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Supplement of

The carbon footprint of a Malaysian tropical reservoir: measured versus modelled estimates highlight the underestimated key role of downstream processes

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- **References**
Table S1: Summary of the mean, standard deviation (SD), range (min and max), and number of observation (n) of physical and chemical variables measured at the surface of the reservoir and its inflows.

| Variables          | Units         | Reservoir | Inflows |
|--------------------|---------------|-----------|---------|
|                    |               | Mean | SD | Min | Max | n  | Mean | SD | Min | Max | n  |
| Water temperature  | °C            | 31   | 0.8| 24  | 32  | 134 | 27   | 2.4| 24  | 30  | 10 |
| DOC                | mg L⁻¹        | 0.9  | 0.2| 0.3 | 1.8 | 115 | 0.8  | 0.4| 0.4 | 1.3 | 8  |
| TP                 | µg L⁻¹        | 5.9  | 2.4| 2.8 | 23.3| 114 | 20.7 | 7.6| 11.7| 36  | 8  |
| TN                 | mg L⁻¹        | 0.11 | 0.04| 0.06| 0.33| 115 | 0.14 | 0.04| 0.07| 0.19| 8  |
| Chla               | µg L⁻¹        | 1.3  | 0.7| 0.3 | 4.0 | 112 | 2.1  | 1.7| 0.1 | 4.4 | 9  |
| CO₂ diffusion      | mmol m⁻² d⁻¹ | 7.7  | 18.2| -30.8| 80.0| 129 | 137.3| 192.4| 9.7 | 593.9| 8 |
| CH₄ diffusion      | mmol m⁻² d⁻¹ | 0.6  | 0.6 | 0.03| 3.7 | 129 | 30.7 | 37.4| 1.2 | 113.4| 8 |
| N₂O diffusion      | nmol m⁻² d⁻¹ | -0.2 | 2.1 | -7.1| 2.7 | 15  | 60.1 | 34.9| 10.1| 113.5| 10|
| [CO₂]              | µmol L⁻¹      | 16.3 | 5.2| 6.8 | 36.2| 132 | 6.6  | 4.3| 0.6 | 14.8| 10 |
| [CH₄]              | µmol L⁻¹      | 0.2  | 0.2| 0.0 | 1.2 | 137 | 6.1  | 5.2| 7.0 | 2   |
Figure S1: Profile example of water temperature (black squares), dissolved oxygen concentration (gray diamonds), CO\textsubscript{2} and CH\textsubscript{4} concentrations (black circles) and isotopic $\delta^{13}$C signature (gray triangles) in the main basin of the reservoir right upstream of the dam in Aug 2018. The horizontal dashed line represent the water withdrawal depth.
Figure S2: Maps of the spatially interpolated surface CO₂ diffusion in Batang Ai reservoir for each sampling campaign. Unit is in mmol m⁻² d⁻¹. Graph axes are the spatial coordinates (latitude and longitude).
Figure S3: Maps of the spatially interpolated surface CH$_4$ diffusion in Batang Ai reservoir for each sampling campaign. Unit is in mmol m$^{-2}$ d$^{-1}$. Graph axes are the spatial coordinates (latitude and longitude).
Figure S4: Simulated below dam emissions (degassing + downstream emissions) of CO₂ (gray squares) and CH₄ (black circles) under different water withdrawal depth raise. Simulated emissions do not take into account CH₄ oxidation in the outflow river.
Table S2: Equations used to derive modeled CO$_2$ and CH$_4$ emissions based on the G-res and Barros et al. models. Input variables are described in Table S3.

| Equation                                      | G-res model                                                                 | Barros et al. model                                                                 |
|-----------------------------------------------|----------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| $\log_{10}(\text{CO}_2\text{ diffusion})$   | $1.7892 - 0.3364 \log_{10}(\text{Age}) + 0.0400 \text{ Effective temperature CO}_2 + 0.06918 \log_{10}(\text{Reservoir area}) + 0.0216 \text{ Soil C content} + 0.1472 \log_{10}(\text{TP})$ | $3.06 - 0.16 \log_{10}(\text{Age}) - 0.01 \text{ Latitude} + 0.41 \log_{10}(\text{DOC input}) - \log_{10}(400)$ |
| $\log_{10}(\text{CH}_4\text{ diffusion})$   | $0.8804 - 0.0116 \text{ Age} + 0.6068 \log_{10}(\text{\% littoral area / 100}) + 0.04828 \text{ Effective temperature CH}_4$ | $1.33 - 0.36 \log_{10}(\text{Age}) - 0.32 \log_{10}(\text{Mean depth}) + 0.39 \log_{10}(\text{DOC input}) - 0.01 \text{ Latitude}$ |
| $\log_{10}(\text{CH}_4\text{ ebullition})$  | $-0.98574 + 1.0075 \log_{10}(\text{\% littoral area / 100}) + 0.04928 \text{ Cumulative global horizontal radiance}$ | -                                                                                   |
| $\text{CH}_4\text{ degassing}$              | $10 \times (5.5029 + 2.2857 \log_{10}(\text{Modeled CH}_4\text{ diffusion}) + 0.9866 \log_{10}(\text{Water residence time})) \times \frac{\text{Discharge}}{\text{Reservoir area}}$ | -                                                                                   |
Table S3: Input variables values, units, and sources used in the modeling of Batang Ai CO$_2$ and CH$_4$ emissions.

| Input variable               | Value  | Unit         | Source                                                                 |
|------------------------------|--------|--------------|------------------------------------------------------------------------|
| % Littoral area              | 5.15   | %            | (1 - (1 - (3 / Maximum depth)) / (Maximum depth / Mean depth - 1)) x 100 |
| Age                          | 33     | year         | Mean reservoir age at sampling years (2016 - 2018)                      |
| Annual runoff                | 2219   | mm yr$^{-1}$ | UNH/GRDC Composite Runoff Fields V1.0 (Fekete et al., 2002)             |
| Catchment area               | 1142   | km$^2$       | GranD database V1.3 (Lehner et al., 2011)                               |
| Cumulative global horizontal radiance | 56.4   | kWh m$^{-2}$yr$^{-1}$ | Surface meteorology and Solar Energy (NASA, 2008)                      |
| Discharge                    | 106    | m$^3$ s$^{-1}$| Average during the four sampling times (provided by Sarawak Energy)    |
| DOC                          | 0.8    | mg L$^{-1}$  | Average of measured surface values in this study                       |
| DOC input                    | 81.93  | mg m$^{-2}$ d$^{-1}$ | (DOC x Volume) / (Reservoir area x Water residence time x 1000 x 365) |
| Effective temperature CH$_4$ | 26.37  | °C           | Mean annual temperature corrected for the effect on CH$_4$ from G-res tool (Prairie et al., 2017) |
| Effective temperature CO$_2$ | 26.37  | °C           | Mean annual temperature corrected for the effect on CO$_2$ from G-res tool (Prairie et al., 2017) |
| Latitude                     | 1.16   | Decimal degrees | Google earth                                                               |
| Maximum depth                | 85     | m            | GranD database V1.3 (Lehner et al., 2011) – Height dam wall             |
| Mean depth                   | 34.4   | m            | GranD database V1.3 (Lehner et al., 2011)                               |
| Modeled CH$_4$ diffusion     | 134    | gCO$_2$eq m$^{-2}$ yr$^{-1}$ | Average over 100 years of CH$_4$ diffusion modeled based on the G-res equation (Table S2) |
| Reservoir area               | 68.4   | km$^2$       | GranD database V1.3 (Lehner et al., 2011)                               |
| Soil C content               | 2.41   | kg C m$^{-2}$ | Estimated based on Wasli et al. 2011                                   |
| TP                           | 6.77   | μg L$^{-1}$  | Average of measured surface values in this study                       |
| Volume                       | 2360 x 10$^6$ | m$^3$    | GranD database V1.3 (Lehner et al., 2011)                               |
| Water residence time         | 0.93   | year         | (Mean depth x Reservoir area) / (catchment area x Annual runoff) x 1000  |


Modeling downstream river oxidation

The following section describes the conceptual framework underlying the isotopic model used to estimate CH$_4$ oxidation in the outflow of the reservoir. For that, we assume that the only source of water and CH$_4$ to the outflow (starting right downstream of the power house) is the reservoir discharge. We also assume oxidation and evasion to the atmosphere are the only two loss processes for CH$_4$ in the outflow, and that both reactions have a constant specific rate (they are a linear function of CH$_4$ concentration). When following a parcel of water travelling along the river, the change in CH$_4$ concentration can thus be described as:

\[ \frac{d[CH_4]}{dt} = -k_{oxi}[CH_4] - k_{eva}[CH_4], \]  
(S1)

with $k_{oxi}$ and $k_{eva}$ the rate coefficients of CH$_4$ oxidation and evasion respectively, and $[CH_4]$ the CH$_4$ concentration. Integration of Eq. (S1) yields the following generic time-depend solution:

\[ [CH_4]_t = [CH_4]_0 e^{-(k_{oxi}+k_{eva})t}, \]  
(S2)

The instantaneous oxidation rate at a given time ($t$) or at a given point in the river is equal to:

\[ oxidation\ rate = k_{oxi} [CH_4]_t, \]  
(S3)

Combining Eq. (S2) and Eq. (S3) yields the following equation:

\[ oxidation\ rate = k_{oxi} [CH_4]_0 e^{-(k_{oxi}+k_{eva})t}, \]  
(S4)

Hence, the total amount of CH$_4$ oxidized between time 0 and time $t$ (or between km 0 and $t$ in the river) is derived from the integration of Eq. (S4):

\[ amount\ oxidized = \int_0^t k_{oxi} [CH_4]_0 e^{-(k_{oxi}+k_{eva})t} dt, \]  
(S5)

Simplifying Eq. (S5) yields:

\[ amount\ oxidized = [CH_4]_0 \left( \frac{k_{oxi}}{(k_{oxi}+k_{eva})} \right) \left( 1 - e^{-(k_{oxi}+k_{eva})t} \right), \]  
(S6)
The amount oxidized can also be calculated as the product of the original CH₄ concentration and the fraction of CH₄ oxidized (F_ox):

\[ \text{amount oxidized} = [CH₄]₀ F_\text{ox} , \]  

(S7)

According to Eq. (S6) and Eq. (S7), we can derive F_ox from the following equation:

\[ F_\text{ox} = \left( \frac{k_{\text{oxi}}}{(k_{\text{oxi}}+k_{\text{eva}})} \right) \left( 1 - e^{-(k_{\text{oxi}}+k_{\text{eva}})t} \right) , \]  

(S8)

In Eq. (S8), the second term of the product can be rearranged using Eq. (S2) to represent the remaining fraction of CH₄ concentration at time or km t:

\[ F_\text{ox} = \left( \frac{k_{\text{oxi}}}{(k_{\text{oxi}}+k_{\text{eva}})} \right) \left( 1 - \left[ \frac{[CH₄]_t}{[CH₄]₀} \right] \right) , \]  

(S9)

Given a fractionation factor α for CH₄ oxidation, the behavior of the two CH₄ isotopes (¹²CH₄ and ¹³CH₄) can be described based on Eq. (S2) as following:

\[ [¹²CH₄]_t = [¹²CH₄]₀ e^{-(k_{\text{oxi}} ¹² + k_{\text{eva}})t} , \]  

(S10)

\[ [¹³CH₄]_t = [¹³CH₄]₀ e^{-\left( \frac{k_{\text{oxi}} ¹³}{α} + k_{\text{eva}} \right)t} , \]  

(S11)

With \([¹²CH₄]\) and \([¹³CH₄]\) the concentrations of the two isotopes, and \(k_{\text{oxi}} ¹²\) the rate coefficient of oxidation for the ¹²CH₄ isotope. The isotopic ratio of CH₄ concentration at t \((R)\) can be derived from Eq. (S10) and Eq. (S11) as following:

\[ R_t = \frac{[¹³CH₄]_t}{[¹²CH₄]_t} = \frac{[¹³CH₄]₀ e^{-\left( \frac{k_{\text{oxi}} ¹³}{α} + k_{\text{eva}} \right)t}}{[¹²CH₄]₀ e^{-\left( k_{\text{oxi}} ¹² + k_{\text{eva}} \right)t}} , \]  

(S12)

By simplifying Eq. (S12), \(R_t\) can be written as:

\[ R_t = R_0 e^{\left( 1 - \frac{1}{α} \right)k_{\text{oxi}}t} , \]  

(S13)

The term t can be isolated from equation Eq. (S13):
\[ t = \frac{\ln(R_t/R_0)}{(1-\frac{1}{\alpha})k_{oxi}}, \quad (S14) \]

Similarly, the term \( t \) can be isolated by rearranging Eq. (S2):

\[ t = \frac{\ln([CH_4]_t/[CH_4]_0)}{-(k_{oxi}+k_{eva})}, \quad (S15) \]

Combining Eq. (S14) and Eq. (S15) results in:

\[ \frac{\ln(R_t/R_0)}{(1-\frac{1}{\alpha})k_{oxi}} = \frac{\ln([CH_4]_t/[CH_4]_0)}{-(k_{oxi}+k_{eva})}, \quad (S16) \]

Rearranging E. (S16) yields:

\[ \frac{-\ln(R_t/R_0)}{(1-\frac{1}{\alpha})\ln([CH_4]_t/[CH_4]_0)} = \frac{k_{oxi}}{(k_{oxi}+k_{eva})}, \quad (S17) \]

Using Eq. (S9) and Eq. (S17), we can derive \( F_{ox} \) as:

\[ F_{ox} = \frac{k_{oxi}}{(k_{oxi}+k_{eva})} \left( 1 - \frac{[CH_4]_t}{[CH_4]_0} \right) = \frac{-\ln(R_t/R_0) \cdot (1 - \frac{[CH_4]_t}{[CH_4]_0})}{(1-\frac{1}{\alpha})\ln([CH_4]_t/[CH_4]_0)}, \quad (S18) \]

The isotopic ratios \( (R_t \text{ and } R_0) \) can be converted to \( \delta^{13}CH_4 \) expressed in \( \%_o \) using the following standard isotopic equation calculation:

\[ \delta^{13}CH_4 = \left( \frac{[13CH_4]}{[13CH_4]_{std}} \cdot \frac{[12CH_4]}{[12CH_4]_{std}} - 1 \right) \times 1000, \quad (S19) \]

with \([13CH_4]_{std} \cdot [12CH_4]_{std}\) the standard reference Pee Dee Belemite isotopic carbon ratio. The conversion of \( R_t \) and \( R_0 \) to \( \delta^{13}CH_4 \) in Eq. (S18) results in the following equation for \( F_{ox} \) calculation:

\[ F_{ox} = \frac{-\ln(\delta^{13}CH_4_{t}+1000)-\ln(\delta^{13}CH_4_{0}+1000)}{(1-\frac{1}{\alpha})\ln([CH_4]_t/[CH_4]_0)}, \quad (S20) \]

Eq. (S20) was used to determine \( F_{ox} \) and \( CH_4 \) oxidation (product of \( F_{ox} \) and \([CH_4]_0\)) in Batang Ai river outflow using km 0 and 19 as a start and end points of the river stretch. Sampling of \( CH_4 \)
concentration and isotopic signature was conducted at two other points within this river stretch (km 0.6 and 2.7). This additional sampling resolution can help test the adequacy of the model and its conceptual assumptions by recalculating CH$_4$ oxidation in individual segments (between 0-0.6 km, 0.6-2.7 km, and 2.7-19 km). If the model assumptions are correct (absence of other CH$_4$ source in the river, constant specific oxidation rate, and constant river velocity), the amount of CH$_4$ oxidized in the entire stretch ($O_{\text{X-total}}$) should equal the sum of the amount oxidized in each individual segment ($O_{\text{X-sum}}$). In two of the sampling campaigns (Apr-May 2017 and Feb-Mar 2018), the difference between $O_{\text{X-total}}$ and $O_{\text{X-sum}}$ was very small (CV < 5 %). In the two other campaigns, this difference was larger (CV of 12 and 35 % for Nov-Dec 2016 and Aug 2018 respectively), due to an additional CH$_4$ source causing occasional increases of CH$_4$ concentration along the stretch. Overall, model assumptions appear reasonable, however, to avoid overestimating the amount oxidized in cases of additional CH$_4$ sources, we considered $O_{\text{X-total}}$ as the more suitable estimate, since it is less influenced by CH$_4$ addition in individual segments.
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