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Review on the role of terrestrial aquatic photosynthesis in the global carbon cycle

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Abstract

Approximately 50% of the photosynthesis on Earth each year occurs in aquatic environments. Therefore, aquatic carbon fixation is particularly relevant in the regulation of the global climate. However, previous work concentrated mainly on the role of ocean aquatic photosynthesis in the uptake of CO_2 and/or HCO_3^-. Here, it is shown that the role of terrestrial aquatic photosynthesis in the CO_2 uptake, which utilizes dissolved inorganic carbon (DIC) by rock weathering to form the autochthonous organic carbon, and thus decreases the CO_2 release to atmosphere from terrestrial aquatic systems, should not be neglected in global budgeting in the carbon cycle. The magnitude of this carbon sink may account for a few hundred million tons of carbon per year, and might increase with the rise in DIC caused by global warming and anthropogenic activities. The finding that terrestrial aquatic photosynthesis results in the storage of significant amounts of DIC (CO_2) has broad implications. It indicates that the rock weathering-related carbon sink is largely underestimated if only the DIC concentrations at river mouths are considered, and transformation of DIC to autochthonous TOC is neglected. It also indicates that the atmospheric CO_2 sink due to carbonate weathering might be significant in also controlling long-term climate changes, due to the substantial production and burial of autochthonous organic carbon. This challenges the traditional point of view that only the chemical weathering of Ca–silicate rocks might potentially control long-term climate change.

Keywords: rock weathering; terrestrial aquatic photosynthesis; DIC fertilization; autochthonous organic carbon burial; water-rock-gas-organism interaction; global carbon cycle

1. Introduction

One of the most important challenges in the science of global climate change is effective accounting of the global budget for atmospheric CO_2 [1,2]. Anthropogenic activities have clearly altered the global

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carbon cycle. Significant gaps exist in our understanding of the change. Roughly half of the CO_2 emitted by burning fossil fuels remains in the atmosphere. The oceans and the terrestrial biosphere absorb the remaining half [1,2]. The partitioning between these two sinks is the subject of considerable debate. Without robust accounting for the fate of CO_2 leaving the atmosphere, predictions of future CO_2 concentrations will remain uncertain [3].

As Falkowski and Raven [4] pointed out, approximately 50% of the annual photosynthesis on Earth occurs in aquatic environments. Therefore, aquatic carbon fixation is of enormous importance in the regulation of the global climate. Previous work has concentrated mainly on the role of ocean aquatic photosynthesis in the CO_2 and/or HCO_3^- uptake [5-7]. For example, Falkowski [5] stressed the significance of oceanic aquatic photosynthesis and respiration in regulating the atmospheric CO_2. Over geological timescales, it shows that fixed nitrogen, not phosphorus, limits primary productivity. The ratio of photosynthetic carbon fixation in the oceans and respiratory oxidation of organic carbon appears to be determined by the oxidation state of the ocean and the supply of trace elements. In addition, Cassar et al. [6] found that although iron fertilization has been shown to significantly enhance phytoplankton growth and may potentially increase the carbon flux to the deep ocean, an important source of the inorganic carbon taken up by phytoplankton in their study was HCO_3^-, whose concentration is negligibly affected by the anthropogenic rise in CO_2. They conclude that biological productivity in Southern Ocean is unlikely to be directly regulated by natural or anthropogenic variations in atmospheric CO_2 concentrations because of the presence of a constitutive CCM (Carbon Concentrating Mechanism). However, what is the role of terrestrial aquatic photosynthesis in the global carbon cycle is still not very clear [8], therefore, this paper aims to review the potential carbon contribution of inland aquatic photosynthesis.

2. Terrestrial aquatic photosynthesis and the carbon cycle

Inland water ecosystems (particularly lakes, rivers, and reservoirs) have rarely been considered as potentially important quantitative components of the carbon cycle budget at either global or regional scales because they covers such a small fraction of the Earth's surface area [2]. Although Battin et al. [2] and Tranvik et al. [9] have stressed the role of inland waters in processing large amounts of organic carbon (TOC), they gave little attention to the role of terrestrial aquatic photosynthesis in processing dissolved inorganic carbon (DIC). However, a recent study [10] has shown that the contribution of autochthonous organic carbon (AOC), derived from DIC transformations by aquatic photosynthesis [8,11], in the Mississippi River (the largest river system in North America) could be 20% to 57% of the TOC, depending on the methods used ($\delta^{13}C_{TOC}$ and lipid biomarker respectively). If the lower value of 20% is multiplied with the result (1.1 Pg C/a) of inland water sediments of organic carbon (0.6 Pg C/a), and the riverine TOC to oceans (0.5 Pg C/a) [9,12], a value of 0.22 Pg C/a AOC is obtained, which is similar to CO_2 consumption fluxes by carbonate and silicate weathering deduced from the inorganic chemistry of large rivers in the world (0.288 Pg C/a) [13]. Therefore, to obtain more accurate estimates of rock weathering-related carbon sinks from river chemical data, both the concentrations of DIC and of autochthonous TOC must be considered.

In a new attempt to estimate the atmospheric CO_2 budget by considering the combined effects of carbonate dissolution, the global water cycle and photosynthetic uptake of DIC by aquatic organisms (or the carbonate weathering based on the water-rock-gas-organism interaction), Liu et al. [8] found that the net photosynthetic uptake of DIC by aquatic organisms on the continents could be as large as 0.233 Pg C/a, which is very close to the AOC value (0.22 Pg C/a) shown above.

More recently, Liu et al. [14] performed an experimental study of the utilization of DIC by Oocystis solitaria Wittr (a common alga in fresh waters), and observed a DIC-fertilization effect. They found that the HCO_3^- was utilized by O. s. Wittr as a carbon source for photosynthesis when CO_2 concentration was

low. In karst water (with high DIC concentrations) under alkaline pH environment, depending on carbonic anhydrase activity, which catalyzes the HCO_3^- dehydration reaction, O. s. Wittr, however, utilizes HCO_3^- more effectively than in non-karst water (with low DIC). The number of alga cells of O. s. Wittr increased from 1.0×10^8/L to 1.8×10^9/L in high DIC waters, an 18-fold increase, and to 7×10^8/L in low DIC waters, only a 7-fold increase under otherwise identical conditions. These results clearly show the DIC-fertilization effect on biomass production.

The evidence above shows that terrestrial aquatic photosynthesis may be limited by the supply of DIC (mainly HCO_3^- at pH 7-9), and because DIC is mainly produced by rock weathering [8,13], the production rate of terrestrial aquatic organic carbon is tied to rock weathering.

Therefore, the role of terrestrial aquatic photosynthesis in the CO_2 uptake, which utilizes DIC by rock weathering to form the autochthonous organic carbon, and thus decreases the CO_2 release to atmosphere from terrestrial aquatic systems, should not be neglected in global budgeting in the carbon cycle. The magnitude of this carbon sink could be in the order of a few hundred million tons of carbon per year, and may increase with the rise in DIC caused by global warming and anthropogenic activities [8,15].

3. Opportunities and challenges

The finding that terrestrial aquatic photosynthesis results in the storage of significant amounts of DIC has broad implications.

First, it provides the link between autochthonous organic carbon (AOC) in these aquatic ecosystems and the rock weathering-related DIC.

Second, it indicates that the rock weathering-related carbon sink is largely underestimated if only the DIC concentrations at river mouths are considered [13, 16], and transformation of DIC to autochthonous TOC [8,11] is neglected. Therefore, more accurate estimate of rock weathering-related carbon sinks will depend on the consideration of both the river concentrations of DIC and AOC.

Third, it indicates that the atmospheric CO_2 sink due to carbonate weathering might be significant also in controlling the long-term climate changes, due to the substantial production and burial of AOC by the following chemical reactions [8, 17, 18]:

$$CaCO_3+CO_2+H_2O \rightarrow Ca^{2+}+2HCO_3^- \xrightarrow{\text{photosynthesis}} CaCO_3\downarrow+x(CO_2\uparrow+H_2O)+(1\text{-}x)(CH_2O\downarrow+O_2).$$

This challenges the traditional point of view that only the chemical weathering of Ca–silicate rocks might potentially control long-term climate change [19]. Finally, due to the DIC-fertilization effect, the carbon sink by aquatic photosynthesis in terrestrial aquatic ecosystems operates as a positive feedback system: transformation of DIC to terrestrial organic carbon (AOC) will increase with the rise in DIC caused by global warming and anthropogenic activities [8,15]. This shows the importance of terrestrial aquatic ecosystems in regulating CO_2 and mitigating climate change by terrestrial aquatic photosynthesis.

However, for full understanding and more accurate assessment of terrestrial aquatic photosynthesis in DIC uptake, the temporal and spatial variations in concentrations of DIC and TOC and the underlying mechanisms within these aquatic ecosystems need to be better constrained. In addition, in order to evaluate the role of DIC and TOC fluxes in the global carbon cycle, the oceanic and lake responses to river carbon inputs must be quantified. Though aquatic organisms both in the ocean and on land may be fertilized by increased N, P, Si, Fe and/or DIC, it is still unclear how much of this carbon is trapped in the lakes, reservoirs, estuaries and coastal zones by organic sedimentation, and how much returns to the atmosphere through the process of respiration and decay. Clearly, scanning these problems is rich in promise.

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