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## **Freshwater methane emissions offset the continental carbon sink**

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## **Abstract**

Inland waters (lakes, reservoirs, streams and rivers) are often substantial methane (CH<sub>4</sub>) sources in the terrestrial landscape. They are, however, not yet well integrated in global greenhouse gas (GHG) budgets. Data from 474 freshwater ecosystems and the most recent global water area estimates indicate that freshwaters emit at least 103 Tg of CH<sub>4</sub> yr<sup>-1</sup> corresponding to 0.65 Pg C as CO<sub>2</sub> equivalents yr<sup>-1</sup>, offsetting 25% of the estimated land carbon sink. Thus, the continental GHG sink may be considerably overestimated and freshwaters need to be recognized as important in the global carbon cycle.

A cornerstone of our understanding of the contemporary global carbon cycle is that the terrestrial land surface is an important greenhouse gas (GHG) sink (1, 2). The global land sink is estimated to be  $2.6 \pm 1.7 \text{ Pg C yr}^{-1}$  (excluding C emissions due to deforestation) (1). Lakes, impoundments, and rivers are parts of the terrestrial landscape but they have not yet been included in the terrestrial GHG balance (3, 4). Available data suggest, however, that freshwaters can be substantial sources of  $\text{CO}_2$  (3, 5) and  $\text{CH}_4$  (6). Over time, soil carbon reaches freshwaters by lateral hydrological transport where it can meet several fates including burial in sediments, further transport to the sea, or evasion to the atmosphere as  $\text{CO}_2$  or  $\text{CH}_4$  (7).  $\text{CH}_4$  emissions may be small in terms of carbon, but  $\text{CH}_4$  is a more potent GHG than  $\text{CO}_2$ , over century timescales. This study indicates that global  $\text{CH}_4$  emissions expressed as  $\text{CO}_2$  equivalents correspond to at least 25 % of the estimated terrestrial GHG sink.

$\text{CH}_4$  can be emitted from freshwaters through several different pathways, including ebullition (bubble flux from sediments), diffusive flux, and plant-mediated transport through emergent aquatic plants (6). Additional pathways may be important for hydroelectric reservoirs such as emissions upon passage through turbines and downstream of reservoirs (8, 9). We compiled  $\text{CH}_4$  emission estimates from 474 freshwater ecosystems for which the emission pathways were clearly defined (Table 1, 10).

Using recent data on the area and distribution of inland waters (11, 12), we estimate the total  $\text{CH}_4$  emission from freshwaters to  $103 \text{ Tg CH}_4 \text{ yr}^{-1}$  (Table 1). Expressed as  $\text{CO}_2$  equivalents this corresponds to  $0.65 \text{ Pg C (CO}_2 \text{ eq) yr}^{-1}$  or 25% of the estimated land GHG sink, assuming that 1 kg  $\text{CH}_4$  corresponds to 25 kg  $\text{CO}_2$  over a 100-year period (13). Ebullition and plant flux, which are both poorly represented in the data set, dominate the other flux pathways

which have been studied more frequently (Table 1). Ebullition is most likely to be underestimated because it is episodic and not representatively captured by the usual short term measurements (6). Accordingly, our global estimate of freshwater CH<sub>4</sub> emissions is probably conservative. For further discussion of the results see supporting online text.

Altogether this study indicates that CH<sub>4</sub> emissions from freshwaters can substantially affect the global land GHG sink estimate. Moreover, proper consideration of ebullition and plant mediated emission will most likely result in increased future estimates of CH<sub>4</sub> emission. Combining the present CH<sub>4</sub> emission estimate of 0.65 Pg C (CO<sub>2</sub> eq) yr<sup>-1</sup> with the most recent estimate of freshwater CO<sub>2</sub> emissions, 1.4 Pg C (CO<sub>2</sub> eq) yr<sup>-1</sup> (5) – together corresponding to 79 % of the estimated land GHG sink – it becomes clear that freshwaters are an important component of the continental GHG balance. Accordingly, the terrestrial GHG sink may be smaller than currently believed and data on GHG release from inland waters are needed in future revision of net continental GHG fluxes.

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### **Supporting Online Material**

[www.sciencemag.org](http://www.sciencemag.org)

Materials and Methods

Supporting text

Supporting References and Notes

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Table 1. Freshwater CH<sub>4</sub> emissions estimated from average areal estimates (flux m<sup>-2</sup> yr<sup>-1</sup>) times the areal estimates for different latitudes (10). “Tot open water” is the sum of open water fluxes, i.e. ebullition (Ebul), diffusive flux (Diff), and flux when CH<sub>4</sub> stored in the water column is emitted upon lake over turn (Stor), respectively. *n* and *CV* denotes the sample size (number of systems) and the coefficient of variation. Note the small sample size for many large emission values. The total sums of the yearly fluxes are expressed in Tg CH<sub>4</sub>.

Type and latitude	Emission Tg CH <sub>4</sub> yr <sup>-1</sup>												Area <sup>a</sup> km <sup>2</sup>
	Tot open water	<i>n</i>	<i>CV</i> %	Ebul	<i>n</i>	<i>CV</i> %	Diff	<i>n</i>	<i>CV</i> %	Stor	<i>n</i>	<i>CV</i> %	
<b>Lakes</b>													
>66	6.8	17	72	6.4	17	74	0.7	60	37				288318
>54-66	6.6	5	155	9.1	9	60	1.1	271	185	0.1	217	2649	1533084
25-54	31.6	15	127	15.8	15	177	4.8	33	277	3.7	36	125	1330264
<24	26.6	29	51	22.2	28	54	3.1	29	97	21.3	1		585536 <sup>b</sup>
<b>Reservoirs</b>													
>66	0.2 <sup>c</sup>												35289
>54-66	1.0	24	176	1.8	2	140	0.2	4	93				161352
25-54	0.7 <sup>d</sup>												116922
<24	18.1	11	87										186437
<b>Rivers</b>													
>66	0.1	1											38895
>54-66	0.2 <sup>c</sup>												80009
25-54	0.3	20	302										61867
<24	0.9 <sup>d</sup>												176856
<b>Sum open water</b>	93.1	116		55.3	59		9.9	343		25.1	254		
<b>Plant flux<sup>e</sup></b>	10.2												
<b>Sum all</b>	104												

<sup>a</sup> Lake and river area from (11). Reservoir area from (12),

<sup>b</sup> Likely underestimated – for comparison the mean flooded area for the major South American savanna wetlands) and the lowland Amazon (below 500 m.a.s.) is 115 620 km<sup>2</sup> and 750 000 km<sup>2</sup>, respectively (14).

<sup>c</sup> Estimated assuming similar emissions per area unit at latitudes > 54 degrees.

<sup>d</sup> Estimated assuming similar emissions per area unit at latitudes from 0 to 54 degrees.

<sup>e</sup> Plant flux (plant mediated emission) according to (10).