



# 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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## **Supplementary information content:**

• **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.

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• Figure S2: Maps of the spatially interpolated surface  $CO_2$  diffusion in Batang Ai reservoir for each sampling campaign. Unit is in mmol m<sup>-2</sup> d<sup>-1</sup>. 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<sup>-2</sup> d<sup>-1</sup>. Graph axes are the spatial coordinates (latitude and longitude).

• **Figure S4:** Simulated below dam emissions (degassing + downstream emissions) of  $CO_2$  (gray squares) and  $CH_4$  (dark circles) under different water withdrawal depth raise. Simulated emissions do not take into account  $CH_4$  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.

• Table S3: Input variables values, units, and sources used in the modeling of Batang Ai  $CO_2$  and  $CH_4$  emissions.

## • Modeling downstream river oxidation

## References

		Reservoir					Inflows				
Variables	Units	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 <sup>-1</sup>	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 <sup>-1</sup>	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
CO <sub>2</sub> diffusion	mmol m <sup>-2</sup> d <sup>-1</sup>	7.7	18.2	-30.8	80.0	129	137.3	192.4	9.7	593.9	8
CH₄ diffusion	mmol m <sup>-2</sup> d <sup>-1</sup>	0.6	0.6	0.03	3.7	129	30.7	37.4	1.2	113.4	8
N <sub>2</sub> O diffusion	nmol m <sup>-2</sup> d <sup>-1</sup>	-0.2	2.1	-7.1	2.7	15					0
[CO <sub>2</sub> ]	µmol L <sup>-1</sup>	16.3	5.2	6.8	36.2	132	60.1	34.9	10.1	113.5	10
[CH4]	µmol L <sup>-1</sup>	0.2	0.2	0.0	1.2	137	6.6	4.3	0.6	14.8	10
[N <sub>2</sub> O]	nmol L <sup>-1</sup>	5.6	1.2	3.9	7.8	15	6.1		5.2	7.0	2

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.



Figure S1: Profile example of water temperature (black squares), dissolved oxygen concentration (gray diamonds), CO<sub>2</sub> and CH<sub>4</sub> 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 CO<sub>2</sub> diffusion in Batang Ai reservoir for each sampling campaign. Unit is in mmol m<sup>-2</sup> d<sup>-1</sup>. Graph axes are the spatial coordinates (latitude and longitude).



Figure S3: Maps of the spatially interpolated surface CH<sub>4</sub> diffusion in Batang Ai reservoir for each sampling campaign. Unit is in mmol m<sup>-2</sup> d<sup>-1</sup>. Graph axes are the spatial coordinates (latitude and longitude).



Figure S4: Simulated below dam emissions (degassing + downstream emissions) of CO<sub>2</sub> (gray squares) and CH<sub>4</sub> (black circles) under different water withdrawal depth raise. Simulated emissions do not take into account CH<sub>4</sub> oxidation in the outflow river.

Table S2: Equations used to derive modeled CO<sub>2</sub> and CH<sub>4</sub> emissions based on the G-res and Barros et al. models. Input variables are described in Table S3.

	G-res model	Barros et al. model		
log₁₀ (CO₂ diffusion)	1.7892 - 0.3364 log <sub>10</sub> (Age) + 0.0400 Effective temperature CO <sub>2</sub> + 0.06918 log <sub>10</sub> (Reservoir area) + 0.0216 Soil C content + 0.1472 log <sub>10</sub> (TP)	3.06 - 0.16 log <sub>10</sub> (Age) - 0.01 Latitude + 0.41 log <sub>10</sub> (DOC input) - log <sub>10</sub> (400)		
log₁₀ (CH₄ diffusion)	0.8804 - 0.0116 Age + 0.6068 log_10 (% littoral area / 100) + 0.04828 Effective temperature $CH_4$	1.33 - 0.36 log10 (Age) - 0.32 log10 (Mean depth) + 0.39 log10 (DOC input) - 0.01 Latitude		
log₁₀ (CH₄ ebullition)	-0.98574 + 1.0075 log <sub>10</sub> (% littoral area / 100) + 0.04928 (Cumulative global horizontal radiance)	-		
CH₄ degassing	10 (-5.5029 + 2.2857 log10 (Modeled CH4 diffusion) + 0.9866 log10 (Water residence time)) x Discharge / Reservoir area	-		

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 <sup>-1</sup>	UNH/GRDC Composite Runoff Fields V1.0 (Fekete et al., 2002)
Catchment area	1142	km <sup>2</sup>	GranD database V1.3 (Lehner et al., 2011)
Cumulative global horizontal radiance	56.4	kWh m <sup>-2</sup> yr <sup>-1</sup>	Surface meteorology and Solar Energy (NASA, 2008)
Discharge	106	m <sup>3</sup> s <sup>-1</sup>	Average during the four sampling times (provided by Sarawak Energy)
DOC	0.8	mg L <sup>-1</sup>	Average of measured surface values in this study
DOC input	81.93	mg m <sup>-2</sup> d <sup>-1</sup>	(DOC x Volume) / (Reservoir area x Water residence time x 1000 x 365)
Effective temperature CH <sub>4</sub>	26.37	Ĉ	Mean annual temperature corrected for the effect on CH <sub>4</sub> from G-res tool (Prairie et al., 2017)
Effective temperature CO <sub>2</sub>	26.37	C	Mean annual temperature corrected for the effect on CO <sub>2</sub> 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 <sub>4</sub> diffusion	134	gCO <sub>2</sub> eq m <sup>-2</sup> yr <sup>-1</sup>	Average over 100 years of CH <sub>4</sub> diffusion modeled based on the G-res equation (Table S2)
Reservoir area	68.4	km <sup>2</sup>	GranD database V1.3 (Lehner et al., 2011)
Soil C content	2.41	kgC m <sup>-2</sup>	Estimated based on Wasli et al. 2011
ТР	6.77	µg L⁻¹	Average of measured surface values in this study
Volume	2360 x 10 <sup>6</sup>	m <sup>3</sup>	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

Table S3: Input variables values, units, and sources used in the modeling of Batang Ai CO<sub>2</sub> and CH<sub>4</sub> emissions.

#### 1 Modeling downstream river oxidation

The following section describes the conceptual framework underlying the isotopic model used to estimate CH<sub>4</sub> oxidation in the outflow of the reservoir. For that, we assume that the only source of water and CH<sub>4</sub> 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<sub>4</sub> in the outflow, and that both reactions have a constant specific rate (they are a linear function of CH<sub>4</sub> concentration). When following a parcel of water travelling along the river, the change in CH<sub>4</sub> concentration can thus be described as:

9 
$$\frac{d[CH_4]}{dt} = -k_{\text{oxi}}[CH_4] - k_{\text{eva}}[CH_4],$$
 (S1)

10 with  $k_{\text{oxi}}$  and  $k_{\text{eva}}$  the rate coefficients of CH<sub>4</sub> oxidation and evasion respectively, and [*CH*<sub>4</sub>] the 11 CH<sub>4</sub> concentration. Integration of Eq. (S1) yields the following generic time-depend solution:

12 
$$[CH_4]_t = [CH_4]_0 e^{-(k_{\text{oxi}} + k_{\text{eva}})t}$$
, (S2)

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

14 
$$oxidation rate = k_{oxi} [CH_4]_t$$
, (S3)

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

16 
$$oxidation rate = k_{oxi} [CH_4]_0 e^{-(k_{oxi}+k_{eva})t}$$
, (S4)

Hence, the total amount of CH<sub>4</sub> oxidized between time 0 and time t (or between km 0 and t in the
river) is derived from the integration of Eq. (S4):

19 
$$amount \ oxidized = \int_0^t k_{oxi} \ [CH_4]_0 \ e^{-(k_{oxi}+k_{eva})t} \ dt,$$
 (S5)

20 Simplifying Eq. (S5) yields:

21 
$$amount \ oxidized = [CH_4]_0 \left(\frac{k_{\text{oxi}}}{(k_{\text{oxi}}+k_{\text{eva}})}\right) \left(1 - e^{-(k_{\text{oxi}}+k_{\text{eva}})t}\right),$$
 (S6)

The amount oxidized can also be calculated as the product of the original  $CH_4$  concentration and the fraction of  $CH_4$  oxidized ( $F_{ox}$ ):

24 amount oxidized = 
$$[CH_4]_0 F_{\text{ox}}$$
, (S7)

25 According to Eq. (S6) and Eq. (S7), we can derive  $F_{ox}$  from the following equation:

26 
$$F_{\text{ox}} = \left(\frac{k_{\text{oxi}}}{(k_{\text{oxi}} + k_{\text{eva}})}\right) \left(1 - e^{-(k_{\text{oxi}} + k_{\text{eva}})t}\right), \tag{S8}$$

In Eq. (S8), the second term of the product can be rearranged using Eq. (S2) to represent the remaining fraction of  $CH_4$  concentration at time or km t:

29 
$$F_{\text{ox}} = \left(\frac{k_{\text{oxi}}}{(k_{\text{oxi}} + k_{\text{eva}})}\right) \left(1 - \frac{[CH_4]_{\text{t}}}{[CH_4]_0}\right),\tag{S9}$$

30 Given a fractionation factor  $\alpha$  for CH<sub>4</sub> oxidation, the behavior of the two CH<sub>4</sub> isotopes (<sup>12</sup>CH<sub>4</sub> and 31 <sup>13</sup>CH<sub>4</sub>) can be described based on Eq. (S2) as following:

32 
$$[12CH_4]_t = [12CH_4]_0 e^{-(k_{oxi}^{12} + k_{eva})t}$$
, (S10)

33 
$$[13CH_4]_t = [13CH_4]_0 e^{-\left(\frac{k_{\text{oxi}}^{12}}{\alpha} + k_{\text{eva}}\right)t}$$
, (S11)

With  $[12CH_4]$  and  $[13CH_4]$  the concentrations of the two isotopes, and  $k_{\text{oxi}}^{12}$  the rate coefficient of oxidation for the <sup>12</sup>CH<sub>4</sub> isotope. The isotopic ratio of CH<sub>4</sub> concentration at t ( $R_t$ ) can be derived from Eq. (S10) and Eq. (S11) as following:

37 
$$R_{t} = \frac{[13CH_{4}]_{t}}{[12CH_{4}]_{t}} = \frac{[13CH_{4}]_{0} e^{-(\frac{k_{\text{oxi}}}{\alpha} + k_{\text{eva}})t}}{[12CH_{4}]_{0} e^{-(k_{\text{oxi}} + k_{\text{eva}})t}},$$
(S12)

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

39 
$$R_{\rm t} = R_0 \, e^{(1-\frac{1}{\alpha}) \cdot k_{\rm oxi} \, {\rm t}},$$
 (S13)

40 The term t can be isolated from equation Eq. (S13):

41 
$$t = \frac{\ln(R_t/R_0)}{(1-\frac{1}{\alpha})\cdot k_{\text{oxi}}},$$
 (S14)

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

43 
$$t = \frac{\ln([CH_4]t)/[CH_4]_0)}{-(k_{\text{oxi}}+k_{\text{eva}})},$$
(S15)

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

45 
$$\frac{\ln({^{R}t}/_{R_0})}{(1-\frac{1}{\alpha})\cdot k_{\text{oxi}}} = \frac{\ln({^{[CH_4]t}/_{[CH_4]_0}})}{-(k_{\text{oxi}}+k_{\text{eva}})},$$
(S16)

46 Rearranging E. (S16) yields:

47 
$$\frac{-\ln(R_{t/R_{0}})}{(1-\frac{1}{\alpha})\cdot\ln([CH_{4}]t/[CH_{4}]_{0})} = \frac{k_{\text{oxi}}}{(k_{\text{oxi}}+k_{\text{eva}})},$$
(S17)

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

49 
$$F_{\text{ox}} = \frac{k_{\text{oxi}}}{(k_{\text{oxi}} + k_{\text{eva}})} \left( 1 - \frac{[CH_4]_t}{[CH_4]_0} \right) = \frac{-\ln({^{R_t}/_{R_0}}) \cdot (1 - {^{[CH_4]_t}/_{[CH_4]_0}})}{(1 - \frac{1}{\alpha}) \cdot \ln({^{[CH_4]_t}/_{[CH_4]_0}})},$$
(S18)

50 The isotopic ratios ( $R_t$  and  $R_0$ ) can be converted to  $\delta^{I3}CH_4$  expressed in ‰ using the following 51 standard isotopic equation calculation:

52 
$$\delta^{13}CH_4 = \left(\frac{[13CH_4]:[12CH_4]}{[13CH_4]_{\text{std}}:[12CH_4]_{\text{std}}} - 1\right) \times 1000, \tag{S19}$$

with  $[13CH_4]_{\text{std}}$ :  $[12CH_4]_{\text{std}}$  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  $F_{\text{ox}}$  calculation:

55 
$$F_{ox} = \frac{-[\ln(\delta^{13}CH_{4t} + 1000) - \ln(\delta^{13}CH_{40} + 1000)] \cdot (1 - \frac{[CH_4]t}{[CH_4]_0})}{(1 - \frac{1}{\alpha}) \cdot \ln(\frac{[CH_4]t}{[CH_4]_0})},$$
(S20)

Eq. (S20) was used to determine  $F_{ox}$  and CH<sub>4</sub> 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<sub>4</sub>

58 concentration and isotopic signature was conducted at two other points within this river stretch 59 (km 0.6 and 2.7). This additional sampling resolution can help test the adequacy of the model and 60 its conceptual assumptions by recalculating CH<sub>4</sub> oxidation in individual segments (between 0-0.6 61 km, 0.6-2.7 km, and 2.7-19 km). If the model assumptions are correct (absence of other CH<sub>4</sub> source in the river, constant specific oxidation rate, and constant river velocity), the amount of CH4 62 63 oxidized in the entire stretch  $(Ox_{total})$  should equal the sum of the amount oxidized in each 64 individual segment (Ox<sub>sum</sub>). In two of the sampling campaigns (Apr-May 2017 and Feb-Mar 2018), 65 the difference between  $Ox_{total}$  and  $Ox_{sum}$  was very small (CV < 5 %). In the two other campaigns, 66 this difference was larger (CV of 12 and 35 % for Nov-Dec 2016 and Aug 2018 respectively), due 67 to an additional CH<sub>4</sub> source causing occasional increases of CH<sub>4</sub> concentration along the stretch. 68 Overall, model assumptions appear reasonable, however, to avoid overestimating the amount oxidized in cases of additional  $CH_4$  sources, we considered  $Ox_{total}$  as the more suitable estimate, 69 70 since it is less influenced by CH<sub>4</sub> addition in individual segments.

71

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