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海洋浮游植物功能类群对大气 CO_2 浓度增加的生理响应

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PHYSIOLOGICAL RESPONSES OF PHYTOPLANKTON FUNCTIONAL GROUPS TO ELEVATED CO_2 CONCENTRATIONS

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摘　要

大气 pCO_2 逐渐增加对海洋生物碳循环的影响已经引起广泛关注。海洋浮游植物功能类群，例如硅化和钙化的浮游植物以及蓝细菌等，对大气 pCO_2 增加的响应是其中的核心问题之一。目前，硅藻与钙化球石藻对大气 pCO_2 变化生理响应的比较研究还涉及不多，而对于微型蓝细菌聚球藻的不同株系则尚未见报道。本研究中，我们通过植物生长气候箱调节空气中 CO_2 分别为中浓度（600ppm）和高浓度（800ppm），正常空气 CO_2 浓度为参照，以海洋浮游植物硅藻中肋骨条藻（*Skeletonema costatum*）、艾氏球石藻（*Emiliania huxleyi*）以及分别富含藻红蛋白（PE）和藻蓝蛋白（PC）的聚球藻（*Synechococcus* sp.CCMP839）和（*Synechococcus cf_elongatus* CCMP1379）为实验材料，研究了 CO_2 浓度增加对它们生长、光合作用率、RNA/DNA 比率、生物化学组成、单细胞红色荧光（RFL）和橙色荧光（ORFL）、营养盐利用以及碳酸酐酶（CA）活性的影响。研究结果表明：

1. 艾氏球石藻生长没有受到 CO_2 浓度变化的影响，而中肋骨条藻在高浓度 CO_2 下生长率提高了 23.6%，细胞 RNA/DNA 比率相应提高了 66.6%，并且 RNA/DNA 比率与生长率之间呈显著的正相关关系（$R^2 = 0.764$）。艾氏球石藻光合作用率在中、高浓度 CO_2 下分别增加了 46.6%和 81.7%，其光合作用产物碳水化合物也随之分别增加了 75.2%和 57.9%，而中肋骨条藻光合作用率与生物化学组成均未受到 CO_2 浓度增加的影响。中肋骨条藻和艾氏球石藻叶绿素 a、叶绿素 c 和类胡萝卜素等光合色素的含量均未受到高浓度 CO_2 处理的影响。正常浓度 CO_2 下中肋骨条藻培养液中硝酸盐和

磷酸盐分别剩余 12.6%和 6.8%，而高浓度 CO_2 下则分别仅剩余 3.01%和 2.97%。这表明中肋骨条藻在高浓度 CO_2 下对硝酸盐和磷酸盐消耗量大于正常浓度 CO_2。艾氏球石藻在各浓度下对营养盐的利用则无显著变化。中肋骨条藻 CA 酶活性随着 CO_2 浓度的提高而逐渐降低，高浓度 CO_2 下降低了 39.1%，而艾氏球石藻 CA 酶活性处于相对较低的水平，并且各浓度 CO_2 处理下无显著变化。艾氏球石藻细胞表面钙化量为 0.269~0.286 g/L，并没有受到高浓度 CO_2 的影响。细胞化学组成以无机物为主（69.7~72.2%）。

2．PE-聚球藻的生长没有受到 CO_2 浓度变化的显著影响，而 PC-聚球藻在高浓度 CO_2 下生长率提高了 36.7%，细胞 RNA/DNA 比率相应提高了 36.4%，并且细胞 RNA/DNA 比率与生长率之间呈显著的正相关（R^2 = 0.84）。PE-聚球藻细胞碳水化合物、蛋白质和脂类含量以及 C/N 比率在各浓度 CO_2 下均无显著变化。PC-聚球藻细胞碳水化合物含量在高浓度 CO_2 下增加了 25.4%，而蛋白质和脂类含量以及 C/N 比率则未受到影响。PE-聚球藻单细胞 RFL 和 ORFL 在各浓度 CO_2 下均有逐渐下降的趋势，并且与藻细胞浓度之间呈明显的负相关关系。PC-聚球藻在正常浓度 CO_2 下与 PE-聚球藻表现有类似的规律，而在高浓度 CO_2 下，则没有明显下降趋势，整个培养过程中基本维持在同一水平。PE-和 PC-聚球藻细胞 CA 酶均有较高表达活性，各浓度 CO_2 处理之间无显著变化，数值范围分别为 71.6~82.1 和 78.6~87.1（W.A. units/mg chla）。

以上实验结果揭示了海洋主要功能类群硅藻和球石藻以及不同生态位的聚球藻株系之间对 CO_2 浓度变化适应的差异性，初步探讨了 CO_2 对海洋浮游植物作用过程的生理机制，为我们更好的了解大气 CO_2 浓度与海洋生物过程相互作用的生理机制以及预测

未来环境变化对海洋生物碳循环的影响提供了科学依据。

关键词：CO_2；生理响应；球石藻；硅藻；聚球藻；主要功能类群

Abstract

There has been increasing interest in understanding the effects of increasing atmospheric CO_2 on biological processes in terms of ocean carbon cycling. Responses of marine functional groups of phytoplankton, such as silicifying or calcifying phytoplankton and cyanobacteria, to CO_2 concentration variations remain one of the central questions. However, few studies on marine diatoms and coccolithophorids, and almost no study on picocyanobacterial *Synechococcus* have been conducted in this regard so far. In the present study, physiological changes in a marine coccolithophorid *Emiliania huxleyi*, a diatom *Skeletonema costatum*, and a phycocyanin (PC)-rich *Synechococcus* strain *Synechococcus cf_elongatus* CCMP1379 and a phycoerythrin (PE)-rich strain *Synechococcus* sp.CCMP839 with increasing CO_2 concentrations (350, 600 and 800 ppm) were examined under manipulations using a plant growth chamber. The results showed that:

1. *E. huxleyi* showed no significant change in growth rate over the entire experimental CO_2 range, while 23.6% increase in *S. costatum* was observed under 800 ppm CO_2. The RNA/DNA ratio of *S. costatum* cells correspondingly increased by 66.6% and positively correlated with growth rate ($R^2 = 0.764$). 46.6% and 81.7% increase were observed in photosynthetic rate of *E. huxleyi* at 600 and 800 ppm CO_2, correspondingly 75.2% and 57.9% increase in carbohydrates, respectively. *S. costatum* showed no significant change in

photosynthetic rate and cellular biochemical composition over the entire experimental CO_2 range. No significant changes in chlorophyll *a*, chlorophyll *c* and total colored carotenoids contents were observed in both *S. costatum* and *E. huxleyi*. Nitrate and phosphate in culture media of *S. costatum* remained 12.6% and 6.8%, 3.01% and 2.97% at 350 and 800 ppm, respectively. A greater utilization of nutrients by *S. costatum* was observed at higher level of CO_2, but almost the same utilization of nutrients by *E. huxleyi* at both CO_2 treatments. A significant decrease (39.1%) in carbonic anhydrase activity (CA) from 350 to 800 ppm CO_2 was observed in *S. costatum*, whereas CA activity in *E. huxleyi* remained unaffected by CO_2 variation. Coccolithophore *E. huxleyi* showed no significant change in calcification amount (ranging from 0.269 g/L to 0.286 g/L) and chemical compositions (inorganic matter accounting for 69.7~72.2%) over the entire experimental CO_2 range.

2. The *Synechococcus* PE strain had no significant change in growth rate over the entire experimental CO_2 range, while significant increase in the *Synechococcus* PC strain (36.7%) was observed under 800 ppm CO_2. The RNA/DNA ratio of PC strain correspondingly increased by 36.4% and positively correlated with growth rate (R^2 = 0.8399). PC strain showed no significant change in cellular biochemical composition over the entire experimental CO_2 range. A substantial increase (25.4%) in the carbohydrates content of the PE strain was observed at 800 ppm pCO_2, however, no significant changes in proteins and lipids content and C/N ratio were observed at all pCO_2

treatments. Cellular red fluorescence (RFL) and orange fluorescence (ORFL) of the PE strain tended to decline during the experiment at all pCO_2 treatments. However, no such decline was observed at 600 and 800 ppm CO_2 in the PC strain. Higher pCO_2 treatments seemed to alleviate the declines in cellular RFL and ORFL of the PC strain during the incubation course. The declines in cellular RFL and ORFL were negatively correlated with cell density of the *Synechococcus* strains. CA activity in both the *Synechococcus* PE and PC strains showed no significant change, and remained at relatively high level， ranging from 71.6 to 82.1 and from 78.6 to 87.1 W.A. units/mg chla, respectively.

These findings revealed some species- and habitat-specific differences in CO_2 responses of major phytoplankton functional groups, contributing to a small but growing body of knowledge about physiological mechanisms underlying the interaction between CO_2 variation and marine biological processes and to the enhancement of our ability to predict how future environmental changes may affect the biological carbon cycle in the oceans.

Key words: CO_2; Coccolithophorid; Diatom; Physiological response; *Synechococcus*; major phytoplankton functional group