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RETRACTED: Globally, Freshwater Ecosystems Emit More CO_2 Than the Burning of Fossil Fuels

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Freshwater emits substantial volumes of CO_2 to the atmosphere. This has largely gone unnoticed in global carbon budgets. My aim was to quantify the CO_2 emanating from freshwater from 66° N to 47° S latitudes via *in situ* bacterial respiration (BR). I determined BR (n = 326) as a function of water temperature. Freshwater is emitting CO_2 at a rate of 58.5 Pg C y^{-1} (six times that of fossil fuel burning). Most is emitted from the Northern Hemisphere. This is because the high northern summer temperatures coincide with most of the world's freshwater. Diffuse DOC sources, for example dust, may be driving high freshwater BR. However, many sources remain elusive and not individually quantified in the literature. We must include freshwater CO_2 emissions in climate models. Identifying, quantifying and managing freshwater's diffuse sources of Dissolved Organic Carbon (DOC) will hopefully provide us with another opportunity to change our current climate trajectory.

Keywords: freshwater DOC flux, bacterial respiration, BR, climate change, global carbon budget, freshwater global CO_2 emissions

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INTRODUCTION

Of all the water on the planet only 0.009% is in our freshwater lakes (0.0086%) and rivers (0.0002%) (Shiklomanov, 1993). This is a miniscule fraction of the Earth's surface water (**Figure 1**). Hence, the global carbon budget focuses on the oceans with the land taking up most of the carbon. But is this justified? Surface freshwaters mediate large transfers of organic carbon to the atmosphere and must be considered if we want to change our current climate change track (Battin et al., 2009). The latest IPCC, (2021) Sixth Report shows freshwater outgassing of CO_2 is a 0.3 Pg C y-1 of the total global respiration and fire of 142 Pg C y-1.

We are now seeing the crucial global role of freshwater transitioning carbon from terrestrial to atmospheric biomes. This perspective has come with the advent of high-resolution satellite mapping of freshwater (Pekal et al., 2016) and limnologists collaborating as part of global freshwater research networks (http://www.laketemperature.org/index.html) (Hamilton et al., 2015) — freely sharing long-term data (especially that of water temperatures). Lakes and rivers are quantitatively being seen as connecting the lithosphere to the atmosphere (Ward et al., 2017). Freshwater's critical role in the global carbon balance is being unraveled. With freshwater warming faster than the atmosphere at an alarming rate (O'Reilly et al., 2015) understanding these connections has become a matter of urgency.

Freshwater connects the soil with the oceans and the atmosphere to complete the global cycle (del Giorgio and Williams, 2005). Aerobic freshwater bacteria respiration contributes profoundly to the global atmospheric carbon budget (Richey et al., 2002; Cole et al., 2007; Aufdenkampe, et al., 2011;

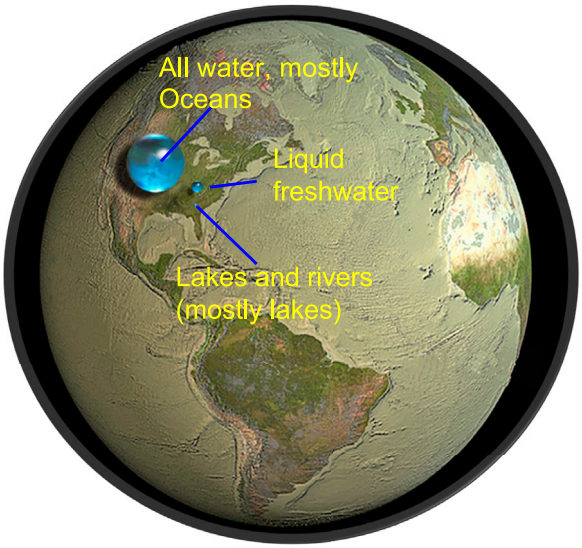

FIGURE 1 | How water is distributed on Earth. The tiny pixel over Georgia represents all surface freshwater lakes and rivers. Illustration after USGS depiction by Perlman, Cook and Nieman who used the data of Shiklomanov (1993). https://water.usgs.gov/edu/gallery/global-water-volume.html.

Ward et al., 2017). This carbon return pathway has gone unnoticed in the predictive mathematical modelling of our climate. But does appear in the latest IPCC, (2021)report showing a 0.3 Pg C y^{-1} being emitted from freshwater globally.

Since 2007, estimates of the carbon emissions from freshwater lakes and rivers have doubled every 3 years to the current estimate of 3.8 Pg C y^{-1} (Cole et al., 2007; Tranvik et al., 2009; Raymond, et al., 2013; Ward et al., 2017). Recent reviews are trying to make quantitative sense of the complex interactions of global carbon cycling across the Atmosphere, Biosphere, Hydrosphere and Lithosphere (Borges et al., 2015; Sawakuchi et al., 2017). They make the valid point that we are still underestimating freshwater carbon outgassing. Some, and myself included, have seen the tropical and sub-tropical freshwater CO_2 emissions as disproportionally larger than the temperate environments of the Northern Hemisphere (Pollard and Ducklow, 2011; Ward et al., 2017). This all goes to highlight our uncertainty of the global rate of carbon passing from terrestrial organic carbon through the lakes and rivers to the atmosphere.

Freshwater CO_2 outgassing measures have been biased towards temperate Northern latitudes (Sobek et al., 2005; 2007) resulting in global estimates of around 1 Pg C y^{-1} outgassing (Cole et al., 2007). While tropical freshwater

FIGURE 2 | Sampling sites used in this study.

TABLE 1 | Global freshwater surface area in each 15°latitude bandwidth is shown in this table.

Northern hemisphere	$\times 10^3 Km^2$
75°–82.5°	1.4
60°–75°	724.9
45°–60°	932.1
30°–45°	437.9
15°–30°	114.6
0°–15°	106.1
Southern hemisphere	
0°–15°	285.5
15°–30°	55.5
30°–45°	50.6
45°–60°	25.6

The map of global freshwater published in Pekel et al., 2016 was used to determine these surface areas within each 15°latitude bandwidth. Northern cf Southern Hemisphere freshwater surface area is 2,317,000 cf 414,300 km^2 respectively. There is more than five times more freshwater surface area in the Northern cf the Southern hemisphere.

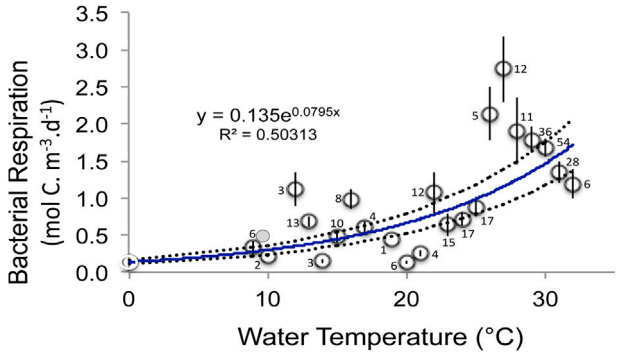

FIGURE 3 | Global freshwater bacterial respiration as a function of each whole degree of water temperature ($\bar{x}\mu \pm$ SE; n = number on each data point) The average (n = 273). Percentile error for data was 20% (shown as the dotted lines). Additional Arctic bacterial respiration data (Great Bear Lake) (n = 85) is shown as the shaded circle, was overlaid on the rest of the global respiration data. The additional data fit well with the relationship between bacterial respiration and water temperature.

CO_2 outgassing measures range from 0.9 Pg C y^{-1} from African inland waters to 2.9 Pg C y^{-1} for the Amazon (Ward et al., 2017).

Few consider the global quantitative consequences of lakes and rivers as major sources of CO_2 to the atmosphere (Richey et al., 2002; Cole et al., 2007; Battin et al., 2009; Travik et al., 2009; Sawakuchi et al., 2017). This is made even more difficult with traditional methods that are complicated with terrestrial dissolved inorganic carbon (DIC) inputs to freshwater (Johnson et al., 2008; Weyhenmeyer et al., 2015). Determining the relationship of temperature with bacterial respiration (BR) across the globe is an important part of this study and is independent of these terrestrial DIC inputs.

Proportionally, more terrestrial organic carbon is processed within freshwater lakes and rivers through BR than primary production; a major part of whole community respiration (Mayorga et al., 2005; Pace and Prairie 2005; Cole et al., 2007; McCallister and del Giorgio, 2008; Pollard and Ducklow, 2011; Cardoso et al., 2013; Cole, 2013; Soares et al., 2019). Others have shown that pCO_2 might be controlled by external groundwater inputs of dissolved inorganic carbon rather than by internal metabolism. Feijoó et al., 2022, Arroita, M. Messetta, M. L. et al. (2022) showed all streams in their study were net emitters of CO_2, supersaturated with CO_2, to the atmosphere, even those that were not net heterotrophic.

Bacterial metabolic activity (respiration; mineralisation of organic carbon) and pCO_2 supersaturating freshwater are positively correlated with temperature (Marotta et al., 2009; Cardoso et al., 2013). Climate change is causing global freshwater temperatures to rise rapidly (Acuna et al., 2008; O'Reilly et al., 2015). Yet, the impact this increase will have on freshwater BR and subsequent ecosystem health and global carbon balance is a big gap in our knowledge (Acuna et al., 2008).

The aims of this study of global freshwater were to: 1) quantify BR emissions of the greenhouse gas carbon dioxide from freshwater across latitudes; 2) compare and contrast CO_2 emissions from the Northern and Southern Hemispheres seasonally; 3) deliver an informed discussion on the role of freshwater in the global carbon budget; 4) Predict future CO_2 emission as freshwater temperatures rise.

MATERIALS AND METHODS

Bacterial Respiration (BR) dominates community respiration in most freshwater lakes and rivers (Pollard and Ducklow, 2011; Berggren et al., 2012; Cole, 2013). Hence, I simply refer to "BR" throughout this manuscript.

Freshwater Sampling

The rate bacterial respiration converted DOC to CO_2 was determined *in situ* for 337 freshwater incubations between 2008 and 2017. Lakes (n = 253), rivers (n = 55; mostly Amazon and Mississippi) and streams (n = 18) were sampled at sites from latitudes 66°N to 47°S. In 2018 another 85 measurements were made in the Arctic 66°N (Great Bear Lake). Details of each sample site are shown on a global map (**Figure 2**) and in a **Supplementary Table S1** in the **Supplementary Material** linked to this manuscript. The **Supplementary Table S1** shows the incubation sites with place names, country, sampling date, their corresponding longitudes and latitudes with a brief description of the site that includes water temperature and depth of incubation.

BR rates (mol C.m^{-3}. d^{-1}) were determined using the mathematical relationship between dissolved oxygen (DO) and time in the incubation chamber (*in situ*). The relationship and correlation co-efficient (average r^2 = *0.8*) for each sample is shown in the **Supplementary Table S1**.

Global freshwater surface area in each 15° latitude bandwidth is shown in **Table 1**. The map of global freshwater published in Pekel et al., 2016 was used to determine these surface areas within each 15° latitude bandwidths across the globe. Northern *cf* Southern Hemisphere freshwater surface area is 2,317,000 cf 414,300 km^2 respectively. There is more than five times more

TABLE 2 | A few Great Bear Lake water sample calculations of bacterial respiration.

Date/notes	Site	Depth	Temp	mgO2/m-3/d	Bacterial Respiration	Dissolve O_2 relationship with time
	Longitude Latitude	(m)	°C		(mol C. $m^{-3}.d^{-1}$)	(mg $O_2.L^{-1}$ vs 'x' min)
Narkie Islands - West Channel Island						
22-Jul-18	N66°42.521' W 119°56.849'	3.5	6.9	5040	0.189	y = -0.0035x + 12.588
22-Jul-18	N66°42.521' W 119°56.849'	3.5	6.93	6624	0.248	y = -0.0046x + 12.347
22-Jul-18	N66°43.237' W 119°43.768'	1	9.9	1584	0.059	y = -0.0011x + 11.784
22-Jul-18	N66°43.237' W 119°43.768'	3.5	9.83	5184	0.194	y = -0.0036x + 11.751
22-Jul-18	N66°43.237' W 119°43.768'	6	9.69	3600	0.135	y = -0.0025x + 11.521
Old Rusty Island - outer Falcon Islands						
23-Jul-18	N66°51.305' W119°32.216' W	1	11.08	3312	0.124	y = -0.0023x + 11.418
23-Jul-18	N66°51.305' W119°32.216' W	1	11.41	111283.2	4.173	$y = -8E\text{-}05x^3 + 0.0046x^2 - 0.0818x + 11.794$
23-Jul-18	N66°51.305' W119°32.216' W	3	7.99	6480	0.243	y = -0.0045x + 12.262
23-Jul-18	N66°51.305' W119°32.216' W	3	7.88	5616	0.211	y = -0.0039x + 12.259
23-Jul-18	N66°51.305' W119°32.216' W	9	7.55	720		y = -0.0005x + 12.27
Echo Island - Falcon Islands						
23-Jul-18	N66° 51.954' W119°27.971	0.5	10.92	28972.8	1.086	$y = -2E\text{-}05x^3 + 0.0011x^2 - 0.0212x + 11.813$
23-Jul-18	N66° 51.954' W119°27.971	0.5	11.25	27662.4	1.037	$y = -1E\text{-}05x^3 + 0.001x^2 - 0.0202x + 11.735$
23-Jul-18	N66° 51.954' W119°27.971	3	9.88	3600	0.135	y = -0.0011x + 11.612
23-Jul-18	N66° 51.954' W119°27.971	3	10	7776	0.292	y = -0.0054x + 11.851
23-Jul-18	N66° 51.954' W119°27.971	3	10	3168	0.119	y = -0.0022x + 11.654
23-Jul-18	N66° 51.954' W119°27.971	9	9.42	4464	0.167	y = -0.0031x + 11.653
23-Jul-18	N66° 51.954' W119°27.971	9	9.25	6480	0.243	y = -0.0045x + 11.877
Deese Main Arm lake - Caraboo Point						
24-Jul-18	N66°41.001' W120° 9.679'	1	8.9	13680	0.513	y = -0.0095x + 12.301
24-Jul-18	N66°41.001' W120° 9.679'	1	9.14	16588.8	0.622	$y = -2E\text{-}05x^3 + 0.0008x^2 - 0.0143x + 12.222$
24-Jul-18	N66°41.001' W120° 9.679'	5	7.28	14411.52	0.540	$y = -8E\text{-}06x^3 + 0.0005x^2 - 0.0105x + 12.515$
24-Jul-18	N66°41.001' W120° 9.679'	5	6.44	12240	0.459	$y = 0.0005x^2 - 0.009x + 12.721$
24-Jul-18	N66°41.001' W120° 9.679'	20	4.7	1872		y = -0.0013x + 12.461
24-Jul-18	N66°41.001' W120° 9.679'	20	4.7	2592		y = -0.0018x + 12.483

The relationship between dissolved oxygen and time in the incubation chamber was determined in situ *at the depths shown. This relationship in the incubation chamber was then used to determine the rate oxygen was being consumed at time zero. This rate of oxygen consumed was then used to determine bacteria respiration rates* in situ. *(mol C m^{-3}. d^{-1}). A full copy of the data collected can be found in the* ***Supplementary Material*** *attached to this manuscript.*

freshwater surface area in the Northern *cf* the Southern hemisphere.

In Situ Measurement of Aquatic Bacterial Respiration

A YSI Sonde 6920 (Yellow Springs United States) series equipped with a YSI 6150 Rox Optical dissolved oxygen probe was used to measure dark chamber BR as the loss of dissolved oxygen *in situ*. The Sonde was set to continuously log the depth, dissolved oxygen, temperature, salinity and pH every minute. The probe was then sealed in a dark chamber (2 L) made of black Perspex with one-way scuba diving regulator valves, top and bottom' of the chamber (Pollard, 2013).

The Sonde and chamber were lowered to the sampling depth, flushed *in situ* and allowed to stabilise until there was no change in the water temperature. To start the incubation the chamber was again flushed *in situ* and left for 10 min. GPS co-ordinates, time (start and finish of incubation), date and depth were noted and later matched with the retrieved Sonde logged data. I describe the chamber design and validate the technique elsewhere (Pollard, 2013), a free open access publication.

The rate bacteria used oxygen in the chamber was used to calculate the rate bacteria mineralised DOC to emit CO_2 using a respiration quotient of 1.2 : 1 (RQ; mole of CO_2 produced per mole of O_2 consumed). This respiratory quotient was determined for bacterioplankton across a range of freshwater environmental gradients (Berggren et al., 2012).

The mathematical relationship between water temperature and the *in situ* BR rates (n = 273) was determined a depth of 10 m of lakes from latitudes 66 N° to 47° S. Mean monthly global lake freshwater surface temperatures from 1991 to 2011 were used from Layden et al. (2015). Their data set was missing temperatures in the 15°–30° latitude band. This was supplemented with monthly water surface temperatures for 2007 and from 2010 to 2014 for three reservoirs between latitudes 15° S and 30° S in South East Queensland (SEQ Water, Australia, kindly provided water temperatures from their *in situ* monitoring stations).

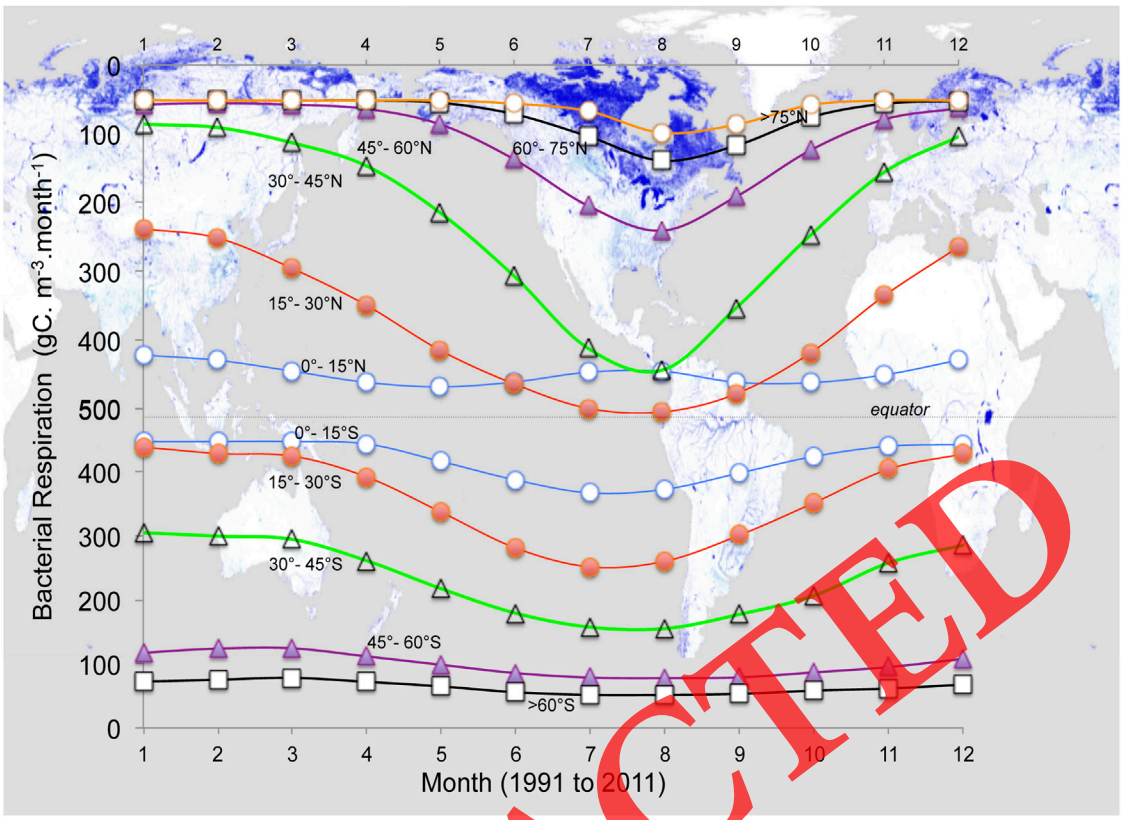

FIGURE 4 | Global freshwater bacterial respiration in each 15° latitude bandwidth. The underlying maps of global freshwater (Modified from Pekel et al., 2016) with the 15° latitude bandwidths of bacterial respiration (BR) overlayed. Notice BR in the Northern Hemisphere is similar to BR around the equator that also aligns with the largest surface freshwater area (also see **Table 1**). This combination is the reason the North Hemisphere outgases the South Hemisphere.

Some lake profile BR measurements were in deep waters (>20 m). Two representative profiles are presented in the main section of the paper. The remaining deep-water data can be found in a **Supplementary Table S1**. I did not have enough information to establish the global relationship of BR as a function of deep water-temperatures. Hence only the top 10 m data is presented in the main manuscript.

I divided the globe into 15° band widths from latitudes 75° N to 60° S. The freshwater surface area in these bins is given in **Table 1**. Using the monthly average of freshwater surface temperatures over 20 years of Layden et al. (2015). I determined the average monthly rates of BR using the relationship in **Figure 3**. With high-resolution maps of global freshwater surface areas of Pekel et al. (2016), global BR rates were determined for each 15° band shown in **Table 1**. Cumulative rates of CO_2 freshwater emission in the Northern and Southern Hemispheres could finally be directly compared as Pg C y^{-1} for the top 10 m depth globally for freshwater lakes.

This top 10 m depth was chosen to calculate the global freshwater emissions of CO_2 for three reasons. A depth of 10 m is the: average depth Lichens (1973) estimated for global freshwater lakes. This is the typical thermal stratification depth separating the top 10 m from the hypolimnion. Hence surface water temperatures could be applied to this depth (Wetzel 2001; p75). This is also the average depth of the Amazon, the world's largest river (Ward et al., 2017).

Data Handling

Table 2 shows a few Great Bear Lake water sample calculations of bacterial respiration (mol C m^{-3} d^{-1}). The relationship between dissolved oxygen and time in the incubation chamber was determined *in situ* at the depths shown. This relationship of dissolved oxygen with time in the incubation chamber was then used to determine the rate oxygen was being consumed at time zero. This rate of oxygen consumed was then used to determine bacteria respiration rates (mol C m^{-3} d^{-1}) *in situ*.

The observational respiration data and respiration quotient were used to determine respiration rates. The temperature-respiration relationship was fitted using an exponential equation in EXCEL (Microsoft Office) accompanied by an estimate of error (dashed lines).

I have calculated the percentile error for the bacterial respiration data points and included the error associated with BR measurements for each whole degree of water temperature. The number of samples (n) at each temperature is shown in **Figure 3**. The mean percentile error, determined using all the data in **Figure 3**, was 20%. This value was used to determine the uncertainty of BR as a function of water temperature **Figure 3**

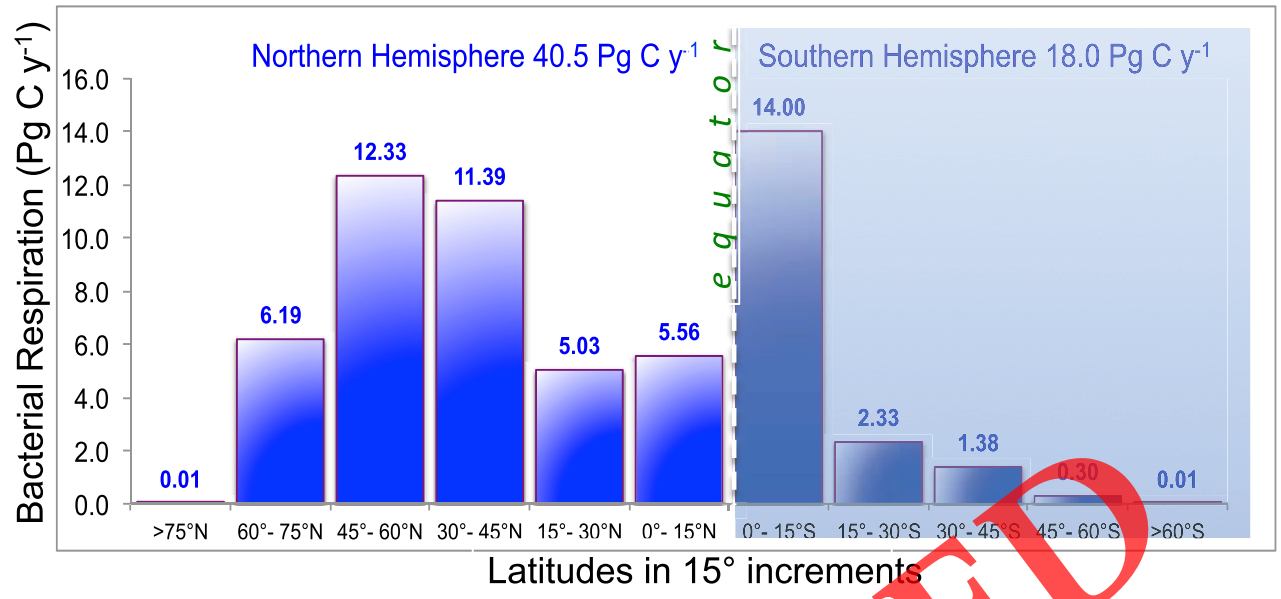

FIGURE 5 | From 1991 to 2011 the annual rates of carbon respired from each 15° latitude bandwidth is shown for the freshwater top 10 m. The Northern Hemisphere (not shaded) is emitting CO_2 at twice the rate of the Southern Hemispheres (shaded area); 2.25 : 1, respectively.

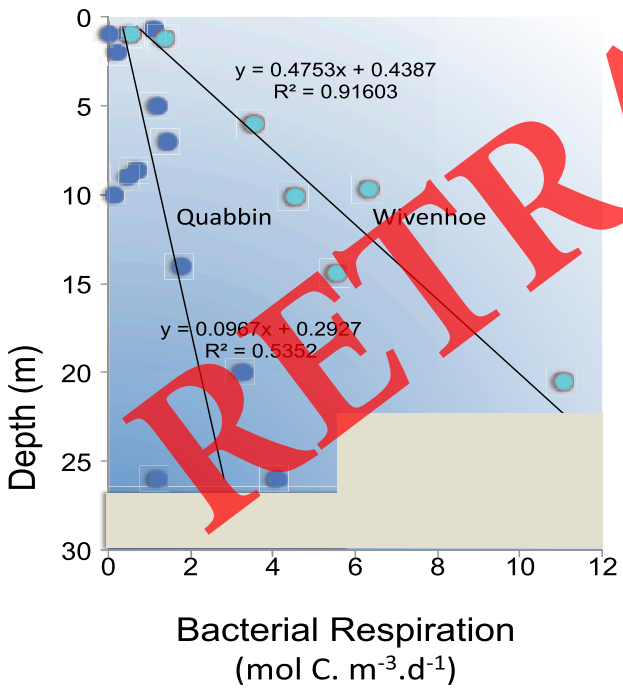

FIGURE 6 | Bacterial respiration is plotted as a function of water depth for two major reservoirs. In each case highest mineralisation rates or organic carbon were at the bottom of each reservoir. The blocked are represents the sediment.

(dashed lines). The same percentile error has been applied to the predictions of increased CO_2 emissions using projected global water temperature increases of O'Reilly et al. (2015).

All data generated or analysed during this study are included in this published article and its supplementary information files. Any additional data are available from the corresponding author on request.

RESULTS

Figure 3 is a plot of BR (mole C.m^{-3}. d^{-1}) as a function of water temperature (C°) for the top 10 m between latitudes 66° N to 47° S. BR was best described (r^2 = 0.5) with the following exponential function:

$$\text{Bacterial respiration}\left(\text{mol C.m}^{-3}\text{.d}^{-1}\right) = 0.135e^{0.0795\times\text{temperature}(^{\circ}\text{C})} \quad (1)$$

Figure 4 shows bacterial respiration in each 15° latitude bandwidth. The Northern and Southern Hemispheres can be compared. The underlying map is of global freshwater surface area (based on maps of Pekel et al., 2016). Notice the BR in the Northern summer is similar to those of the equatorial regions, coinciding with largest freshwater surface areas of the world **Table 1**. BR in the North is in harmony with that of the warmer tropics and subtropics.

Globally, the lower latitudes (0°–15°) containing the equatorial lakes and rivers (e.g., Amazon River, South America; Lake Victoria, East Africa; Lake Tanganyika, East Africa) showed high rates of respiration and emission of CO_2. However, globally the highest rates of BR were seen in the 15° to 30° Northern latitude band during the Northern summer (June, July, August, and September).

For the higher Northern latitudes, summer months showed high rates of BR, similar to equatorial latitudes. The North's

FIGURE 7 | Great Bear Lake. This is an Arctic lake at a Latitude of 66° N in the North Western Territories of Canada. It is the largest lake totally in Canada. By area, it is the eighth largest freshwater lake in the world with a surface area of 31,080 km^2.

combined emissions of CO_2 dominated. This was because most of the Earth's freshwater lies North of 30° N (Pekel et al., 2016) **Table 1**. The Northern Hemisphere BR remained high all year round in the latitude of 0° to15 °N bin. (**Figure 4**). The 0°–15° S latitude bandwidth contained the highest rates of bacterial respiration globally; within these latitudes you find the Amazon River and the sub-Sahara lakes and rivers of Africa that were responsible for most of this BR. Further south BR was limited by the lack of freshwater in southern latitudes greater than 15°S (Pekel et al., 2016) (**Table 1**).

Figure 5 lets you compare the amount of CO_2 emitted from the Northern and Southern Hemispheres. CO_2 emissions from the Northern Hemisphere were twice those of Sothern Hemisphere — 40.5 Pg C y^{-1} *cf* 18.0 Pg C y^{-1} respectively. In the Northern Hemisphere the higher latitudes (above 45° N) were responsible for the bulk of global BR—CO_2 emissions. This was due to areas of freshwater above 45° North that coincided the Northern summer BR that are similar to those around the equatorial regions **Table 1**.

Figure 6 is a plot of bacterial respiration as a function of depth for two lakes. Quabbin Reservoir (depth 28 m); Massachusetts, United States (Boston's drinking water supply) in the Northern Hemisphere. The other, Lake Wivenhoe (depth 22 m) South East Queensland, Australia (Brisbane's drinking water supply) is in the Southern Hemisphere. These are temperate and sub-tropical freshwaters, respectively. Both water bodies showed a positive correlation (r^2 = 0.54 and 0.92, respectively) of the rate of BR with increasing depth. This relationship was also seen in other deep Lakes (data shown in **Supplementary Table S1**).

The Arctic (Latitude 66° North): Great Bear Lake, Canada

When you first venture onto the lake, what strikes you most is the horizon—the lake is indistinguishable from the sky (**Figure 7**). With an average depth of 72 m, the lake's visibility goes down for what seems forever; a remarkable 30 m. Great Bear Lake is truly pristine.

Of all the sites sampled in this study Great Bear Lake was the most pristine sampled and by area, it is the eighth largest freshwater lake in the world. With a surface area of 31,080 km^2, it is only 420 km^2 shy of Russia's massive Lake Baikal. Surprising, the results fit within the trends seen for every other lake sampled in this study irrespective of the degree of human impact (**Figure 3**).

Bacterial respiration rates were measured across the lake between a latitude of N66°41.001′ and N66°53.840′. Bacterial respiration rates averaged 6 $gC.m^{-3}.d^{-1}$ (SE = 0.1, n = 85) to a max depth of 10 m. Unlike the depth profiles of bacterial respiration rates in man-made reservoirs seen in **Figure 6**, bacterial respiration rates were much lower at depths of between 20 and 40 m (1.2 $gC.m^{-3}.d^{-1}$ (SE = 0.3, n = 5). The sediments of Great bear Lake were not the major source of organic carbon driving bacterial respiration in the upper water column.

DISCUSSION

Northern Hemisphere Outgases the Southern Hemisphere

Globally freshwater CO_2 emissions were 58.5 Pg C y^{-1}. This is 6 times the current annual burning of fossil fuels of 9.97 Pg C y^{-1}

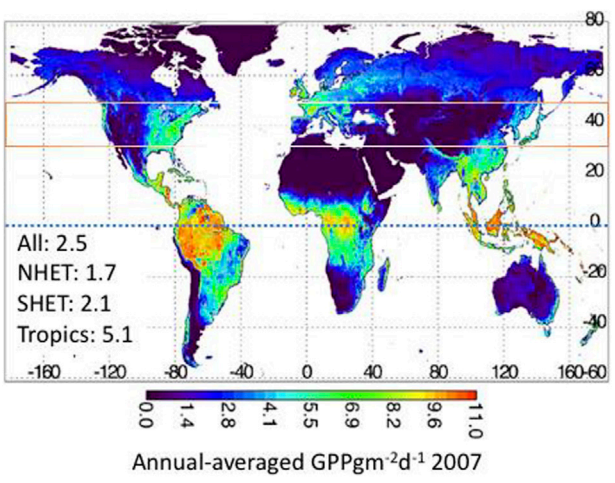

FIGURE 8 | Global map of annual averaged Gross Primary Production (GPP) estimated with remote sensing data for the year 2007. The means are listed in the lower left corner for all grid boxes (All), along with subsets from the Tropics (latitudes <20°). Northern Hemisphere Extra Tropics (NHET: latitudes >20°N) and Southern Hemisphere extra-tropics (latitudes below 20°S (SHET) (Joiner et al., 2018; Yoshida, Y.; Zhang et al., 2018) republished under creative commons.

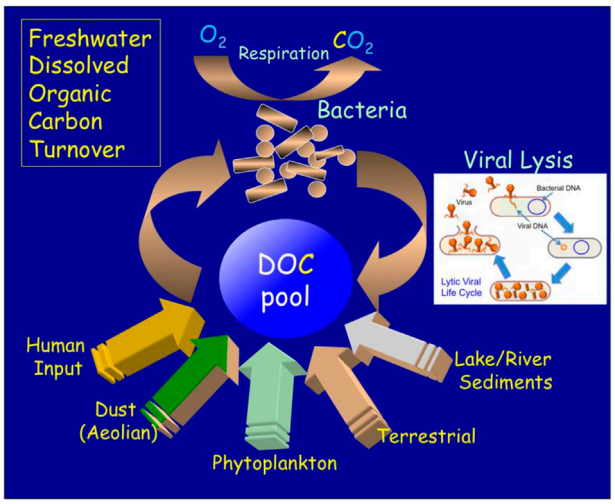

FIGURE 9 | Model of how bacteria use carbon from the DOC pool to respire the sources of DOC to emit CO_2 from freshwater (DOC) in the pool remains constant—input = output. Viral lysis of the bacteria facilitates bacterial respiration by recycling organic carbon through the DOC pool.

(Le Quéré et al., 2017). The Northern latitudes dominate, even though the rates of CO_2 emissions from tropical and subtropical from lakes and rivers were high for their latitudes (e.g., the Amazon, Congo and Sub Sahara). Twice as much CO_2 is being emitted (mostly above the latitude of 45° N) from the Northern compared to the Southern Hemisphere. This begs the question "What are the sources of the DOC driving such high rates of BR CO_2 emissions?"

Organic Carbon Sources of the Dissolved Organic Carbon Pool

There are large scale and diffuse sources and fluxes of DOC in freshwater (Mulholland, (2003)) driving the BR and CO_2 emissions from freshwater. Possible sources include DOC mineralised in lake sediments mobilising organic carbon deposited in the present and the distant past; Aeolian organic matter transported from any and every corner of the global not to mention the anthropogenic inputs from agriculture, land clearing and urbanisation, However, identifying and Quantifying these DOC sources remain elusive. As diffuse sources of DOC, they are not simple to individually quantify on a global scale.

Because freshwater ecosystems are generally net heterotrophic (Cole, 2013), by definition, their source of DOC is allochthonous (defined here as organic carbon from elsewhere, in either space or time). Indeed, when you consider lake and river sources of DOC from the surrounding landscape, you are hard pressed to find any system without a watershed/catchment inputting terrestrial organic carbon (**Figure 4** *cf* **Figure 8**). Bacteria readily mineralise terrestrially derived macromolecules, considered refractory, like lignin and phenolic compounds in freshwater (Ward et al., 2013).

Freshwater sediment bacterial mineralization processes are a major source of the DOC driving high rates of surface water DOC inputs (Pace and Prairie, 2005; Cardoso, et al., 2013). This also

TABLE 3 | DOC concentrations in freshwater lakes and rivers in different biomes from low to high Latitudes of Northern and Southern Hemispheres (Adapted from Mulholland, (2003) additional data from Pollard and Ducklow, 2011; *Oliver et al., 2017).

Freshwater Biomes	DOC $mg.L^{-1}$ (Mean)
Tundra	2
Boreal Forests	7
Temperate	4
Temperate Northern rainforest*	6 to 11
Semi-arid	1
Wet Tropics	8
Dry Tropics	3
Dry-subtropics	5
Humid climates	4 to 13

produces the dissolved inorganic carbon (DIC) supersaturating freshwater reaching pCO_2 concentrations as high as 1,500 ppm (Cardoso, et al., 2013). Freshwater sediments may not be the sinks of terrestrial organic carbon we thought (Cole et al., 2007).

McCallister and del Giorgio (2012) elegantly demonstrated how bacteria respire ancient carbon from lake sediments considered permanently stored (ancient 1,000–3000 BP). Cole and Caraco (2001) also showed that highly ^{14}C-depleted carbon of ancient terrestrial origin (1,000–5,000 years old) were also important sources of labile DOC supporting BR in the Hudson River (NY United States). In Quabbin (Northern Hemisphere) and Wivenhoe (Southern Hemisphere) reservoirs both showed bacterial respiration rates were highest closest to the sediment suggesting bacterial mineralisation processes are sources of DOC (**Figure 8**) as others have also shown (Cardoso, et al., 2013). Hence, the distant past and present organic carbon are allochthonous sources of DOC connected to today's labile DOC pool of **Figure 8**.

Major sources of terrestrial DOC input, ie terrestrial GPP, appear to contribute to the pattern presented in **Figure 5**. For example, between 30–45°N in **Figure 8** the large terrestrial GPP of the Northern temperate forests seen on the East Coast of North America align with some of the highest estimates of rates of CO_2 outgassing in the Northern hemisphere (**Figure 5**).

While there is a healthy debate over whether *"fish eat trees" or "not"*, it is safe to say both views are correct. Freshwater food webs use aquatic and terrestrial primary production; which one dominates depends on the environmental conditions (Cole et al., 2007; Cole et al., 2011; Pollard and Ducklow 2011; Cole, 2013; Carpenter et al., 2016; Brett et al., 2017).

Pace and Prairie, (2005) estimated the gross primary production (GPP) for global freshwater lakes as 0.65 Pg C y^{-1}. Gene Lichens (1973) presented a global review of the total net primary production (NPP) in freshwater as 1.3 Pg C y^{-1}. This compares to >58.5 Pg C y^{-1} respired globally into the atmosphere through bacterial respiration in this study. Taking into account losses of primary production to higher trophic groups, freshwater primary production is not a major source of organic carbon entering the DOC pool (**Figure 9**). There will never be enough freshwater primary production to support the high rates of bacterial respiration. Thus, freshwater primary production globally cannot be considered the major source of the DOC pool of **Figure 9**.

Viral lysis of bacteria motivating high DOC turnover—not a DOC source

Viral lysis of the bacteria is not a fresh or new source of organic carbon entering the DOC pool (**Figure 9**). They do, however, facilitate the emission CO_2 from freshwater. In 2001 Wetzel described how freshwater viruses lysed bacteria. This process releases bacterial carbon back into the DOC pool (**Figure 9**) (Weinbauer et al., 2002). Viral control of high rates of bacterial growth in freshwater 'short circuits' the food chain as high rates of bacterial production are lost to viral lysis (Pollard and Ducklow, 2011). In a freshwater reservoir, Pradeep Ram et al. (2016) also showed higher viral lysis of bacteria is accompanied by higher bacterial respiration rates and leads to a significant loss of organic carbon to the atmosphere through bacterial lysis. Indeed, the viral lysis of bacteria shifted their reservoir ecosystem to net heterotrophy. Thus, viral lysis of bacteria ensures the DOC in freshwater is efficiently respired and returned to the atmosphere as shown in **Figure 8**. Ecologically this helps explain why we see such high rates of BR and DOC turnover in freshwater **Figure 5**.

[DOC] Pool (Concentration) Versus DOC Turnover—Flux

Many studies of freshwater follow changes in the concentration of DOC. Yet, globally there is little difference between these concentrations in rivers and lakes amid a range of latitudes and vastly different biomes (**Table 3**). There is a fundamental difference between DOC concentrations and DOC turnover that is not readily appreciated. Quantifying the turnover of the DOC pool (**Figure 9**) is a precondition for modelling the organic carbon entering the DOC pool and CO_2 being emitted into the atmosphere via freshwater bacterial respiration.

The high bacterial respiration rates in freshwater measured here (**Figure 3**) are coupled with a low and stable concentration pools of DOC (2–13 mg/L) (**Table 3**). This requires that the rate of input of organic carbon to the DOC pool of **Figure 9** must also be high and equal to the rate of bacterial respiration. Hence there are major sources DOC supporting the rapid turnover of the DOC pool as discussed above.

Bacterial respiration as a function of temperature

Water temperature plays a major role in determining the rate of freshwater BR (Apple et al., 2006). Freshwater temperatures have the greatest impact on bacterial physiology—increasing BR, decreasing bacterial production and lowering bacterial growth efficiencies (Price and Sowers, 2004; Scofield et al., 2015). The microbial mineralisation of organic material is most often described as a simple exponential relationship (Bridgham and Ye, 2013), as I have used in **Figure 3**.

In this study, the Q_{10} (temperature coefficient) of 2.1 determined using **Eq. 2** (n = 326) (**Figure 3**) was as expected for bacterial respiration.

$$Q_{10} = \left(BR2/BR1\right)^{10^{\circ}/(T2-T1)} \quad (2)$$

Others have found a similar Q_{10} value for natural and cultured populations of bacteria, describing Q_{10} values of around 2 (Carignan et al., 2000; Apple et al., 2006; Berggren et al., 2010).

The observed dependence of BR on temperate in freshwater (Sobek and Transvik, 2005; Apple et al., 2006) also suggests there is no shortage of external DOC sources to freshwater ecosystems (**Figure 9**) (Oliver et al., 2017); as does the prevalence of net heterotrophy in freshwater lakes (Cole et al., 2000; Pace and Praire, 2005). Global freshwater temperatures are, justifiably, substituted into **Eq. 1** to determine BR rates across the globe to generate **Figure 4**.

Bacterial Respiration Rates in Context

We see tropical freshwaters emitting carbon at rates of 1 Pg C y^{-1} for African inland waters and were 0.9–2.9 Pg C y^{-1} for the Amazon (Borges et al., 2015; Sawakuchi et al., 2017; Ward et al., 2017). These estimates were made using evasive fluxes of CO_2 into floating chambers and gas transfer co-efficient. Their estimates are consistent with the tropical biomes I have estimated on both sides of the equator Panama Canal *cf* Amazon River (**Figure 5**). Others have also found freshwater lakes can be responsible for a quarter of the carbon in the atmosphere (Tanentzap, et al., 2019).

Pace and Prairie reviewed BR methods in 2005 and provided an overview of BR in freshwater lakes. Globally, estimates of planktonic respiration (using a respiration quotient of 1.0) that ranged from 0.7 to 162 mmol C m^{-3} d^{-1}. They estimated 0.83 Pg C y^{-1} was emitted from freshwater lakes globally. This compares to nearly 4 Pg C. y^{-1} that Ward et al. (2017) estimated. The rate of BR measures in this study averaged 2.46 ± 0.32 mol C.m^{-3}. d^{-1} ($\bar{x}\mu$ ± SE, n = 326). This study results fits within these ranges.

Freshwater CO_2 Emissions and the 2021 Global Carbon Budget

Global greenhouse emissions from fossil fuels and industry are on track to grow by 2% in 2017, reaching a new record high of 9.9 Pg y^{-1} (Le Quéré, et al., 2017). This study found global surface freshwater CO_2 emissions are 6 times this rate — > 58.5 PgC.$y.^{-1}$

The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (IPCC, (2021)) assessed the global CO_2 fluxes. The atmosphere stores 871 PgC, 283 of which is the result of anthropogenic inputs. This is increasing by 4 PgC. y^{-1} (IPCC, (2021)). The report shows freshwater CO_2 outgassing as a mere 0.3 PgC. y^{-1}. However, this study found global freshwater lakes are outgassing CO_2 at a rate of 58.5 PgC. y^{-1} (**Figure 5**).

These differences are likely due to the indirect methods used in the past to measure freshwater BR, compared to the *in situ* measures applied in this study and others who used direct CO_2 flux methods (Ward et al., 2017). The evasive fluxes of CO_2 methods used in the sub-Sahara, Congo in Africa and South America are also *in situ*-based techniques, and they align with my *in situ* global estimate of BR and CO_2 emissions.

Using 423 km^3 mean volume of the Amazon (Grace et al., 2002) and multiplying by my mean BR for the same areas of the Amazon, I estimate CO_2 emissions from the Amazon to be 3.3 ± 1 ($\bar{x}\mu$ ± SE, n = 20) PgC. y^{-1}. This result fit well with the 2.29 PgC. y^{-1} that Ward et al. (2017) estimated for the Amazon. This is independent supporting evidence, with another direct method, that my global freshwater emission data are indeed related to the real world.

Today we are seeing major sources of DOC from lake sediment organic matter both today and from biomes thousands of years in the past. Add to that the sources of DOC from almost every sphere in the present day—Atmosphere, Biosphere, Hydrosphere (excluding Oceans) and Lithosphere (**Figure 9**). Little wonder freshwater CO_2 emission is such a big part of the global carbon budget. However, this is not recognised in the latest IPCC's sixth report (2021).

Future of Freshwater Emissions

O'Reilly et al. (2015) estimated (from 1985 to 2009) that global lake surface water temperatures are rising by 0.34 °C per decade. Based on my relationship between surface water temperature and rates of BR in **Eq. 1** (depth of 10 m), each decade will deliver and extra 1.1 ± 0.2 PgC. y^{-1} to the atmosphere from the Northern Hemisphere and 0.5 ± 0.1 PgC. y^1 from the Southern Hemisphere. The average anthropogenic increase in atmospheric carbon is around 4 PgC y^{-1} (IPCC, (2021)). Freshwater emissions will account for 3% of this increase per year.

The higher freshwater emissions in the Northern Hemisphere *cf* the Southern Hemisphere are also consistent with the conclusions of Weyhenmeyer et al. (2015). They connected land use and climate temperature increases with diffuse sources of DOC. They conclude emissions from boreal lakes (Northern Hemisphere) are approaching those of lakes in warmer latitudes closer to the equator. Sound familiar? See **Figure 5**.

CONCLUSION

I have shown here that global freshwater returns carbon to the atmosphere at a momentous rate! Yet it is either not considered in current climate models or is shown at rates that are two orders of magnitude lower than what I have measured in this global study. Conspicuously absent or very low estimates of freshwater CO_2 emissions, such as in the latest IPCC (2022) report.

Given the magnitude of the freshwater carbon return to the atmosphere that I have measured here, gauging future responses of our climate to warming demands we quantitatively connect the land—freshwater - atmosphere into today's climate change predictions. While the overall climate change jigsaw picture will not change, how the puzzle pieces are arranged will change. We need to find and include the freshwater puzzle piece that fell off the table. Only when we work together to globally identify and quantify the diffuse sources of DOC entering freshwater that is drive bacterial respiration can we even dream of managing freshwater CO_2 emissions. Doing so, hopefully, will give the human race another opportunity to change our current climate change trajectory.

'THE END' of 'The BEGINNING'

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.904955/full#supplementary-material

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