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Abiotic CO2 Sequestration via River Runoff: A Potential "Missing Sink" Dampening Atmospheric Warming?

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Abstract

The international system for greenhouse gas emission accounting relies on national emission and absorption accounting. The effectiveness of these systems in accounting for carbon sinks is questionable due to the complexities of local carbon dioxide control in the atmosphere and uncertainties in forestry carbon balance assessments. This review proposes that irreversible abiotic mechanisms for removing carbon from the cycle of substances should play a major role in carbon sink accounting, as a complement to biotic carbon capture. While the capture and fixation of carbon by ecosystems is a reversible process and represents only the first step toward its removal from the atmosphere, subsequent steps leading to irreversible carbon sequestration depend mainly on the interaction of ecosystems with water flows that form continental runoff. This paper provides estimates that suggest a significant increase in previously existing values of carbon removal via river runoff, and concludes that continental runoff is a primary mechanism leading to long-term carbon sequestration.

Keywords

Carbon sequestration, continental runoff, "missing sink," river runoff, global warming, review

Introduction

Carbon sinks play a crucial role in the global carbon cycle, helping to regulate the concentration of CO2 in the atmosphere. Among them, terrestrial and oceanic carbon sinks receive significant attention due to their absorption and storage of substantial amounts of carbon. River runoff, as a

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link between land and ocean, plays an important role in this process by transporting organic and inorganic carbon to the oceans. This review examines various estimates of carbon fluxes associated with river runoff, compares them with other studies, and analyzes the reasons for discrepancies between them. The novelty of this review lies in highlighting the significant role of abiotic processes, specifically CO2 dissolution in river runoff, in long-term carbon sequestration, which has been underestimated in previous studies. We explore the hypothesis that abiotic CO2 sequestration in river runoff constitutes a significant component of the "missing carbon sink" in global carbon budget assessments.

Estimates of Carbon Absorption and the "Missing Sink" Problem

The magnitude of estimated land ecosystem carbon absorption varies greatly among different researchers. For example, based on an analysis of the FLUXNET database, the net ecosystem production (NEP, representing the net carbon absorption) of land ecosystems is estimated at 4.3 Gt per year, defined as the difference between plant respiration (118.7 Gt/year) and gross primary production (GPP, 123 Gt/year). Computer models of ecosystems estimate more than 2.5 GtC/year for northern forests; however, database estimates reduce these figures to 1.5 GtC/year for the entire Northern Hemisphere. The difference between model predictions and database instrumental estimates is discussed in Pan et al. (2011), Schimel et al. (2015), Keenan et al. (2016), and Piao et al. (2019). These discrepancies highlight the challenges in accurately quantifying carbon fluxes at regional and global scales.

Instrumental estimates, based on direct measurements of CO2 in the air via airplane sampling (e.g., the NASA Atmospheric Carbon and Transport (ACT) project, formerly NACA), often underestimate carbon absorption. For example, Schimel (2014) stated that tropical forests absorb 1.4 billion tons of carbon dioxide, while the global absorption of land ecosystems does not exceed 2.5 billion tons of C/year. Disputes also exist regarding the role of savannas, which account for approximately 25% of total land area and contribute significantly to global carbon

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cycling. The accurate assessment of savanna carbon dynamics remains a challenge due to their complex interactions with climate, fire, and land management practices.

A simplified calculation of CO2 absorption by forests, based on model forests, yields an average of 3 tons of CO2 per hectare. FAO data for Asian forests suggest a value of 5 tons/ha, meaning that carbon absorption varies from 0.8 to 1.4 t C/ha. This value yields an absorption of approximately 1 GtC for the forest area of Russia alone, which constitutes about 25% of the world's forests. Accordingly, the estimated global forest absorption would be 4 GtC, which does not align with the lower instrumental estimates. This discrepancy may be attributed to factors such as forest age structure, management practices, and the inclusion of non-forest land in the instrumental data.

Considering the classic method for estimating the increase in CO2 in various regions of the planet based on data from ground-based measuring stations (the Keeling time series, which began in 1958), an important feature of the Keeling curve is that the increase in concentration over 50 years averaged 1.8-1.9 ppm/year (approximately 0.5%/year). The increase in CO2 at a rate of 0.5% per year lags behind the rate of growth of anthropogenic emissions, which in the first decade of the 21st century was approximately 3%/year, six times higher than the actual average increase in CO2. Estimates of the rate of carbon sequestration at 3 GtC/year obtained by the ACT project for land are almost three times less than the average emission rate of 9 GtC/year – insufficient to ensure such a low rate of increase in CO2 concentration. This discrepancy suggests the existence of additional carbon sinks or underestimation of existing sinks.

Thus, the rate of carbon sequestration in land biosystems (approximately 3 GtC/year) must be supplemented by a flow into the ocean of at least 3.5 GtC/year to ensure a total flow of 6.5-6.7 GtC, necessary to maintain the real growth rate of CO2 concentration at the current relatively low level. These estimates conflict with the global estimates provided in "The global carbon budget 1959–2011" (2012), which state that, from 1960 to 2010, CO2 absorption by all land ecosystems and the ocean surface increased at an average rate of 0.05 Gt of carbon per year, and

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the total absorption increased, for the entire surface of the globe (including the ocean), it doubled over 50 years: from 2.4±0.8 to 5.0±0.9 billion tons of carbon per year. Ocean absorption is estimated as constant acidification at 2.5 billion tons of C/year. The carbon balance of the atmosphere consists of input and output. Data on the burning of fossil fuels and deforestation indicate that, in the period 2002-2011, approximately 9.3 billion tons of C entered the atmosphere annually. According to the balance summarized by the authors, 28% or 2.6 billion tons of C were absorbed by land vegetation, 2.5 billion tons (26%) went into the ocean, and the remaining 46% increased the gas concentration in the atmosphere, adding approximately 4.3 GtC/year to the atmosphere. The uncertainties associated with these estimates highlight the need for improved monitoring and modeling of carbon fluxes.

The data presented here differ from estimates based on the Keeling curve, which grows at a rate corresponding to an addition to the atmosphere of no more than 3.8 Gt/year. More striking is the difference in the assessment of the total absorption capacity of the ocean, considering Schimel's (2014) data, indicating that instrumental land ecosystem measurements "prove" the absorption of 3 GtC/year. The ocean absorption estimates differ by at least 1 GtC/year. These discrepancies underscore the need for a more comprehensive understanding of the processes governing carbon cycling in both terrestrial and marine environments.

The origin of these differences is a matter of debate and is often called the problem of the "missing sink." Zavarzin (2007) explicitly formulated this problem in his monograph. In the same work, Zavarzin estimated the carbon stock in the soils of Russia, accumulated during the Holocene (8 thousand years), at 300 GtC. However, even in this estimate, there is a "missing sink," since the average annual flow over these millennia should not have exceeded 300/8 = 37.5 million tons of C/year. For Russia, this estimate seems underestimated; it is unclear where the remaining carbon that should have been stored during this historical period is. We will address this question by considering the potential role of abiotic carbon sequestration in river runoff.

The Process of Gas Dissolution

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Carbon dioxide is relatively inert; therefore, direct chemical bonding without fixation in a substrate does not significantly affect it. However, it is soluble in water, making water the most critical substrate for dissolving gaseous CO2. In this context, dissolution in water is considered an effective mechanism for CO2 sequestration.

For considering CO2 dissolution on a planetary scale, high latitudes and great ocean depths (hypolimnion) are particularly important because the solubility of carbon dioxide increases with decreasing temperature.

This characteristic causes a significant flow of CO2 absorption in the ocean. Only the upper, relatively warm layers of the ocean (100-150 meters) become saturated, while the deeper layers, lying below the "thermocline" (called "hypolimnion" in stratified bodies of water as a layer below the convective mixing boundary), remain unsaturated with CO2, forming a constant reservoir for CO2 burial. The efficiency of this process is influenced by factors such as ocean circulation patterns, biological activity, and the availability of nutrients.

The problem of ocean acidification primarily affects "shallow water" – at depths where mixing effectively evens out the temperature – as a result, the flow of dissolving CO2 cannot proceed further. Additionally, solar heating of the seabed reduces gas solubility. Therefore, the potential for long-term carbon sequestration through CO2 dissolution is greater in deeper, colder ocean waters.

In deep waters, "dead zones" or oligotrophic waters exist, practically devoid of both oxygen and CO2. All oxygen-containing compounds are consumed by bacteria or converted into low-oxidized forms, such as nitrogen oxide NO2 losing oxygen due to bacterial activity to form nitrous oxide N2O... These regions, while limited in their biological activity, may still contribute to carbon sequestration through the dissolution of CO2 and subsequent burial in sediments.

Additionally, we believe that consideration of the processes occurring on land does not sufficiently account for the dissolution of CO2 in waters that are in a suspended state – in the form of fog, low cloud cover, and especially in river runoff. A dissertation by Jean Yaming

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(2023) provides strong evidence that variations in seasonal CO_2 absorption reliably increase with latitude, supporting the importance of high-latitude processes in atmospheric CO_2 dynamics. This latitudinal gradient in CO_2 absorption suggests a significant role for cold-water environments in carbon sequestration.

During the summer in high latitudes, coinciding with the vegetation period of northern forests, large volumes of water actively dissolve CO_2. These large volumes result from the melting of permafrost combined with the fog-mediated water exchange of taiga biomes. However, absorption itself quickly reaches saturation, so significant absorption volumes require flowing waters. Rivers flowing to the North – Yenisei, Lena, Ob, Kola, Northern Dvina, and many other Siberian rivers – meet the conditions of flow and movement toward increased solubility. A fundamental factor is that the great rivers of Russia carry their waters to the North and flow into cold oceans. This involves a complex of processes: on the one hand, CO_2 solubility in salt water is less than in fresh water, potentially leading to increased carbon dioxide release at river mouths. However, the temperature difference between the upper reaches and the mouth can eliminate this effect, and the overall process leads to net carbon sequestration.

Calculations

To assess the solubility of CO_2 in rivers, data on annual water flow and water temperature were used (Haine et al., 2015; Magritskii, 2008; Déry et al., 2016). The annual water flow of rivers flowing into the northern seas is approximately 4,200 km^3 for Canada and Russia combined, of which Russia provides approximately 2,900 km^3.

The solubility of CO_2 in water in the temperature range of 0-5°C varies from 0.3346 g/100 ml at 0°C to 0.2774 g/100 ml at 5°C (IUPAC-NIST Solubilities Database). To simplify calculations, the average solubility of CO_2 in this range was used, approximately 0.3055 g/100 ml.

Calculation of Annual CO2 Flow

The total annual CO_2 flow (Canada and Russia) comes from the flow volume of rivers: 4,200 km^3/year.

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The results of the calculations are summarized in the following tables:

Table 1. Estimated Annual CO2 Sequestration via River Runoff

Parameter	Value
Total River Runoff Volume	4200 km^3/year
Average CO2 Solubility	0.3055 g/100 ml
Estimated CO2 Sequestration	12.831 Gt CO2/year
Estimated C Sequestration	3.503 Gt C/year

Table 2. Key Parameters and Data Sources

Parameter	Value	Source
River Runoff Volume	4200 km^3/year	Haine et al. (2015), Déry et al. (2016)
CO2 Solubility	0.3055 g/100 ml	IUPAC-NIST Solubilities Database
Temperature Range	0-5°C	IUPAC-NIST Solubilities Database

This calculation does not yet account for the carbon that is released with methane entering the seas along with river runoff. It is known that reservoir ices of permafrost are thousands of times oversaturated with methane (Strelestskaya, 2016), which suggests its entry in the form of bubbles and methane hydrates. The fate of this methane in the Arctic Ocean and its potential contribution to greenhouse gas emissions require further investigation.

Discussion

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The estimated value of 3.5 GtC/year suggests a re-evaluation of the role of the taiga/boreal forests in the Northern Hemisphere. Traditionally, the role of permafrost and boreal forests is considered as direct absorbers of CO_2. However, our assessment suggests that forests play a role not so much in direct carbon absorption as in ensuring the consolidation of the flow of underground and surface moisture, i.e., they carry out critical management of moisture turnover. At the same time, the main role is played by the amount of condensed water in the forest turnover, and then filling the flow of Siberian rivers. Water stores an additional amount of CO_2, which remains dissolved along the entire course of the river to the north, in areas of increasingly lower temperatures. This flow of northern rivers stores a much larger amount of CO_2 than previously made estimates based solely on carbon storage in wood or permafrost ice. The hydrological function of boreal forests in facilitating abiotic carbon sequestration in river runoff deserves greater attention.

From the point of view of photosynthesis, the taiga should have yielded to tropical forests in the competition for primacy in managing carbon dioxide balances. If tropical forests led, seasonal CO_2 absorption would not reliably increase with latitude, as evidenced by the data presented in Yaming (2023). The observed latitudinal gradient supports the importance of high-latitude processes, including abiotic carbon sequestration in river runoff, in regulating atmospheric CO_2 levels.

Our estimates differ significantly from previous studies, such as the global carbon budget reports, which estimate ocean carbon uptake at around 2.5 GtC/year. This discrepancy may arise from the underestimation of abiotic CO_2 dissolution in river runoff in previous assessments. Further research is needed to refine these estimates by incorporating more complex models that account for factors such as river temperature, pH, salinity, and hydrological characteristics. The

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use of remote sensing data and improved modeling techniques can help reduce the uncertainties associated with these estimates.

Conclusion

This study highlights the significant role of river runoff in the absorption of atmospheric carbon dioxide, particularly in high-latitude regions. Our estimates suggest that the amount of carbon removed by this mechanism has been underestimated in previous studies. The findings emphasize the importance of considering abiotic processes, such as CO2 dissolution in river water, in assessing the global carbon cycle. Future research should focus on refining these estimates by incorporating more detailed data and models, as well as investigating the fate of dissolved carbon in the Arctic Ocean. The accurate assessment of carbon sequestration through river runoff is critical for developing effective strategies to mitigate climate change. This includes incorporating these processes into global carbon budget models and developing policies that promote sustainable water management practices.

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Competing inteests

The author declare that have no conflict of interest.

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References

Arctic Great Rivers Observatory (ArtRO).
http://www.arcticgreatrivers.org/ (accessed February 19, 2025).

Déry, S. J.; Hernández-Henríquez, M. A.; *et al.* *Cryosphere* **2016**, *10*(6), 2645–2662.

Global Runoff Data Centre (GRDC).
https://www.bafg.de/GRDC/EN/Home/homepage_node.html (accessed February 19, 2025).

https://doi.org/10.5194/egusphere-2025-1329
Preprint. Discussion started: 23 April 2025

IUPAC-NIST Solubilities Database. (http://srdata.nist.gov/) (accessed February 19, 2025).

Keenan, T. F.; *et al.* *Nat. Ecol. Evol.* **2016**, *1*(3), 59.

Magritskii, D. V. *General Hydrology*; Vysshaya shkola, 2008.

Pan, Y.; Birdsey, R. A.; Fang, J.; *et al.* *Science* **2011**, *333*(6044), 988–993.

Piao, S. L.; *et al.* *Nature* **2019**, *572*(7769), 267–270.

Schimel, D. *Global Environmental Change* **2014**, *25*, 1–8.

Schimel, D.; *et al.* *Proc. Natl. Acad. Sci.* **2015**, *112*(28), 8650–8655.

Strelestskaya, I. Proceedings of the VIII All-Russian Conference of Young Scientists "Science. Technology. Production"; 2016; C. 193–196.

Zavarzin, G. A. *Lecture on Symbiotic Microbiology*; KMK Scientific Press Ltd.: Moscow, 2007.

Yaming, J. Dissertation, San Diego 2023. Dissertation, "Advances in Representing Atmospheric Circulation and Structure for Carbon Cycle Studies" (2023). Chapter 1.4.1, entitled "Mapping Northern Hemisphere CO2". Thesis is available through the University of California San Diego eScholarship, (https://escholarship.org/uc/item/9f34j49m)