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Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude

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Hydroelectric reservoirs cover an area of 3.4×10^5 km^2 and comprise about 20% of all reservoirs. In addition, they contain large stores of formerly terrestrial organic carbon. Significant amounts of greenhouse gases are emitted[2], especially in the early years following reservoir creation, but the global extent of these emissions is poorly known. Previous estimates of emissions from all types of reservoir indicate that these human-made systems emit 321 Tg of carbon per year (ref. 4). Here we assess the emissions of carbon dioxide and methane from hydroelectric reservoirs, on the basis of data from 85 globally distributed hydroelectric reservoirs that account for 20% of the global area of these systems. We relate the emissions to reservoir age, location biome, morphometric features and chemical status. We estimate that hydroelectric reservoirs emit about 48 Tg C as CO_2 and 3 Tg C as CH_4, corresponding to 4% of global carbon emissions from inland waters. Our estimates are smaller than previous estimates on the basis of more limited data. Carbon emissions are correlated to reservoir age and latitude, with the highest emission rates from the tropical Amazon region. We conclude that future emissions will be highly dependent on the geographic location of new hydroelectric reservoirs.

Reservoirs are anthropogenic aquatic systems with a substantial impact on the global water cycle. For example, the annual increase in reservoir volume is equivalent to an annual rise of the global sea level of 0.55 mm (ref. 1). Hydroelectric reservoirs have been identified as potentially important sources of greenhouse gas (GHG) emissions[2]. These reservoirs are widely distributed around the world, and steadily increasing in number owing to the growth of the world's economy and related energy needs[3]. Globally, only 17% of the potential hydroelectric sites have so far been used. Further, the current area covered by hydroelectric reservoirs worldwide represents up to 25% of the area used for human-made freshwater systems (irrigation, water supply, energy generation and so on)[4]. Although initially considered a source of 'clean', GHG-free energy, there is increasing awareness that hydroelectric reservoirs are not carbon neutral, and there has been an ongoing scientific debate on the role of the reservoirs in the global carbon emissions to the atmosphere[5].

Decomposition of flooded vegetation and soil organic matter are potentially an important source of GHGs in hydroelectric reservoirs[6]. Thus, the initial flooding phase is associated with particularly high rates of both bacterial activity and GHG production[7]. Moreover, the bottom waters and sediments of reservoirs are often anoxic, mainly in tropical regions, contributing to CH_4 production. Continued organic matter inputs from inflowing rivers, algal production and regrowth of plants along shores during drawdown periods may become the main sources of organic carbon as the reservoirs age[8]. During the ageing process, emissions tend to decline[6], exponentially at initial stages and at slower rates with time[7], more rapidly in cold-water environments than in warm waters.

There are several possible fates for the GHGs produced: (1) direct flux across the air–water interface at the surface of the reservoir itself, (2) turbulent exchange with the atmosphere immediately downstream of the hydroelectric turbines and (3) flux across the air–water interface in the river outflow downstream of the reservoir. Further, methane can be transported by either diffusion or ebullition to the atmosphere[9]; methane can also be oxidized in the water column and be emitted as CO_2 (ref. 10). Despite the widespread evidence of significant GHG emissions by hydroelectric reservoirs, there is no consensus about the real impact and their contribution to the global carbon cycle[5]. In some extreme cases, particularly in tropical areas, GHG emissions per megawatt electricity produced could be as high as those from fossil-fuel power plants[11]. A previous study suggested, on the basis of the limited data set available at that time[4], that reservoirs could be globally important sources of GHG to the atmosphere. Within the decade following that study[4], the increasing awareness and interest in the GHG dynamics in hydroelectric reservoirs have resulted in a large data collection on GHG emission from the reservoirs, enabling a more comprehensive exploration of their global significance.

Here we explore the global significance of CO_2 and CH_4 emissions from hydroelectric reservoirs, using published data from 85 different hydroelectric reservoirs with a global distribution, situated between 68° N and 25° S. In total we assembled 141 estimates of CO_2 emissions and 89 estimates of CH_4 emissions.

In this data set, all the reservoirs were sources of CH_4 to the atmosphere and the majority (88%) was also a source of CO_2. Only 12% of reservoirs were net sinks of CO_2, and the strength of the sink was small in all cases (<500 mg C m^{-2} d^{-1}). In contrast, there was a large range in emissions, with reservoirs ranging from values approaching zero to being very large sources of GHGs $>2{,}000$ mg C m^{-2} d^{-1} as CO_2, and >500 mg C m^{-2} d^{-1} as CH_4 (Fig. 1a; Supplementary Table S2).

The areal emissions of both CO_2 and CH_4 from hydroelectric reservoirs were significantly negatively correlated to both reservoir age and latitude ($p < 0.0001$; Fig. 1 and Supplementary Fig. S1). The

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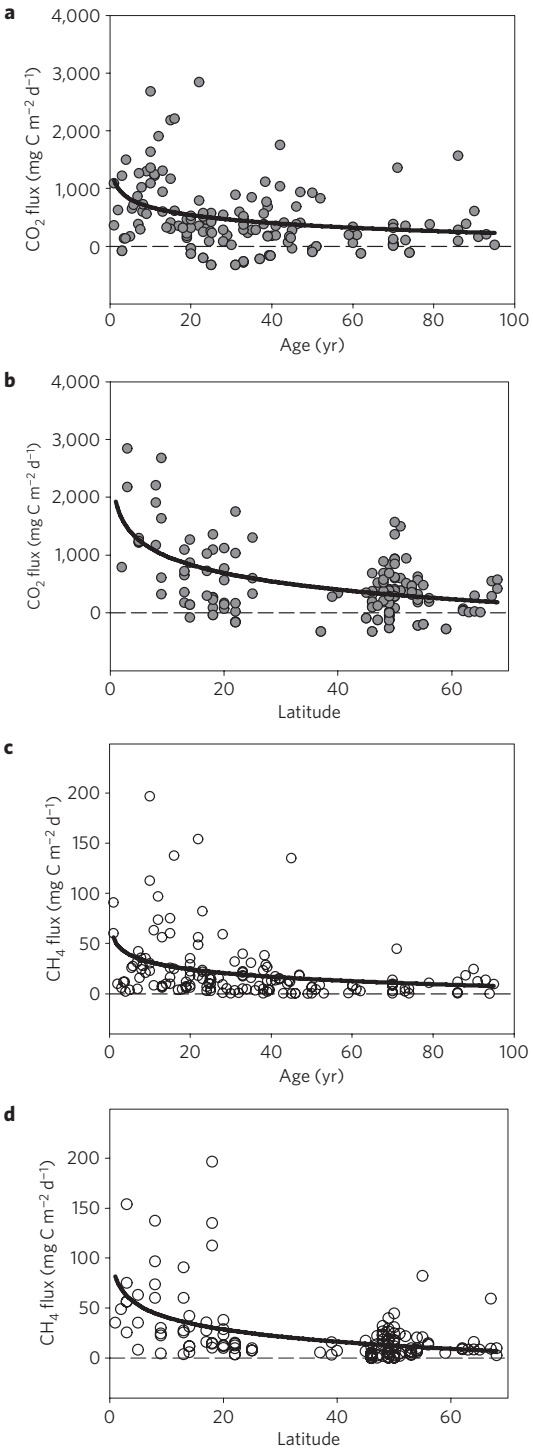

Figure 1 | Scatter plot and exponential decline for the relationships between CO_2 and CH_4 and age and latitude. **a**, CO_2 versus age (adjusted R^2, Adj $R^2 = 0.31$; degrees of freedom (df) = 136; significance probabilities (p) < 0.0001). **b**, CO_2 versus latitude (Adj $R^2 = 0.16$; df = 120; $p < 0.0001$). **c**, CH_4 versus age (Adj $R^2 = 0.39$; df = 149; $p < 0.0001$) and **d**, CH_4 versus latitude (Adj $R^2 = 0.17$; df = 144; $p < 0.0001$).

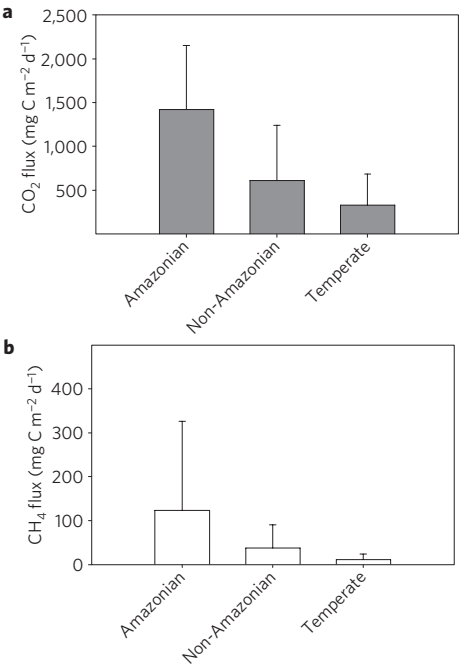

Figure 2 | Fluxes of CO_2 and CH_4 in different zones. Mean (bars) and standard deviation (lines) of the **a**, CO_2 and **b**, CH_4 fluxes in the 85 hydroelectric reservoirs worldwide distributed clustered by region. The tropical region was split into Amazonian and non-Amazonian regions.

negative correlation with reservoir age corroborates the previous evaluation of emissions from human-made freshwater systems[4]. In addition to age, areal emissions of both CO_2 and CH_4 were correlated to latitude, with highest emission rates near the tropics and lowest emission rates at high latitudes (Fig. 1b), a pattern that has been previously hypothesized[11], but never empirically tested. The latitudinal pattern of emissions is probably related to the corresponding gradient in water temperature[12]. Furthermore, higher flooded biomass in tropical regions leads to higher emissions (Fig. 2), and may increase the ratio of GHGs (for example CH_4/CO_2) that are released[13].

The emissions of both CO_2 and CH_4 were positively correlated to the input of dissolved organic carbon (Adj. $R^2 = 0.13$; $p = 0.0012$; $n = 110$ for CO_2 and Adj. $R^2 = 0.35$; $p < 0.0001$; $n = 89$ for CH_4) (Supplementary Fig. S2). Dissolved organic carbon (DOC) is a substrate for bacterial respiration and methanogenesis. Areal methane emission rates were negatively correlated to mean reservoir depth ($r^2 = 0.31$; $p = 0.0147$; $n = 88$), possibly reflecting the fact that CH_4 is primarily produced in sediments. A longer distance to the surface will both increase the fraction of the CH_4 that is oxidized and reduce the fluxes by ebullition and through vegetation (which enables CH_4 to avoid water-column oxidation)[14].

The most robust multiple-regression model for CO_2 contains reservoir age, latitude and input of DOC as independent variables and explains 40% of the variation in CO_2 flux ($p < 0.0001$; Fig. 3a). For CH_4, the most robust multiple-regression model also includes age, latitude and input of DOC as independent variables and furthermore includes mean depth, and explained 54% of the variation in CH_4 flux ($p < 0.0001$; Fig. 3b). Among all the variables considered, age seems to be the most important in determining the time course of carbon emissions in reservoirs. The literature indicates that in younger reservoirs (less than ~15 years) the main source of carbon is flooded biomass[7]. Exceptions are highly eutrophic reservoirs, which are sinks of CO_2 regardless of age or of the latitude where they are located. High levels of nutrient input, especially phosphorus, induce an increase in primary production, which is responsible for the sequestration of CO_2. In these cases, photosynthesis exceeds respiration of organic carbon, reducing the amount of CO_2 that is emitted[15]. Some of the highest CH_4 fluxes were recorded in the most eutrophic systems.

Clearly, most of the hydroelectric reservoirs emit GHGs to the atmosphere. On the basis of the area-specific rates extracted from

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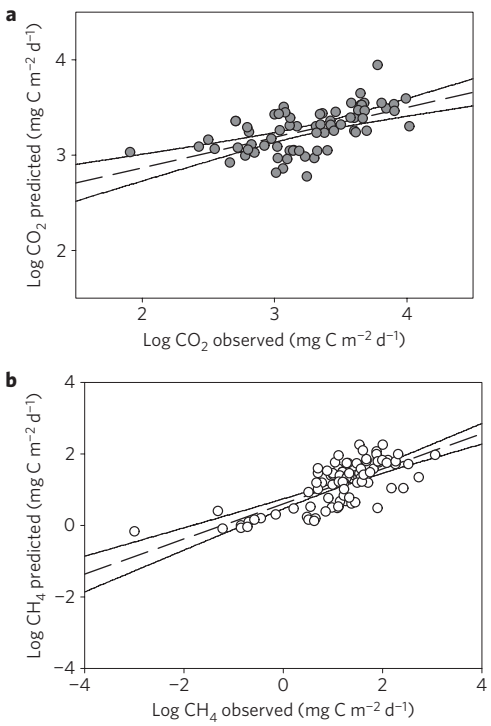

Figure 3 | Relationship between CO_2 and CH_4 predicted by the multiple regression and all data measured. a, Log CO_2 predicted by the multiple-regression model ($\log(y+400) = 3.06 - 0.16$ log age -0.01 latitude $+0.41$ log DOC; Adj $R^2 = 0.40$; df $= 73$; $p < 0.0001$). **b**, Log CH_4 predicted by the multiple-regression model ($\log y = 1.33 - 0.36$ log age -0.32 log mean depth $+0.39$ log DOC $- 0.01$ latitude; Adj $R^2 = 0.53$; df $= 89$; $p < 0.0001$).

the literature, we estimated the annual emissions of CO_2 and CH_4 from the entire area occupied by hydroelectric reservoirs. Globally, hydroelectric reservoirs emit about 48 Tg C as CO_2 per year and 3 Tg C as CH_4 per year from the reservoir surface (Table 1). GHGs emitted in the turbines (degassing)[16] and in the outflowing river[17] are unlikely to increase this estimate by more than twofold. As an example, in the Balbina reservoir, a case of high degassing and downstream emissions, approximately 50% of the total emissions take place at the reservoir surface[16]. These emissions are small relative to the total anthropogenic emissions[18] of either CO_2 (10,000 Tg of C–CO_2 yr^{-1}) or CH_4 (400 Tg C–CH_4 yr^{-1}). According to IPCC (ref. 18), 15–18% of global CO_2 emissions are due to land-use-change activities including agriculture and deforestation. The fossil-fuel burning is responsible for the complementary CO_2 emission. On the other hand, human waste, cattle ranching and agriculture (rice crops) are responsible for the main portion of CH_4 emission. The contribution from hydroelectric reservoirs here presented is minor when considering the global-warming potential of CO_2 and CH_4 (288 Tg of CO_2 equivalent/year, Table 1). Carbon emissions by hydroelectric reservoirs are also small in comparison to the total emissions reported for natural inland waters; lakes and rivers emit from 750 Tg C yr^{-1} (ref. 19) to 1,400 Tg C yr^{-1} (ref. 20).

Despite increased interest in the global extent of GHG emissions from hydroelectric reservoirs, data for these systems are still sparse and fragmented, and there is very little resolution on spatial and temporal variability in reservoir fluxes and related processes. For example, most of the data available represent emissions from the surface of deeper areas of hydroelectric reservoirs, which are assumed to be representative of the whole-reservoir emissions, and this is probably not the case for CO_2 and especially for CH_4 flux. Furthermore, our analysis does not take into account the loss of the potential carbon sink in the flooded area that became the reservoir, and therefore the actual net emissions due to the reservoir are currently systematically underestimated. Hydroelectric reservoirs also undergo sedimentation and therefore may accumulate large amounts of carbon, which would offset the gas emissions, but the balance between these processes is still not well understood. To our knowledge, there has been only one study approaching the actual net carbon emissions directly associated with the construction and operation of a hydroelectric reservoir, on the basis of a complete mass balance of the pre- and post-flood carbon budget (Teodoru, personal communication). More such studies are thus needed to better quantify the net impact of reservoirs.

Table 1 | Global estimates of CO_2 and CH_4 emissions from reservoirs and natural lakes.

Systems	Area ($\times 10^5$ km^2)	Carbon emission ($\times 10^{12}$ g yr^{-1})			
		C-CO_2	C-CH_4	Total C	CO_2 equivalents
	Age gradient				
Younger than 20 years	0.3	11	0.7	12	62
Older than 20 years	3.1	38	2.9	41	234
	Latitudinal gradient				
Boreal	0.8	6	0.2	7	31
Temperate	1.3	5	0.1	5	24
Tropical	1.2	37	3.0	40	233
Tropical—Amazonian	0.2	8	1.0	9	63
Tropical—non-Amazonian	1.0	25	1.5	27	143
	Global scenario				
Human-made fresh waters*	15	273	48	321	2,600
Hydroelectric reservoirs	3.4	48	3	51	288
Natural lakes	42	530†	54‡	584	3,743
Hydroelectric reservoir emissions/total human-made freshwater emissions (%)		18	7	16	11
Hydroelectric reservoir emissions/total natural lake emissions (%)		9	6	9	8

The areas of reservoirs and natural lakes, and the carbon fluxes of both C-CO_2 and C-CH_4, were used to calculate carbon emissions as C-CO_2, C-CH_4, total C and CO_2-equivalent emissions by hydroelectric reservoirs. For comparison, estimates of global emissions from natural lakes were included. The CO_2 equivalent was calculated as the data for CO_2 plus the CH_4 data multiplied by 25 according to IPCC (ref. 18), on the basis of the CH_4 global warming potential (see Methods). All data used to produce these estimates are available in Supplementary Information. *Data from ref. 4 (updated data using the factor of 25 according to IPCC (ref. 18)). †Data from ref. 20. ‡Data from ref. 22.

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Our analysis shows that hydroelectric reservoirs emit carbon as CO_2 as well as CH_4 to the atmosphere, and that emissions are approximately 16% of those from all human-made reservoirs (Table 1), and 4% of all total (natural plus human-made) carbon emissions by fresh waters. Therefore, according to currently available data, hydroelectric reservoirs do not seem to be major players in the global carbon budget at present. On the other hand, our study does not imply that hydroelectricity generation has a negligible carbon footprint. Although this contribution is somewhat smaller than previously estimated, it will no doubt increase as more reservoirs are built. How much the global reservoir GHG source will increase will depend greatly on where the new reservoirs are built. For example, on the basis of the average emission that we found from reservoirs in different regions, if the surface area of hydroelectric reservoirs increases by 5,000 km^2 (which is about twice the area of Tucuruí reservoir in Brazil, one of the largest reservoirs in the Western Hemisphere), the carbon emissions (as CO_2 equivalents) could increase by 1–2 Tg C yr^{-1} if this occurred in northern temperate and boreal regions. However, a similar expansion of hydroelectric reservoirs in the tropical (non-Amazonian) region could increase emissions by 4 Tg of C yr^{-1}, and this would further increase to 7 Tg of C yr^{-1} in the Amazonian region. In addition, more standardized assessment methods that better capture the natural heterogeneity of whole reservoirs will probably lead to increased emission estimates, but it is unclear by how much.

Future plans for hydroelectric development should not only aim at minimizing the overall environmental impact, but also aim at minimizing CO_2 and especially CH_4 emissions per unit of energy generated, by carefully selecting the location, design and operation of new reservoirs. Our data highlight that hydroelectric reservoirs in the Amazon region require particular attention, because they emit more GHGs than reservoirs in other regions.

Methods

Data collection. We collected data for CO_2 and CH_4 emissions in hydroelectric reservoirs, from the literature complemented with some unpublished studies (Supplementary Table S1). The CO_2 equivalent was calculated by adding the data of CO_2 plus the data of CH_4 multiplied by 25, on the basis of CH_4 global-warming potential[18]. We also recorded data of geographic coordinates, age, mean depth, perimeter, area, volume, residence time and DOC for each reservoir. Because not all of these variables are routinely reported, missing values are frequent in the database. Flow rate was calculated by dividing the volume by the residence time. The input of DOC was calculated as concentration times flow rate and then extrapolated to hydroelectric-reservoir surface areas. Data for perimeter and area were estimated using the image process with the software ArcGis for all reservoirs. The calculated area was strongly correlated to the area obtained in the published literature ($r^2 = 0.92$; $p < 0.0001$), which means that our error in the calculated perimeter is very small. Data for reservoir areas were obtained from the International Commission on Large Dams (ICOLD 2003). We also compared the CO_2 and CH_4 emission by hydroelectric reservoirs with the emission by natural lakes in Table 1 and analysed the CH_4 to CO_2 ratio of the emitted GHGs.

Global rates. We estimated the total emission from hydroelectric reservoirs on the basis of our database of published data (see Supplementary Table S1). The average emission (in mg C m^{-2} d^{-1}) was multiplied by the area covered by reservoirs in each of the three climatic zones (boreal, temperate and tropical), resulting in the total emission per zone (in Tg C yr^{-1}). The global emission of GHGs from hydroelectric reservoirs was calculated as the sum of the emissions from the three climatic zones.

Statistical analysis. Relationships between variables were analysed by means of linear and exponential regressions. Variables with non-normal distribution were log-transformed to approach normality. Because the influx of CO_2 is a negative number, its log is undefined. In the regressions we added 400 to all data to avoid the negative values' influence on the regressions. This procedure does not alter the correlations and is supported by other authors[21]. Because all reservoirs emitted CH_4 to the atmosphere, this procedure was not needed for CH_4. We used stepwise multiple regressions to identify which variables explain the variance in CO_2 and CH_4 emission, and used $p < 0.05$ for the significance probability for each regressor to be considered stepwise forward or backward in the model. All statistical analysis was carried out using the program JMP 7.0.

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Author contributions

F.R., J.J.C., L.J.T. and D.B. contributed to study design. N.B. and F.R. mined data. N.B., F.R., J.J.C. and Y.T.P. analysed the data. N.B., J.J.C., L.J.T., V.L.M.H., P.d.G. and F.R. wrote major portions of the manuscript. Y.T.P. and N.B. carried out and refined other statistical analyses. All authors discussed the results and commented on the manuscript.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://www.nature.com/reprints. Correspondence and requests for materials should be addressed to F.R.

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