH 漂移法研究水生植物对岩溶水中无机碳的利用策略、水生植物对岩溶水体无机碳转化效率的研究, 从机理上揭示水生植物与岩溶水环境之间的相互作用; 在流域尺度上以典型岩溶地下河补给的寨底河为例, 通过昼夜监测水化学、水体无机碳浓度及稳定碳同位素变化, 同时结合水生植物稳定碳同位素组成, 深入剖析自然条件下水生植物对岩溶无机碳的利用策略及岩溶碳汇稳定性的影响。利用溶解氧法评估水生植物对输入寨底河水生生态系统中无机碳的固定量, 并对比溶解氧法与水化学流量法用于评估水生植物对岩溶碳汇转化量的差异。最终以寨底河为例初步建立岩溶地表河中无机碳的迁移转化模型。研究结果表明: (1)花溪河、寨底河和潮田河调查断面的水生植物隶属于水鳖科(*Hydrocharitaceae*)、眼子菜科(*Potamogetonaceae*)、小二仙草科(*Haloragaceae*)、金鱼藻科(*Ceratophyllaceae*)和轮藻科(*Characeae*), 且均为沉水植物。花溪河水生植物优势种分别为苦草(*Vallisneria natans*)、海菜花(*Ottelia acuminate*)和黑藻(*Hydrilla verticillata*); 寨底河的水生植物优势种分别为苦菜(*Vallisneria natans*)、海菜花(*Ottelia acuminate*)、竹叶眼子菜(*Potamogeton wrightii*)和黑藻(*Hydrilla verticillata*); 潮田河中水生植物优势种为苦草(*Vallisneria natans*)、竹叶眼子菜(*Potamogeton wrightii*)和黑藻(*Hydrilla verticillata*)。与潮田河相比, 花溪河和寨底河中水生植物优势种分布相对比较均匀; 而潮田河中, 苦草与其它优势种之间差距相对较大。在岩溶水生植物调查中, 与通过频度确定河道中水生植物优势种的方法相比, 以优势度确定的水生植物优势种与实际调查结果更吻合。基质与水质是影响水生植物分布及其群落特征的主要因素。在岩溶地表河中, 苦草群落对环境的适应范围最广, 对水质条件、基质类型要求均相对较低。海菜花群落则仅分布于岩溶地表河段, 其对水质要求较高, 对基质适应范围较广。黑藻群落则对河道基质、光照条件要求较高, 对水质要求相对较低。竹叶眼子菜则对环

本文由中国地质调查局项目“岩溶地区固碳增汇试验示范”(编号: 12120113005300)、国土资源部/广西壮族自治区岩溶动力学重点实验室开放课题(编号: 14-B-04)联合资助。本文分别获 2014 年度和 2015 年度国土资源部/广西壮族自治区岩溶动力学重点实验室优秀论文。
收稿日期: 2016-08-04; 改回日期: 2016-08-12。责任编辑: 闫立娟。
第一作者简介: 王培, 男, 1987 年生。博士研究生。主要从事生物地球化学研究。E-mail: ecogene_wp@cugb.edu.cn。
*通讯作者: 曹建华, 男, 1963 年生。博士, 研究员。主要从事岩溶生态系统研究。E-mail: jhcaogl@karst.ac.cn。

境要求相对较低, 在不同类型基质中均能生长。(2)从生物量看, 岩溶水中黑藻生物量的增加量是非岩溶水中的 2.6 倍; 从植株长度来看, 黑藻在岩溶水中长度的增加量是非岩溶水中的 1.5 倍。揭示了岩溶水对水生植物的生长具有显著的促进作用, 不仅能促进水生植物植株长度的增加, 同时也能促进水生植物分根及分枝的生长。岩溶水对水生植物的生长具有显著的“施肥效应”。Ca^{2+}是水生植物生长必需的矿质元素。当水环境中 Ca^{2+}浓度为 1.25 mmol/L 时, 最有利于水生植物生物量的积累; 高浓度 Ca^{2+}对水生植物生长表现为促进分枝的分蘖。岩溶水生生态系统中, 高浓度的 Ca^{2+}水环境能促进水生植物生物量的增加, 其作用主要表现在促进水生植物分枝的生长, 对水生植物植株长度及分根的生长并无明显的促进作用。HCO_3^-能为水生植物光合作用提供充足碳源, 当水环境中 HCO_3^-浓度为 4 mmo/L 时, 最适宜水生植物生物量的积累; 在 8 mmol/L 时, 对水生植物分枝和分根的生长促进作用最强。岩溶水中高浓度 HCO_3^-促进水生植物分根和分枝的生长, 为水生植物适应以砂粒为主的河道基质环境提供了保障。在岩溶水生生态系统中, 高浓度 HCO_3^-是对水生植物产生“施肥效应”的主导因子, 高浓度 Ca^{2+}则促进水生植物对无机碳利用。pH 漂移实验揭示岩溶区水生植物优势种均具有利用 HCO_3^-的能力。其中, 仅生长于岩溶地表河段的海菜花对岩溶水中 HCO_3^-的利用能力最强。黑藻和狐尾藻光合作用优先利用岩溶水中 CO_2为无机碳源, 再利用岩溶水中 HCO_3^-, 同时会在植株叶表面形成 $CaCO_3$沉淀。狐尾藻和黑藻对岩溶碳汇的转化率分别为 54.29%和 54.43%。水生植物通过光合作用将岩溶水中相对不稳定的无机碳转化为相对稳定的有机碳储存于植株体, 同时通过沉积作用将一部分岩溶作用产生的 Ca^{2+}与 HCO_3^-以 $CaCO_3$的形式沉淀并向水环境中释放 CO_2。因此, 在岩溶水生生态系统中, 水生植物对岩溶水中不稳定无机碳的固定发挥着重要作用, 以水生植物为代表的初级生产者对岩溶碳汇的固定作用至关重要。(3)岩溶地下河补给是寨底河水生生态系统无机碳的最主要来源。河道沉积物大多以直径为 0.075~2 mm 的砂粒为主, pH 介于 8.23~8.88 之间, 有机质含量为 0.12%~0.95%, 其分解产生的内源无机碳含量远低于外源无机碳输入量。寨底河水-气界面平均脱气量为 4 581.87 mg/m^2/h, 沿流程方向脱气量呈降低趋势, 入口处脱气量最大, 为 6 719.80 mg/m^2/h; 出口处最小, 为 2 935.89 mg/m^2/h。寨底河上、下游水体游离 CO_2、HCO_3^-和 Ca^{2+}浓度变化量分别为 2.86 mg/L、7.05 mg/L 和 0.38 mg/L。河道中水生植物优势种的稳定碳同位素组成沿流程方向呈“梯度分布”趋势且不断偏正。寨底河水化学、无机碳浓度、溶解氧浓度及 pH 昼夜变化显著, 结合溶解无机碳及沉水植物稳定碳同位素组成沿流程方向偏正共同显示, 水生植物光合作用是控制寨底河水生生态系统各指标昼夜变化的主导因子。受岩溶地下河补给的地表河中无机碳主要以脱气作用、沉积作用及光合作用的方式在系统发生迁移。其中, 脱气作用与沉积作用具有较好的耦联关系, 二者主要受制于河流水文、水化学等。脱气作用与沉积作用使得系统内一部分无机碳在河道垂直剖面发生转移, 即以 CO_2的形式通过水-气界面释放到大气和以 $CaCO_3$的形式沉积到河床; 光合作用则使一部分无机碳在纵剖面发生转化, 其转化效率主要受制于环境因子。沿流程方向, 水生植物通过光合作用不断固定流经地表河水生生态系统的无机碳, 将不稳定的无机碳转化为稳定的有机碳而进入生态系统循环。(4)利用溶解氧法能准确的评估水生植物对输入岩溶水生生态系统中无机碳的固定量。寨底河水生生态系统中水生植物日平均初级生产量为 32.70 mg/L 的当量氧气, 呼吸作用速率为 21.42 mg/L 的当量氧气, 净初级生产力为 11.27 mg/L 的当量氧气, 寨底河水生生态系统具有较高的净初级生产力。水生植物光合作用和呼吸作用是影响寨底河中溶解氧浓度变化的主导因子。利用溶解氧法计算水生植物光合作用转化的岩溶水中无机碳量为 1.02 mmol/L 的氧气, 净固定量为 0.35 mmol/L; 利用水化学流量法计算 HCO_3^-减少量为 0.12 mmol/L。水生植物对输入系统的总无机碳利用量为 36.32%, 被固定为有机碳的量为 12.52%。若以水生植物对岩溶水中无机碳净固定量为例计算, 则水化学流量法计算的水生植物对岩溶碳汇固定量仅占溶解氧法计算结果的 34.29%。因此, 水化学流量法计算结果严重低估了岩溶水体中水生植物对岩溶碳汇的固定量。综上所述, 在岩溶地表河流水生生态系统中, 水生植物对岩溶无机碳的稳定性具有显著的作用。无论从小尺度还流域尺度, 水生植物对岩溶碳汇的固定量均不可忽视。

关键词: 水生植物调查; 施肥效应; 水生植物光合作用; 稳定碳同位素; 溶解氧法
中图分类号: P641.134; Q146 **文献标志码:** A **doi:** 10.3975/cagsb.2017.s1.14

Effects of Typical Aquatic Plants on the Stability of Inorganic Carbon in Karst Aquatic Ecosystem

WANG Pei[1, 2)], CAO Jian-hua[1)*], SHAO Jing-li[2)]

1) *Institute of Karst Geology, Chinese Academy of Geologocal Sciences, Guilin, Guangxi* 541004;
2) *China University of Geosciences (Beijing), Beijing* 100083

The carbon cycle research is the key point in Global Change Science. Its balance has become the frontiers and hot spots in the field of global change and earth science. Missing sink is the focus of the global carbon budget, finding and revealing the mechanism of its existence is of great significance to the study of global carbon cycle. In the global carbon researches, only considering the contribution of the ocean carbon library and the terrestrial ecosystem carbon library, but lack of adequate assessment for the carbonate carbon pool in the earth lithosphere. Research team headed by academician YUAN Dao-xian adopted the Carbonate-rock-tablet-test method, Hydrogen-discharge method and Diffusion Boundary Layer to estimate the amount of carbon sequestration each year caused by karstification around the world for the first time, which account for one-third of the missing sink in the carbon cycle model. Modern karstology in China demonstrated karstification actively involved in the global carbon cycle. However, some scholars have cast doubt on the stability of karst carbon sink thought "carbonate dissolution is only a process of carbon migration but does not produce carbon sequestration". Yet aquatic plants are an important part of aquatic ecosystems occupied the key interface of aquatic ecosystems, aquatic plants photosynthesis is of vital importance to the primary productivity and the carbon biogeochemical cycles. The paper is based on the Water-Rock-Gas-Organism new karst dynamic system model, taking typical karst rivers as study objects, random sampling method is used to survey the communities of aquatic plants in the watershed scale to determine the dominant species of aquatic plants in karst aquatic ecosystems. In order to reveal the interactions between aquatic plants and karst water environment in mechanism, taking the dominant species in the karst aquatic ecosystems as biological materials, making comparative studies of the growth of aquatic plants in karst and non-karst water, pH-drift method is used to study the inorganic carbon utilization strategy and its conversion efficiency for different aquatic plants. In the river basin scale, the Zhaidi river which fed by a typical karst underground river is taken as an example, by monitoring the water chemistry, dissolved inorganic carbon and stable carbon isotope change, combined with the stable carbon isotopic composition of aquatic plants to analyze the dissolved inorganic carbon utilization strategy and stability of the carbon sink in natural conditions by aquatic plants. Dissolved oxygen method is used to evaluate the fixation amount of dissolved inorganic carbon by aquatic plants and make comparison of dissolved oxygen method and hydrogen-discharged method to estimate the accuracy of both methods. Finally, taking Zhaidi river as an example to preliminary establish the dissolved inorganic carbon migration model in a karst surface river. The results show: (1) The aquatic plants in Huaxi, Zhaidi and Chaotian river belong to *Hydrocharitaceae, Potamogetonaceae*, *Haloragidaceae*, *Ceratophyllaceae* and *Characeae*, all of them are submerged plants. The dominant species of aquatic plants are respectively *Vallisneria natans, Ottelia acuminate* and *Hydrilla verticillata* in Huaxi River, *Vallisneria natans, Ottelia acuminate var. jingxiensis, Potamogeton wrightii,* and *Hydrilla verticillata* in Zhaidi River, and *Vallisneria natans, Potamogeton wrightii and Hydrilla verticillata* in Chaotian River. Compared with the Chaotian river, the dominant species of aquatic plants distribution are relatively uniform, meanwhile in the Chaotian river, the differences between *Vallisneria natans* and other dominant species are relatively large. In the investigation of karst aquatic plants, it's more accuracy to determine the dominant of aquatic plants for the method of dominance rather than frequency. Matrix and water quality are the main factors influencing the distribution and community characteristics of aquatic plants. In karst surface rivers, *Vallisneria natans* community possesses the most wide adaption to the environment. To the condition of water quality and matrix types requirements are relatively low. *Ottelia acuminate* community only anchors in karst surface rivers, lives in high water quality environment and adapts to a wide range of matrix. *Hydrilla verticillata* community has higher requirements to the matrix and light conditions, for water quality is relatively low. *Potamogeton wrightii* can grow in different types of matrix and require less to the environment. (2) From the perspective of biomass and plant length, *Hydrilla verticillata* live in karst water is respectively 2.6 times and 1.5 times than that in non-karst water. The result reveals that karst water has significant influence on the growth of aquatic plants, not only can promote the increase of plant length but also can promote the growth of plant roots and shoot tillering. Karst water has a significant "Fertilization effect" in the performance of promoting the growth of root devision and shoot tillering. Ca^{2+} is an essential

mineral element in the growth of aquatic plants. When the Ca^{2+} concentration is 1.25 mmol/L, the biomass of aquatic plants increased the most. High concentration of Ca^{2+} can promote the shoot tillering, but show no promoting on the plant length and shoot tillering. HCO_3^- provide sufficient carbon source for photosynthesis of aquatic plants. When the HCO_3^- concentration reaches 4 mmol/L, the biomass of aquatic plants increases the most; when the HCO_3^- concentration is 8 mmol/L, the promoting effect reaches the climax for aquatic plants. High concentration of HCO_3^- in karst water environment promotes the root growth which guarantees the aquatic plant growing in the matrix dominated by sand. HCO_3^- is the dominant factors in controlling the "Fertilization effect" for the growth of aquatic plants in the karst water environment. Ca^{2+} can strengthen the ability of aquatic plants to utilize dissolved inorganic carbon. pH drift experiments reveal that the dominant species of aquatic plants have the ability to utilize the HCO_3^- as carbon source. *Ottelia acuminate* has the highest ability to utilize HCO_3^- than any other dominant species. In the process of photosynthesis, *Myriophyllum spicatum* and *Hydrilla verticillata* have priority to utilize CO_2 than HCO_3^-, at the same generate precipitation in the form of $CaCO_3$. The karst carbon sink conversion ratios of *Myriophyllum spicatum* and *Hydrilla verticillata* are 54.29% and 54.43%, respectively. Through the photosynthesis of aquatic plants, a part of unstable dissolved inorganic carbon in karst water are converted into organic carbon in the form of biomass, another part are precipitated together with HCO_3^- in the form $CaCO_3$. Karstification remove atmospheric/soil CO_2 into water supplied for photosynthesis. Therefore, in karst water ecosystem, aquatic plants play an important role in fixing unstable inorganic carbon, it's crucial to take consideration of primary producers represented by aquatic plants in karst water ecosystem for estimating karst carbon sink. (3) The discharge of underground river is the main sources of dissolved inorganic carbon to Zhaidi aquatic ecosystem. The river matrixis mainly sand grains with the diameter of 0.075~2 mm, and pH are alkaline between 8.23 to 8.88. The organic matter content range from 0.12% to 0.95%, the endogenous inorganic carbon content generated by the decomposition of organic matters are far lower than that of the input of exogenous inorganic carbon. The average outgassing content is 4581.87mg/m^2/h in Zhaidiriver and decrease with the flow distance, the maximum is 6 719.80 mg/m^2/h at the inlet and the minimum is 2 935.89 mg/m^2/h at the outlet. The concentration decrement of free CO_2, HCO_3^- and Ca^{2+} are 2.86 mg/L, 7.05 mg/L and 0.38 mg/L, respectively. The stable carbon isotopic composition shows a constant positive and a trend of "Gradient Distribution" along the flow direction. Water chemistry, dissolved inorganic carbon, dissolved oxygen and pH show a significant diel change consistent with the change of stable carbon isotopic composition of dissolved inorganic carbon and aquatic plant, all of them demonstrate that photosynthesis of aquatic plants are the dominant factor in controlling the change of each parameter. Outgassing effect, precipitation effect and photosynthesis effect are the main migration ways for dissolved inorganic carbon in the karst aquatic ecosystem. Among them, outgassing effect and precipitation effect have good coupling relationships and both mainly subject to hydrology and water chemistry. Through outgassing and precipitation effect, a part of dissolved inorganic carbon istransformed in vertical section in the form of free CO_2 exchanged with atmosphere and $CaCO_3$. A part of dissolved inorganic carbon are converted in longitudinal section and the conversion efficiency is mainly limited by environmental factors. Along with the flow direction, dissolved inorganic carbon areconstantly fixed by photosynthesis of aquatic plants in surface river and converted unstable inorganic carbon into stable organic carbon, then entering the cycle of ecological system. (4) Dissolved oxygen method can be a very good approach to assess the fixed amount by aquatic plants. The daily average primary production is equivalent to 32.70 mg/L O_2 and the respiration rate is equivalent of 21.42 mg/L O_2, the net primary production in Zhaidiriver is of 11.27 mg/L O_2. Photosynthesis and respiration are the dominant factors influencing the variation of dissolved oxygen. Dissolved oxygen method is used to calculate the conversion and fixation amount of dissolved inorganic carbon by aquatic plants, which are equivalent of 1.02 mmom/L and 0.35 mmol/L O_2, respectively. However, the reduction of HCO_3^- is only 0.12 mmol/L with the method of hydrogen-discharge method. The total utilization amount by aquatic plants is 36.32% and the fixed amount is 12.52% which occupied the total input dissolved inorganic carbon. Taking the fixation amount as an example, the calculation results of hydrogen-discharge method account for 34.29% than that of dissolved oxygen method. Therefore, the hydrogen-discharge method is seriously underestimated the fixation amount of karst carbon sink caused by aquatic plants. To sum up, in the karst aquatic ecosystem, aquatic plants have significant effect to the stability of dissolved inorganic carbon. The karst carbon sink caused by aquatic plants can't be ignored not only in the small scale but also in the watershed scale.

Key words: aquatic plant survey; fertilization effect; aquatic plant photosynthesis; stable carbon isotope; dissolved oxygen method

Acknowledgements:

This study was supported by China Geological Survey (No. 12120113005300) and Karst Dynamics Laboratory, MLR&GZAR (No. 14-B-04).