Main changes in the revised manuscript include:

1. Definition of three distinct and comparable categories: peat, non-peat, delta (their characteristics like water surface area, catchment fraction etc. are summarized in Table 1)
2. Instead of reporting freshwater averages and then peat/non-peat averages, values are reported for the three categories peat, non-peat, delta, and in addition, an area-weighted mean was calculated for peat and non-peat area combined (Table 2)
3. CO_2 fluxes were calculated by comparing three different k-parameterizations. Instead of picking one of these estimates, a range of values (average, minimum, maximum) is given for CO_2 fluxes and derived parameters
4. River loads were recalculated according to point 2 & 3
5. River surface area was recalculated using the GRWL Database.
6. The "non-peat contribution" calculation was removed. After changing the CO_2 flux calculation, the results had such large uncertainties that we were unable to derive a statement from this calculation. Thus, it seemed pointless and was removed.

Point-by-point response to the Referee's comments

In the following, we present a point-by-point response to the reviews. We will keep it short by only outlining the changes we made with regard to those comments. For further justification or more detailed explanations, please see the author's response that we posted on Biogeosciences Discussions.

Comments by Reviewer #1

The manuscript (MS) submitted by Müller-Dum et al. investigates the C exports from the Rajang River and Estuary (Indonesia) based on sampling cruises during wet and dry season. That includes observations of CO_2 partial pressures (pCO_2), calculation of CO_2 emissions from the water surface, and lateral exports of DOC, POC, and DIC. pCO_2 and emissions are detailed for the peat-draining, non-peat-draining and estuarine parts of the river. One important result is that although the peat cover in the basin is significant, its contribution to C exports from the river system is not visible, as the peatlands are concentrated around the river delta. The manuscript of Müller-Dum et al. is of interest for the readership of Biogeosciences, because it reports the first pCO_2 and CO_2 emission estimates of this important river in SE-Asia, which is surprisingly different from what would have been expected from observation from over peat draining rivers in this area. The methodology is well described and seems to be sound. The MS is in most parts well written. The results support the main conclusions drawn in the MS. The discussion of results is thorough and covers well the state of the art with respect to literature references. I suggest the publication of the MS after some moderate revisions. Please, find my comments to the authors below.

Major comment: You have been measuring pCO2 for quite different parts of the delta system delta (estuary and peat part of the river network) during the wet and the dry season. That becomes quite apparent from the figure 4. Did you do anything to compensate for the discrepancy in observed delta parts? If not, I would suggest that you calculate and report the average wet and dry season pCO2 only for the parts you have been sampling in both seasons.
In the revised manuscript, we introduce three distinct categories: peat, non-peat and delta. Observations in the peat and non-peat areas are directly comparable between seasons. They were defined such that they were non-saline and covered by our observations during both seasons. Delta values are reported for the sake of completeness, we made clear in the Methods section that they are not directly comparable between seasons.
The introduction of three new categories required a recalculation of averages. Instead of reporting freshwater averages and then peat/non-peat values, we report averages for peat, non-peat and delta and we calculated an area-weighted mean for peat/non-peat (Table 2). Following this new approach, we recalculated river loads and also emissions to the atmosphere. River surface area was recalculated using the GRWL database.

General comments:
Abstract: The abstract is comprehensible and summarizes well the main findings. However, the abstract would need some minor restructuring:
P2, L8-9: It's not easy to see here how these DIC and delta13C values show that peat-lands are not the main source. That would require some more explanation within the abstract. Maybe you could discard these two number from the abstract.
This sentence was deleted.

P2, L10: This sentence is repeating what was stated two sentences before.
This sentence was deleted.

P2, L10-12: "Thus: : :". I feel this sentence should conclude the abstract.
This sentence now concludes the abstract.

P2, L13-15: "CO2 fluxes: : :". This sentence should come slightly earlier and directly follow your statements related to the pCO2.
The statement about the CO_2 fluxes now directly follows the statement about pCO_2 values.

Introduction:
P3, L2-3: Make clear that you are talking about terrestrial derived C fluxes.
Sentence was changed to: "Tropical rivers transport large amounts of terrestrially derived carbon to the ocean and the atmosphere (Aufdenkampe et al., 2011; Raymond et al., 2013)."

P3, L13-14: Could you report the proportion of the water flux for comparison?
We added the following information: "Because of these high DOC concentrations, Indonesian rivers may account for 75 % of the DOC flux into the South China Sea (SCS) while accounting for 39 % of the discharge (Huang et al., 2017)."

P3, L25-26: Did you do longitudinal transects from no-peat-influenced river reaches to river reaches surrounded by peat? If yes, it would be good to state that here.

We added a sentence for clarification: “To this end, we surveyed longitudinal transects extending from river reaches that were not influenced by peat to the peat-covered delta.”

P3, L26-27: Maybe you should discard that last sentence.
It was deleted.

Methodology:
The only thing I miss is an explanation why you observed the delta13C of DIC, and maybe the endmembers you used for your isotopic mixing model, if you applied one.
We added the following justification: “In August 2016, water samples were also taken for the determination of dissolved inorganic carbon (DIC) and the isotopic composition ($\delta^{13}C$) of DIC, because the isotopic composition of DIC can help in identifying its sources (Das et al., 2005; Campeau et al., 2017; 2018).” An isotopic mixing model was not applied.

Results
P9,L5-12: With regard to the positive correlation between delta13C and DIC concentration in the estuary: What is the marine endmember of delta 13C in DIC here?
Please see the reply to this question in our Author Comment. No changes were made with regards to this comment.

With regard to the negative correlation between delta13C and DIC concentration in the freshwater part: Is that correlation even stronger between delta13C and pCO2?
Please see the reply to this question in our Author comment. No changes were made with regard to this comment.

P9, L8: “Calculate DIC for the wet : : :”. For which part of the river network? The freshwater part? Please, clarify!
This now reads: “Calculated DIC for the wet season averaged 289.8 ± 32.1 $\mu mol\ L^{-1}$ (area-weighted mean for the non-peat and peat area).”

P9, L21-13: Is it possible to distinguish pCO2 observations you made during high, rising, falling, and low tide during your cruises? Or were your cruises in the delta predominantly done during a specific part of the tidal cycle? Were those different for wet and dry season cruises?
Tidal variability is now discussed in Section 3.2 and 4.2.3 and time series of both pCO2 and water level are shown in the revised Supplement.

P9, L27-28: Does that mean you cannot distinguish the diurnal variations from tidal variations for the delta? And you do not have enough data from the non-tidal part to identify a diurnal signal? Please, clarify.
We added the following explanation: “Unfortunately, our data did not allow identification of a diurnal signal for either pCO_2 or DO. In the tidal part of the river, we had only the one stationary measurement overnight, when a diurnal signal could not be identified due to the strong tidal signal. In the non-tidal part of the river, we had insufficient night-time data to make a statement about a day-night difference for pCO_2 and DO.”

P9, L30 – P10,L1: How did you calculate those gas exchange velocities? I see how your calculations compare well to the A11 model, but R01 model seems to be quite far off. Are those the results for the whole river system?

The calculation of gas exchange velocities is now described in more detail in Section 2.3. We have changed our approach according to a major comment by Reviewer 2. We now present the three parameterizations as equally valid and present the range of values that they give (average, minimum, maximum).

P10, L3-5: Those emission rates refer to the entire observed river network? Did you weight the emission rates along the longitudinal profile by stream width?
We have now calculated emission rates separately for peat, non-peat area and for the delta and calculated emissions (g/month) using the water surface area in each of the categories using stream widths from the GRWL database.

Comments by Reviewer #2

General comment: The manuscript focus on an important topic that I believe is suitable for publication in Biogeosciences. The transport and emission of carbon/GHGs from river networks has repeatedly been concluded during the last decade as a highly significant component when for example estimating landscape C budgets at various scales and biomes. Although the importance is well-recognized, I would claim that relatively little is known about large rivers and their source contribution of atmospheric CO2. The knowledge that exists is largely restricted by the spatiotemporal resolution of the measurements or by using data being based on indirect measurements of pCO2. There is also a clear bias in existing data-sets towards northern hemisphere river networks and with limited information of tropical rivers, especially south-east Asian ones. In this context this study aims to fill an important gap in our understanding concerning large scale drivers of aquatic C in river networks. The influence of peat deposits in the catchment on the pGHG in the water has been shown for various biomes and river network sizes but more extensive investigations are needed. Hence, this is a highly relevant topic especially for a tropical region like this.
Although the aim of manuscript is important I have some concerns on how suitable the manuscript is for publication in its current form. My main concerns are: 1) How the actual emissions are calculated. I understand that this is a data scarce region but the way the authors have estimated the emissions is not especially convincing. The author's measure pCO2 in a satisfactory way but the entire k calculation component feels very shaky.
No actual measurements of any of the input parameters are conducted. A vague estimate of a fixed water velocity is used in combination with modelled wind data. Three different k parameterizations are then used gaining slightly, to very, different outputs. The model producing intermediate k estimates are then used without any stronger further motivation. The whole procedure feels as I already said very shaky, without knowing anything about the river, investigating seasonal differences in emissions and then using a fixed water velocity sounds for example very strange. On top of these vague calculation steps there are no uncertainty estimate of the calculated emissions (or lateral exports of inorganic and organic C!!). To describe and estimate this in a transparent way would be a requirement in my eyes, especially due to the scarcity in data for the k calculations. If this is problematic to handle, one suggestion is to skip the emission data and solely present the pCO2 patterns and how it varies with wet and dry season and the influence of peatlands. Personally I think this would be the way to go and would be highly interesting in itself. 2) I am not totally

convinced of the interpretations of the 13C-DIC data, I am surprised by the generally high 13C-DIC values, the authors claim that the contribution by carbonate containing bedrock to the riverine DIC is minimal in the area and that the river is affected by tidal water sustaining the estuary with marine DIC. That is likely correct but the high 13C-DIC is found even in upstream non-peat area, is the evasion the sole explanation for that? Maybe not relevant, but what about methane production, I understand that methane might have been included in the original plan, but if methane in the peatlands is mainly produced by CO2 reduction this will heavily influence the 13C of the CO2 being delivered to the river (See Campeau et al. 2018 for example). Overall, I find the interpretation of the 13C-DIC data quite short and not as well developed as it could be. 3) Is it really correct to talk about seasonality when just two measurement campaigns are conducted, i.e. wet and dry season? I am not familiar with the region but to call something seasonality or similar would in my mind require a higher sampling resolution in time.

1) As argued in our Author Comment, we kept the CO2 flux estimates as part of the manuscript, but we improved the discussion of uncertainties and the presentation of the "k-story". We now present the three k-parameterizations as equally valid, and since we point out that the mere choice of a k-parameterization is the largest source of uncertainty (Supplement), we present the range of values that they give (average, minimum, maximum) and discuss it as a range of uncertainty.
2) We have included a Keeling plot in Figure 4, improving our ability to discuss DIC sources. We have also significantly changed the discussion of the isotopic composition of DIC in Section 4.2.1. Factors like methanogenesis and pH are now explicitly mentioned, accompanied by additional references.
3) In Section 4.2.2, we added the following sentence: "Note that since our data was collected during two single surveys, they represent only a snapshot and do not allow strong claims about seasonality."

Detailed comments:
P3 Ln 1-10, there is a mix of wetland and peatland, consistency or a clear separation would be good.
We rewrote this paragraph: "Borges et al. (2015) established a relationship between wetland extent and pCO_2 for African rivers. Wit et al. (2015) presented an analog synthesis for Southeast Asian rivers, which flow through peatlands. Peatlands are a special type of wetland, where organic matter accumulates at rates that make them the most effective terrestrial carbon store on a millennial timescale (Dommain et al., 2011). Southeast Asian peatlands store 68.5 Gt carbon (Page et al., 2011). The highest riverine dissolved organic carbon (DOC) concentrations reported so far were found in Southeast Asian peat-draining rivers (Alkhatib et al. 2007; Moore et al., 2011; Müller et al., 2015), with an annual average of 68 mg L^{-1} DOC found in an undisturbed peat-draining river (Moore et al., 2013). Because of these high DOC concentrations, Indonesian rivers may account for 75 % of the DOC flux into the South China Sea (SCS) while accounting for 39 % of the discharge (Huang et al., 2017). Surprisingly, CO_2 emissions from these rivers are not exceptionally high (Müller et al., 2015; Wit et al., 2015). This is attributed to a short residence time of the organic matter in the river, allowing little time for decomposition, and the resistance of peat-derived carbon to bacterial degradation. Nevertheless, the CO_2 flux from peat-draining rivers to the atmosphere increases with

increasing peat coverage in the river basin (Wit et al., 2015), showing that these ecosystems exert an important influence on a river's carbon budget."

P3 Ln 11, Odd formulation and scientifically a bit weird. To claim that something is the highest worldwide is only true until someone else present a higher number. I would recommend to be more open in this formulation.
We rephrased: "The highest riverine dissolved organic carbon (DOC) concentrations reported so far were found in Southeast Asian peat-draining rivers (Alkhatib et al. 2007; Moore et al., 2011; Müller et al., 2015), with an annual average of 68 mg L-1 DOC found in an undisturbed peat-draining river (Moore et al., 2013)."

P5 Ln 20-25 and 30, what about correction for salinity on the pCO2 and emissions?
Please see our author comment for a response to this question. One thing we changed with regard to this comment was adding the sentence: "In-situ k is dependent on in-situ salinity and temperature and was calculated from k_{600}, exploiting its relationship with the Schmidt number (Wanninkhof, 1992)." in Section 2.3.

P6 Ln 8-10 Isn't water velocity dependent on discharge, why is a fixed value used???
We justified this in our author comment, in the revised manuscript, we present this justification in the Supplement.

P6 Ln 10, Is there no wind data to validate this modeled data with? How accurate is the wind data compared to conditions over the river is tricky to judge. Feels very vague and uncertain!!!
Please see our author comment for justification. In the revised manuscript (Section 2.3), we wrote: ". For u_{10}, on-site wind speed data was unfortunately not available. In such cases, other authors (e.g., Bouillon et al., 2012; some estuaries in Chen et al., 2013) have resorted to gridded wind data from the NOAA NCEP NCAR Reanalysis product (Kalnay et al., 1996). While we acknowledge the uncertainty introduced by using gridded data instead of in situ wind speed, we used this product as well, as the best one available for our study area."

P7 Ln 29-30, a bit odd that POC was measured but not DOC. Hard to redo the study but how relevant are the literature DOC values for this study, please motivate better!
Please see our author comment for a reply. In the revised manuscript (Section 2.5), we now wrote: "For DOC, we used the DOC concentrations reported by Martin et al. (2018). This data was acquired during 2017 downstream of Kanowit. Only freshwater values were considered (average for the wet and dry season: 2.0 mg L^{-1} and 2.1 mg L^{-1})."

P8 Ln 25, please clarify what pH that is for wet resp. dry season.
We now wrote: "The Rajang River was slightly acidic (6.7 (wet) and 6.8 (dry), area-weighted mean for the peat and non-peat area, see Table 2)…"

P9 Ln 10-12, was not the purpose to investigate if the peatlands have an influence on the pCO2 in the river. Feels a bit strange then to say that too few 13C-DIC samples were taken.
Please find our response in the author comment that we posted. No changes were made to the manuscript with regard to this comment.

P9 Ln 20, here and elsewhere, what is "distributaries", isn't just tributaries enough???

Please find our response in the author comment that we posted. No changes were made to the manuscript with regard to this comment.

P9 Ln 21-23, important sentence but feels more like discussion than result!!
The second part of the sentence was deleted. Tidal variability is further discussed in the appropriate Section 4.2.3 and in the Supplement.

P9 Ln 27-28, again, feels more like discussion to me.
We did not make any changes with regard to this comment. Please see our author comment for justification.

P10 L4, what does the +-0.52 and +-0.45 mean? Some kind of uncertainty or just spread? Please clarify in the methods. The emission rates (and lateral exports of C) are hard to get a feeling of, how uncertain are they? Impossible to judge for the moment.
We now clarified in Section 2.5: "Averages of measured parameters are reported ± 1 standard error unless stated otherwise. Errors for calculated parameters (e.g., river loads, see below) were determined with error propagation. For fluxes and derived quantities, we report the mean, minimum and maximum from the three *k*-parameterizations."

P10 Ln 17-20, Feels from a reader perspective a bit odd to start to say that the findings are the same as found in other studies. I think the authors could "sell" their study better than that. It is important information but I would not place it first in the discussion.
We rewrote this paragraph, those three lines were deleted as they were redundant after changing the paper.

Also, maybe a matter of personal taste, but why not start with the main focus of the manuscript in the discussion (pCO2 patterns and maybe emissions if included), the SPM and POC story is secondary as I see it.
We kept the previous structure, please see our author comment for justification.

P12 Ln 11-14, Likely true but there is also a strong fractionation in 13C-DIC related to changes/differences in pH which could be up to ca 10 per mille.
In the course of changing the d13C-DIC discussion, we have included this aspect: "With regard to in-stream processes, photosynthesis increases and respiration decreases δ^{13}C-DIC (Campeau et al., 2017). Due to the high turbidity, it can be assumed that photosynthesis in the Rajang River is negligible. In contrast, the correlation of DO and pCO_2 (Fig. 5) suggests that respiration is important. This assumption is supported by the negative correlation of δ^{13}C and DIC for freshwater samples, because with increasing DIC, δ^{13}C values get more depleted, suggesting that organic carbon (with a δ^{13}C of around -26 ‰ for C3 plants, Rózanski et al., 2003) is respired to CO_2 within the river. However, we observed overall relatively high δ^{13}C values. Two processes are likely to be responsible for the downstream increase in δ^{13}C: (1) Methanogenesis and (2) evasion of CO_2. (1) Campeau et al. (2018) observed a strong relationship between CH_4 concentration and δ^{13}C-DIC in a boreal stream draining a nutrient-poor fen, suggesting that fractionation during methanogenesis leads to an increase in δ^{13}C-DIC. As the peat soils in the Rajang delta are also anaerobic and nutrient-poor, it is likely that methanogenesis plays a role there as well. This is consistent with high reported soil CH_4 concentrations of up to 1465 ppm in a peat under an oil palm plantation in Sarawak (Melling et al., 2005). It would therefore be of high interest to investigate CH_4 concentrations in the Rajang

River in the future. (2) CO_2 evasion is also known to lead to a gradual increase of δ^{13}C-DIC values until in equilibrium with the atmosphere (with δ^{13}C-DIC around +1 ‰, Polsenare and Abril, 2012; Venkiteswaran et al., 2014; Campeau et al., 2018). Due to intracarbonate equilibrium fractionation, dissolved CO_2 is more depleted in δ^{13}C than the other carbonate species. Thus, if it is removed, δ^{13}C of the remaining DIC increases. This effect depends on pH and is more pronounced in near-neutral waters and less strong in very acidic water (Campeau et al., 2018). We sampled the lower river reaches downstream of Kapit, which corresponds to approximately the last 200 kilometers of the river. In addition, the terrain is much steeper upstream of Kapit than in the lower river reaches, so that CO_2 fluxes to the atmosphere are presumably much higher due to higher turbulence. This means that a large fraction of CO_2 had likely already been emitted from the river surface before reaching Kapit, leading to the observed high δ^{13}C-DIC values."

Table 2.What is the +- of the emissions, the SE of the mean? I.e. some kind of measure of the spatial variability? Is this driven by something else than just variability in pCO2? Is k fixed for all data? According to the methods I get this feeling. Please clarify in the methods.

We have now clarified in the Methods section 2.5; in addition, the information "+- SE" is found in the Table caption.

Impact of peatlands on carbon dioxide (CO_2) emissions from the Rajang River and Estuary, Malaysia

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Abstract. Tropical peat-draining rivers are known as potentially large sources of carbon dioxide (CO_2) to the atmosphere due to high loads of carbon they receive from surrounding soils. However, not many seasonally resolved data are available, limiting our understanding of these systems. We report the first measurements of carbon dioxide partial pressure (pCO_2) in the Rajang River and Estuary, the longest river in Malaysia. The Rajang River catchment is characterized by extensive peat deposits found in the delta region, and by human impact such as logging, land use and river damming. pCO_2 averaged 2919 2540 ± 573 189 µatm during the wet season and 2732 2350 ± 443 301 µatm during the dry season. Using three different parameterizations for the gas transfer velocity, calculated CO_2 fluxes to the atmosphere were 1.5 (0.5-2.0) gC m^{-2} d^{-1} (mean, minimum – maximum) during the wet season and 1.7 (0.6-2.6) g C m^{-2} d^{-1} during the dry season. This is at the low end of reported values for Southeast Asian peat-draining rivers, but higher than similar to values reported for Southeast Asian rivers that do not flow through peat deposits. However, dissolved inorganic carbon (DIC) and δ^{13}C-DIC data did not suggest that peatlands were an important source of inorganic carbon to the river, with an average DIC concentration of 203.9 ± 59.6 µmol L^{-1} and an average δ^{13}C-DIC of -8.06 ± 1.90 ‰. Also, compared to rivers with similar peat coverage, the pCO_2 in the Rajang was rather low. Thus, we suggest that peat coverage is, by itself, insufficient as sole predictor of CO_2 emissions from peat-draining rivers, and that other factors, like the spatial distribution of peat in the catchment and pH, need to be considered as well. In the Rajang River, peatlands probably do not contribute much to the CO_2 flux due to the proximity of the peatlands to the coast, which limits the opportunity for degradation of organic C during transport. Thus, we suggest that peat coverage is, by itself, insufficient as sole predictor of CO_2 emissions from peat-draining rivers, and that other factors, like the spatial distribution of peat in the catchment and pH, also need to be considered as well. CO_2 fluxes to the atmosphere were 2.28 ± 0.52 gC m^{-2} d^{-1} (wet season) and 2.45 ± 0.45 gC m^{-2} d^{-1} (dry season), making the Rajang River a moderate source of carbon to the atmosphere. .

1 Introduction

Tropical rivers are hotspots of carbon fluxes to the oceantransport large amounts of terrestrially derived carbon to the ocean (Dai et al., 2012) and the atmosphere (Aufdenkampe et al., 2011; Raymond et al., 2013). It has been estimated that 78% of riverine carbon dioxide (CO_2) emissions occur in the tropics (Lauerwald et al., 2015). Tropical wetlands exert a particularly strong influence on the carbon budget of these rivers. Two regional studies independently showed that the partial pressure of CO_2 (pCO_2) in rivers increases with increasing wetland coverage in the catchment. :

Borges et al. (2015) established a relationship between wetland extent and pCO_2 for African rivers. Wit et al. (2015) presented an analog synthesis for Southeast Asian rivers, which flow through peatlands. Peatlands are a special type of wetland, where organic matter accumulates at rates that make them the most effective terrestrial carbon store on a millennial timescale (Dommain et al., 2011). Southeast Asian peatlands store 68.5 Gt carbon (Page et al., 2011). The highest riverine dissolved organic carbon (DOC) concentrations reported so far were found in Southeast Asian peat-draining rivers (Alkhatib et al. 2007; Moore et al., 2011; Müller et al., 2015), with an annual average of 68 mg L^{-1} DOC found in an undisturbed peat-draining river (Moore et al., 2013). Because of these high DOC concentrations, Indonesian rivers may account for 75 % of the DOC flux into the South China Sea (SCS) while accounting for 39 % of the discharge (Huang et al., 2017). Surprisingly, CO_2 emissions from these rivers are not exceptionally high (Müller et al., 2015; Wit et al., 2015). This is attributed to a short residence time of the organic matter in the river, allowing little time for decomposition, and the resistance of peat-derived carbon to bacterial degradation. Nevertheless, the CO_2 flux from peat-draining rivers to the atmosphere increases with increasing peat coverage in the river basin (Wit et al., 2015), showing that these ecosystems exert an important influence on a river's carbon budget.

Borges et al. (2015) established this relationship for African rivers and Wit et al. (2015) for Southeast Asian rivers, many of which flow through peatlands. These peatlands represent a unique type of wetland of global importance. The permanently wet, anoxic soil allows for the accumulation of organic matter at rates which make them the most effective terrestrial carbon store on a millennial timescale (Dommain et al., 2011). Southeast Asian peatlands store 68.5 Gt carbon (Page et al., 2011).

Rivers flowing through these peatlands have the highest riverine dissolved organic carbon (DOC) concentrations worldwide (Alkhatib et al. 2007; Moore et al., 2011; Müller et al., 2015), with an annual average of 68 mg L^{-1} DOC found in an undisturbed peat-draining river (Moore et al., 2013). Because of these high DOC concentrations, Indonesian rivers may account for 75 % of the DOC flux into the South China Sea (SCS) (Huang et al., 2017). Surprisingly, CO_2 emissions from these rivers are not exceptionally high (Müller et al., 2015; Wit et al., 2015). This is attributed to a short residence time of the organic matter in the river, allowing little time for decomposition, and the resistance of peat-derived carbon to bacterial degradation.

However, most Southeast Asian peat-draining rivers are disturbed by human activities such as river damming, urbanization, deforestation (Milliman and Farnsworth, 2011) and discharge of untreated wastewater (Park et al., 2018). Anthropogenic change poses a new challenge to understanding carbon fluxes in Asian river systems, and more data are urgently needed to constrain the carbon budget for this important region (Park et al., 2018). In Malaysia, a the country holding the second largest share of tropical peat (Page et al., 2011), river CO_2 emissions have only been studied in a small undisturbed peat-draining river (Müller et al., 2015), in estuaries (Chen et al., 2013; Müller et al., 2016) and in two river reaches which were not influenced by peat (Müller et al., 2016). In this study, the longest Malaysian river, the Rajang River on the island of Borneo, was investigated. This river flows through largely logged-over tropical rainforest (Gaveau et al., 2014), urban areas and disturbed peat swamps (Gaveau et al., 2016). The aim of this study was to assess the Rajang River and Estuary carbon load and to investigate the impact of peatlands on its CO_2 emissions. To this end, we surveyed longitudinal transects extending from river reaches that were not influenced by peat to the peat-covered delta. We expected to see a clear peat signal, i.e. elevated CO_2 concentrations in the peat area.

2 Materials and Methods

2.1 Study area

The Rajang River is located in the Malaysian state of Sarawak in the northern part of the island of Borneo (Fig. 1a). Sarawak has a tropical climate with high temperatures (average 26.6°C, 1992-2016 in Sibu, DWD, 2018) and high precipitation (average 3,578 mm yr^{-1}, 1992-2016 in Sibu, DWD, 2018). The region experiences two monsoonal periods: the northeastern monsoon with enhanced rainfall and frequent floods occurs between December and February ("wet season", see Fig. 2a), while the southwestern monsoon from May until September is associated with relatively drier weather ("dry season"). However, despite the monsoon seasons, rainfall is high throughout the year (Sa'adi et al., 2017).

The Rajang River originates in the Iran mountains, a mountain range at the border between Malaysia and Indonesia (MacKinnon, 1996) with elevations of up to 1,800 m (Milliman and Farnsworth, 2011). It drains an area of approximately 51,50052,010 km² (Lehner et al., 2006; DID 2017) whose geology is dominated by Cenozoic sedimentary and metamorphic rocks, consisting of siliciclastic rock with minor amounts of carbonates (Staub et al., 2000; Milliman and Farnsworth, 2011). The Rajang River flows approximately 530 km from east to west and discharges into the South China Sea (Milliman and Farnsworth, 2011). Main settlements along the river are the towns of Kapit, Kanowit and the city of Sibu (163,000 inhabitants) (see Fig. 1b). In addition, a large number of longhouses (traditional buildings inhabited by local communities) are located along the river and its tributaries (Ling et al., 2017). Hydroelectric power plants were built on two tributaries in the upper Rajang basin: The Bakun hydroelectric power plant commenced operation in 2011 and the Murum dam in 2015 (Sarawak Energy, 2013, see Fig. 1b). The construction of another hydroelectric power plant on a tributary in the southern Rajang basin is planned for the future (Sarawak Energy, 2013).

The Rajang delta system is comprehensively described in Staub and Gastaldo (2003). It is entirely surrounded by peatlands (Fig. 1b), which extend over an area that corresponds to approximately 11% of the catchment size (Nachtergaele et al., 2009). Most of these peatlands have been converted to industrial oil palm plantations (Gaveau et al., 2016, Fig. 1b). The main distributary channels forming the delta (from north to south) are the Igan, Hulu Seredeng (which splits up into Lassa and Paloh), Belawai and Rajang, which have a maximum tidal range (spring tide) of 3-6 m (Staub and Gastaldo, 2003). Saltwater intrudes into the estuary approximately as far as the point where the Rajang River splits up into its four southernmost distributaries, a few kilometers downstream of Sibu (Fig. 1b), depending on season. Tidal influence extends further inland approximately up to the town of Kanowit (Staub and Gastaldo, 2003).

Monthly discharge (Fig. 2a) was estimated from monthly precipitation (1992-2016; DWD, 2018) and an evapotranspiration rate of 1,545 mm yr^{-1} (Kumagai et al., 2005) or 43.2%. Annual average discharge from 1992-2016 was 3,322 3,355 $m^3 s^{-1}$, in reasonable good agreement with reported discharges of 3,490 $m^3 s^{-1}$ (Milliman and Farnsworth, 2011) and 3,372 $m^3 s^{-1}$ for the years 1991-2015 (Sa'adi et al, 2017).

2.2 Surveys

We sampled the Rajang River during two surveys, which were designed to get spatial coverage of both peat and non-peat areas during the wettest and driest period of one year. The first survey took place at the peak of the monsoon season in January 2016 ("wet season"). The second one was performed during the dry season in August 2016 ("dry season"). In January 2016, we entered the Rajang River through the Rajang river mouth (distributary 5 in Fig.1b), went upstream to the town of Kapit and back downstream to the town of Belawai at the Belawai river mouth (distributary 4 in Fig. 1b). In August 2016, we entered the Rajang River through the Rajang river mouth (5), went upstream to Kapit and back to Sibu. From there, we went out to the coast through the Lassa distributary (2), and back to Sibu through the Igan distributary (1). The last sampling stretch was from Sibu into the Paloh distributary (3) and back to Belawai (4). During this campaign, one stationary measurement was performed overnight in Sarikei in the Rajang distributary in order to assess tidal/diurnal variability.

2.3 CO_2 measurements

The setup on the boat was similar to the one described in Müller et al. (2016). Surface water was pumped through a shower-type equilibrator (Johnson, 1999) at a rate of approximately 15 L min^{-1}. In the beginning, the equilibrator headspace was connected to an FTIR analyzer (Griffith et al., 2012), which allows for the simultaneous measurement of CO_2, methane (CH_4), nitrous oxide (N_2O) and carbon monoxide (CO). During the cruise in January 2016, a failure of the FTIR analyzer occurred and measurements were continued (also in August 2016) using an Li-820 non-dispersive infrared (NDIR) analyzer for the measurement of CO_2 (Licor, USA). For calibration and inter-calibration of the two instruments, a set of gravimetrically prepared gas mixtures (Deuste Steininger) in the range of the World Meteorological Organization (WMO) standard scale was measured, which were calibrated was measured, which were calibrated against the World Meteorological Organization (WMO) standard scale by the Max Planck Institute for Biogeochemistry in Jena, Germany. For the FTIR, spectra were averaged over 5 minutes and dry air mole fractions were retrieved using the software MALT5 (Griffith 1996). Li-820 data were stored with a temporal resolution of 1 minute. Gas partial pressure was determined using measurements of ambient pressure with a PTB110 barometer (Vaisala, Finland) and correction for removal of water according to Dickson et al. (2007). Water temperature was measured in the equilibrator and in the surface water and correction to water surface temperature was performed according to Dickson et al. (2007).

In August 2016, the internal pressure sensor of the Li-820 failed. Because the instrument performs an internal correction based on the cell pressure, this correction had to be reversed and recalculated with an assumed internal cell pressure. This procedure is described in the Supplement.

CO_2 fluxes (FCO_2, in gC m^{-2} d^{-1}) across the water-air interface were computed using the gas transfer equation

$$FCO_2 = kK_0(pCO_2^{water} - pCO_2^{air}) \cdot f_1 f_2 \quad (1),$$

where k is the gas transfer velocity (m s^{-1}), K_0 is the solubility (mol L^{-1} atm^{-1}) calculated according to Weiss (1974), pCO_2^{water} is the partial pressure of CO_2 in water, pCO_2^{air} is the partial pressure of CO_2 in the overlying air (both in µatm), f_1 is a conversion factor from L^{-1} to m^{-3}, and f_2 is a conversion factor from µmol s^{-1} to mg d^{-1}. The atmospheric mole fractions of CO_2 during the months of our measurements were derived from the NOAA ESRL Carbon Cycle Cooperative Global Air Sampling Network (Dlugokencky et al., 2018) for the closest station, which was Bukit Kototabang, Indonesia.

The gas transfer velocity (k) is a critical, yet poorly constrained parameter. Many studies have attempted to relate k to the main drivers of turbulence, such as wind speed (e.g., Wanninkhof, 1992; Nightingale, 2000; Raymond and Cole, 2001) or, especially for rivers, catchment parameters like slope, water flow velocity and discharge (Raymond et al., 2012). We sampled mainly the downstream reaches of the Rajang River, which range in width from 271 m to several kilometers in the delta (Allen and Pavelsky, 2018). Therefore, k-parameterizations that were developed for estuaries or big rivers were considered the most appropriate. We compared three parameterizations to constrain the CO_2 fluxes. The first parameterization is the one by Borges et al. (2004) for estuaries, which is driven both by wind speed and water flow velocity; the one by Alin et al. (2011), which was developed for rivers wider than 100 m and is driven by wind speed; and the one by Raymond and Cole (2001), which is driven by wind speed and was developed for big rivers and estuaries. Those parameterizations read:

$$k_{600,B04} = 1.0 + 1.719 w^{0.5} h^{-0.5} + 2.58\, u_{10} \quad (2),$$

$$k_{600,A11} = 4.46 + 7.11 \cdot u_{10} \quad (3),$$

$$k_{600,R01} = 1.91 \cdot e^{0.35 u_{10}} \quad (4),$$

As no information on the tidal currents was available for the Rajang River, we chose the k-parameterization by Borges et al. (2004) ('B04'), which was established for estuaries and considers water flow velocity and wind speed as the main drivers of turbulence, while tidal currents are neglected:

$$k_{600,B04} = 1.0 + 1.719 w^{0.5} h^{-0.5} + 2.58\, u_{10} \quad (2),$$

where w is the water flow velocity (cm s^{-1}), h is the depth (m) and u_{10} is the wind speed at 10 m (m s^{-1}). h was taken from the bottom sounder recordings of our boat. Water flow velocity w in the lower river reaches was measured by Staub and Esterle (1993) to be 0.7 m s^{-1}. A more recent study by Ling et al. (2017) reports a flow velocity of w = 1.1 m s^{-1} for the Rajang River upstream from Kapit. For the calculation of the gas exchange velocity k, we used the average of w = 0.9 m s^{-1}. For u_{10}, on-site wind speed data was unfortunately not available. In such cases, other authors (e.g., Bouillon et al., 2012; some estuaries in Chen et al., 2013) have resorted to gridded wind data from the NOAA NCEP NCAR Reanalysis product (Kalnay et al., 1996). While we acknowledge the uncertainty introduced by using gridded data instead of in situ wind speed, we used this product as well, as the best one available for our study area. We retrieved daily wind speed at 10 m Wind speed at 10 m was taken from NOAA NCEP Reanalysis for the grid centered at 2.85°N, 112.5°E for the time of our measurements. In-situ k is dependent on in-situ salinity and temperature and was calculated from k_{600}, exploiting its relationship with the Schmidt number (Wanninkhof, 1992).

The calculation of fluxes using k-parameterizations is associated with a large uncertainty, and it is difficult to determine the most suitable parameterization if none of them was developed in the study region. In addition, using input data from the literature (as for the water flow velocity) or gridded instead of measured wind data adds to this uncertainty (see Supplement). However, using three different parameterizations we are able to constrain the magnitude of CO_2 emissions from the Rajang River. We will report the average CO_2 fluxes from the three different parameterizations as well as minimum and maximum fluxes.

As the gas exchange velocity is critical for the calculation of fluxes, we compared the B04-model to k-parametizations by Alin et al. (2011) ('A11') and Raymond and Cole (2001) ('R01'), which were developed for large rivers and estuaries, respectively, and consider only wind speed as the driver of turbulence:

$$k_{600,A11} = 4.46 + 7.11 \cdot u_{10} \quad (3)$$

$$k_{600,R01} = 1.91 \cdot e^{0.35 u_{10}} \quad (4)$$

2.4 Ancillary measurements

In January 2016, individual water samples were taken at 15 stations between the river mouth and Kapit, including the distributary channels Rajang and Belawai. In August 2016, water samples were taken at 34 stations, with a higher sampling frequency and coverage in the delta (Rajang, Igan, Lassa, Paloh and Belawai, Fig. 1b). Water samples were taken from approximately 1 m below the surface using a Van Dorn water sampler. Particulate material was sampled on pre-weighed and pre-combusted glass fiber filters. From the net sample weight and the volume of filtered water, the amount of suspended particulate matter (SPM) was determined. For POC, 1N hydrochloric acid was added in order to remove inorganic carbon from the sample. For the determination of carbon, samples were catalytically combusted at 1050°C and combustion products were measured by thermal conductivity using a Euro EA3000 Elemental Analyzer. Repeatability for C content was 0.04 % (standard deviation).

In August 2016, water samples were also taken for the determination of dissolved inorganic carbon (DIC) and the isotopic composition ($\delta^{13}C$) of DIC, because the isotopic composition of DIC can help in identifying its sources (Das et al., 2005; Campeau et al., 2017; 2018). Samples were poisoned with 200 µL concentrated $HgCl_2$ and filtered through Whatman glass fiber filters (GF/F, pore size 0.7 µm). 40 ml sampling vials were filled to the top, leaving no headspace, checked for the existence of bubbles, and stored refrigerated until analysis. Concentrations and $\delta^{13}C$ of DIC were measured via continuous flow wet-oxidation isotope ratio mass spectrometry (CF-WO-IRMS) using an Aurora 1030W TOC analyzer coupled to a Thermo Delta V Plus IRMS (Oakes et al., 2010). Sodium bicarbonate (DIC) of known isotope composition dissolved in helium-purged milli-Q was used for drift correction and to verify concentrations and $\delta^{13}C$ values. Reproducibility for DIC was ±10 µmol L^{-1} for concentrations and ± 0.10‰ for $\delta^{13}C$ (standard deviations).

During both surveys, dissolved oxygen and water temperature were continuously measured with a temporal resolution of 5 minutes using an FDO 925 oxygen sensor and a WTW 3430 data logger (Xylem Inc., USA). The oxygen sensor was calibrated by the manufacturer, a routine function check was performed before the start of measurements using the check and calibration vessel (FDO © Check) provided by the company. The reported accuracy of a dissolved oxygen measurement at 20°C in air-saturated water is 1.5%, the precision of the accompanying temperature measurement is 0.2°C (WTW, 2012). pH, salinity and temperature were measured at the stations, using a SenTix 940 pH sensor (pH) and a Multiprobe (Aquaread AP-2000). The pH sensor was calibrated before the start of the measurements using NIST (National Institute of Standards and Technology) traceable buffers. Since salinity was only measured at the stations, we spatially interpolated salinity for the interpretation of pCO_2 data. This procedure is described in the Supplement.

Different geographical extents of the river were covered during the two campaigns, and the salt intrusion limits were different during the two seasons. In order to keep the results from the two surveys comparable, we report results for three categories: non-peat (Kapit-Kanowit), peat (Kanowit-Sibu) and delta (downstream of Sibu). Their definition and properties are specified in Table 1. The non-peat and peat areas are directly comparable between seasons, because the same spatial extent was covered during both surveys and they were non-saline during both seasons.

~~Salinity values ≤2 were considered as freshwater, while we define estuary as brackish river reaches with salinity >2 but <33. In the following, results are reported for freshwater and estuary separately. Further distinction was made between peat (longitude<112.1°) and non-peat (longitude≥112.1°). This distinction is equivalent to the distinction between tidal river (=peat) and non-tidal river (=non-peat) (Fig. 1b). The terminology used in this study is: peat (S≤2, longitude <112.1°), non-peat (S≤2, longitude >112.1°), estuary (33>S>2). For certain purposes, we report freshwater (peat + non-peat) or delta (peat + estuary) emissions.~~

2.5 Data analysis and export calculations

Data analysis was performed with Python 2.7.15 and ArcMap 10.5. Averages of measured parameters are reported ± 1 standard error unless stated otherwise. Errors for calculated parameters (e.g., river loads, see below) were determined with error propagation. For fluxes and derived quantities, we report the mean, minimum and maximum from the three *k*-parameterizations. Seasonal differences were tested for significance using the Mann-Whitney U-test from the Python Scipy Statistical Functions module. Data from the delta were excluded from the statistical tests due to the different geographical coverage achieved during the two surveys.

In order to calculate the total carbon export from the Rajang River for the months of our measurements, we derived DOC ~~export~~load, POC ~~export~~load, DIC ~~export~~ load for the peat and non-peat area, ~~and~~ as well as CO_2 outgassing ~~for the months of our measurements~~ as follows:

The river loads of DOC, POC and DIC ~~was~~ were calculated for the peat and non-peat area combined, using

$$RIVER\ LOAD = C \cdot Q \cdot f_3 \qquad (5),$$

where C is the average concentration of DOC/POC/DIC in mg L^{-1}, Q is monthly discharge ($m^3\ s^{-1}$) and f_3 is a conversion factor from s^{-1} to $month^{-1}$.

For DOC, we used the DOC concentrations reported by Martin et al. (2018). This data was acquired during 2017 downstream of Kanowit. Only freshwater values were considered (average for the wet and dry season: 2.0 mg L^{-1} and 2.1 mg L^{-1}).~~the average freshwater DOC concentration reported by Martin et al. (2018) of 2.0 mg L^{-1} (wet) and 2.1 mg L^{-1} (dry).~~ For POC, we used the area-weighted average ~~freshwater concentrations~~ concentration of peat and non-peat river reaches determined during our surveys.

For DIC, we used an area-weighted average concentration as well, which was determined from our measurements during the dry season. For the wet season survey, DIC was calculated from pH and pCO_2 using the program CO_2sys (Lewis and Wallace, 1998). Note that pH measurements were only available at the stations, and sometimes we did not have parallel pCO_2 measurements. Therefore, the number of calculated DIC values for the peat and non-peat area is 6. ~~freshwater DIC values is 9. All errors were calculated with error propagation.~~

For the calculation of total CO_2 emissions from FCO_2, the river surface area was required. River surface area was calculated from the GRWL (Global River Widths from Landsat) Database (Allen & Pavelsky, 2018) using Esri's ArcMap 10.5. Missing segments in the delta were manually delineated using a Landsat satellite image and their surface area was determined. This procedure is described in the Supplement. With the surface area of individual river segments at hand, CO_2 emissions were calculated for the non-peat area, peat area and the delta separately.

~~The freshwater CO_2 emissions were calculated from the average CO_2 flux and the assumption that the river surface area corresponds to 0.89% of the catchment size (average for COSCAT 1328, Raymond et al., 2013). As the river widens~~

substantially in the delta (estuary and peat area), the water surface area in the delta was derived using ArcMap 10.5. The procedure was similar to the one employed by Müller et al. (2016) and is described in the Supplement.

The contribution of non-peat river CO_2 to delta emissions was then calculated according to Rosentreter et al. (2018):

$$Nonpeat\ contribution(\%) = (\frac{F_{Nonpeat}}{F_{Delta}} \cdot 100) \quad (6),$$

where $F_{Nonpeat}$ is the lateral CO_2 flux from the non-peat area (g d^{-1}) and F_{Delta} are the CO_2 emissions from the delta (g d^{-1}). The lateral CO_2 flux from the non-peat area was calculated from riverine excess CO_2:

$$Riverine\ excess\ CO_2 = DIC_{Insitu} - DIC_{Equilibrium} \quad (7),$$

where DIC_{Insitu} was the freshwater average from calculated DIC (wet) and from our measurements (dry) and $DIC_{Equilibrium}$ was calculated using CO_2Sys.

A non-peat contribution of 100% means that all the emissions in the delta can be explained by ventilation of non-peat CO_2. A non-peat contribution of >100% implies that some of the non-peat CO_2 is even exported to the ocean, while a non-peat contribution of <100% implies that in addition to non-peat CO_2, there are CO_2 sources in the delta.

3 Results

3.1 General characterization of the Rajang River

Measured salinity ranged between 0 and 18.6 during the wet season and 0 and 32.1 during the dry season. Saltwater was detected further upstream during the dry season than during the wet season (Fig. 3a and b). Saltwater penetrated further inland in the Rajang and Belawai distributaries than in the Igan distributary (Fig. 3b), suggesting that most freshwater is discharged via the Igan distributary.

The Rajang River was slightly acidic (6.7 (wet) and 6.8 (dry), area-weighted mean for the peat and non-peat area, see Table 2)(average pH = 6.7 and 6.8, see Table 1) and highly turbid, with area-weighted average SPM concentrations of 187.2 ± 75.7 179 mg L^{-1} (wet season) and 51.5 ± 12.1 48 mg L^{-1} (dry season) on average (Table 1, see Table 2). With higher SPM during the wet season (p=0.005<0.001), the organic carbon content of SPM was significantly decreased (1.5 ± 0.4 % on average, p=0.01)(1.6% on average, p=0.0007) if compared to the dry season (2.1 ± 0.6 % on average, see Table 2)(2.3 % on average, see Table 1). POC ranged from 0.7 mg L^{-1} to 9.1 mg L^{-1} during the wet season (average 2.6 ± 0.6 mg L^{-1})(freshwater average 2.9 mg L^{-1}, see Table 1) and from 0.3 mg L^{-1} to 1.9 mg L^{-1} during the dry season (freshwater average 1.1 ± 0.4 mg L^{-1}, see Table 21). The seasonal difference was significant (p=0.0012).

The river water was consistently undersaturated with oxygen with respect to the atmosphere. DO oversaturation was not observed. The area-weighted average DO was similar during the wet and dry seasons (81.1 ± 5.5 % and 79.6 ± 3.5 %, wet/dry), with slightly lower DO in the delta (66.0 ± 6.9 % and 71.2 ± 11.1 % (wet/dry)).

DO averaged 76.8 ± 9.9 % (wet season) and 75.0 ± 7.0 % (dry season, see Table 1) and was on average lower in the peat area (73.0% (wet) and 68.1% (dry)) and in the estuary (68.9% (wet) and 74.3% (dry)) than in the non-peat area (81.1% (wet) and 79.8% mg L^{-1} (dry), see Table 2).

Measured DIC in the dry season ranged from 153.7 µmol L^{-1} in the non-peat area to 2399.2 µmol L^{-1} in the estuary and varied increased linearly with salinity (Fig. 4a, $r = 0.98$, $p<0.001$). Concentrations averaged 177.9 ± 22.4 µmol L^{-1} in the peat and non-peat area and 1302.3 ± 749.2 µmol L^{-1} in the delta (Table 2). Calculated DIC for the wet season averaged 289.8 ± 32.1 µmol L^{-1} (area-weighted mean for the non-peat and peat area). The freshwater average was 203.9 µmol L^{-1} (Table 1). DIC was slightly higher ($p=0.044$) in the peat area (235.1 ± 74.3 µmol L^{-1}) than in the non-peat area (177.9 ± 20.4 µmol L^{-1}) and highest in the estuary (1531.1 ± 593.1 µmol L^{-1}, Table 2). Calculated DIC for the wet season averaged 301.3 µmol L^{-1}. δ^{13}C-DIC ranged between -11.87 9 ‰ and -1.4 ‰ and averaged –7.0 ± 1.5 ‰ in the peat and non-peat area and -5.9‰ in the delta (Table 2) -8.06 ‰ (freshwater average, Table 1). δ^{13}C-DIC was positively correlated with DIC for the delta ($r = 0.81$, $p<0.001$) estuary ($r = 0.70$) and negatively correlated with DIC for the freshwater part (peat and non-peat combined, $r = -0.98$, $p=0.004$, Fig. 4b). A Keeling plot revealed a linear relationship for freshwater samples (Fig. 4c) with a y-intercept (± SE) of -18.6 ± 0.3 ‰.(peat and non-peat combined, $r = -0.87$, Fig. 4b). While Figure 4 indicates that there might be a difference between peat and non-peat samples, the difference was not significant due to the lack of samples.

3.2 Carbon dioxide

The Rajang River was found to be oversaturated with CO_2 with respect to the atmosphere, with an average freshwater pCO_2 of 2531 ± 188 2919 µatm (wet season) and 2337 ± 304 2732 µatm (dry season) in the non-peat area, see Table 1). The pCO_2 and its spatial distribution were strikingly similar during the wet and dry seasons (Fig. 3c and d).. pCO_2 was significantly higher in the peat area ($p<0.001$, both seasons) with 2990 ± 239 µatm (wet season) and 2994 ± 141 µatm (dry season). The area-weighted means for the peat and non-peat area were 2540 ± 189 uatm (wet season) and 2340 ± 301 uatm (dry season). In the delta, pCO_2 was more variable, and the average values of 3005 ± 1039 µatm (wet season) and 2783 ± 1437 µatm (dry season, see Table 2) were also significantly higher than in the non-peat area ($p<0.001$, both seasons). pCO_2 values were strikingly similar between wet and dry season, and so were the spatial patterns in pCO_2 (Fig. 3c and d). Tidal variability of pCO_2 was observed at an overnight station in Sarikei in August 2016. During this time, pCO_2 increased from approximately 3000 µatm to almost 6000 µatm during rising tide (see Supplement).pCO_2 was significantly higher ($p<0.0001$) in the peat area (3472 µatm (wet) and 3053 µatm (dry)) than in the non-peat area (2531 µatm (wet) and 2337 µatm (dry), see Table 2 and Fig. 3c and d). In the estuary, pCO_2 was lower during the wet season (2046 µatm) with an average estimated salinity of 16.5, and higher during the dry season (2608 µatm) with an average estimated salinity of 25.0. Note that this difference may reflect the different sampling strategies (more and different distributaries were included in the dry season survey). Tidal variability of pCO_2 was observed at an overnight station in Sarikei in August 2016. During this time, pCO_2 increased from approximately

3000 µatm to almost 6000 µatm during rising tide (not shown), so the timing of our measurements in the delta relative to the tidal conditions probably also impacted the average values for the estuary.

pCO_2 decreased with increasing salinity in the estuary delta (Fig.3). However, a big spread of data in both the high-salinity region (during the tidal measurement described above) and the freshwater region was observed. pCO_2 was correlated with DO (Fig. 5). An interesting pattern is consistently visible in both the wet and dry season data, by which main stem data can clearly be distinguished from those collected in the Belawai and Paloh distributaries. Unfortunately, our data did not allow identification of a diurnal signal for either pCO_2 or DO. In the tidal part of the river, we had only the one stationary measurement overnight, when a diurnal signal could not be identified due to the strong tidal signal. In the non-tidal part of the river, we had insufficient night-time data to make a statement about a day-night difference for pCO_2 and DO.Night time measurements beyond the tidal part of the river were too few to make a sound statement about a difference between day- and night time pCO_2 and DO.

Wind speed in the grid centered at 2.85°N, 112.5°E averaged 0.57 m s^{-1} during our campaign in January 2016 and 1.09 m s^{-1} during our campaign in August 2016 (Table 2). The calculated gas exchange velocities for a Schmidt number of 600 using the B04 model ($k_{600,\ B04}$) were 8.23 cm h^{-1} and 9.57 cm h^{-1}, respectively. This compares to the A11 model with 8.51 cm h^{-1} and 12.19 cm h^{-1} and to the R01 model with 2.32 cm h^{-1} and 2.79 cm h^{-1} for the wet and dry season, respectively. The resultant CO_2 fluxes (FCO_2) to the atmosphere ranged between 0.5 and 2.4 gC m^{-2} d^{-1} in the wet season and between 0.6 and 3.5 gC m^{-2} d^{-1} in the dry season (per water surface unit area, see Table 2).

Fluxes reported in this study are calculated from the B04 model, which yielded intermediate values. It was chosen because it recognizes flow velocity as a driver of turbulence in addition to wind speed. Results for the other two models are compared in the Supplement. The resultant CO_2 fluxes (FCO_2) to the atmosphere were 2.28 ± 0.52 gC m^{-2} d^{-1} in the wet season and 2.45 ± 0.45 gC m^{-2} d^{-1} in the dry season (per water surface unit area, see Table 2).

3.3 Carbon river load and CO_2 emissions

Discharge was above average in the yearsduring 2016 and 2017 (Fig. 2a). Discharge during January 2016 (wet season) was in accordance with the long-term average, but discharge during August 2016 (dry season) was higher than usual. The Rajang River loads for the peat and non-peat area were 104 (82-123) 146 ± 45 GgC in January 2016 and 65 (45-83) 99 ± 25 GgC in August 2016; another 31 (12-41) (wet) and 34 (12-51) Gg were emitted as CO_2 from the delta (Table 3). Of the river loads of carbonthis, 91 (86-97) % (wet) and 82 (70-94) % (dry) 78 ± 5% (wet) and 65 ± 7% (dry) were exported laterally by discharge. Approximately half of the laterally transported carbon river load was in the organic form (58 57 ± 2712% and 57 60 ± 1718%, wet/dry). River loads were similar during both seasons, except that POC export was 3-fold higher in the wet season. CO_2 emissions to the atmosphere accounted for 9 (3-14) % and 18 (6-30) % (wet/dry) of the total carbon load of the river.for 22 ± 5% and 35 ± 7% (wet/dry) of the total carbon load of the river and 55 ± 24% and 59 ± 24% (wet/dry) of the combined

~~CO_2+DOC export (CO_2/DOC flux ratio as calculated in Wit et al., 2015). The non-peat contribution to delta emissions was 126 ± 66 % in the wet season and 54 ± 52 % in the dry season.~~

4. Discussion

4.1 ~~Organic carbon load and sediment yield~~Sediment yield and organic carbon load

~~The proportion of laterally transported carbon in the Rajang River that is in organic form (58 ± 27% and 57 ± 17%, wet/dry) is similar to what has been reported for the carbon flux to the South China Sea (50 ± 14%, Huang et al., 2017). Likewise, the CO_2/DOC flux ratio of 55 ± 24% and 59 ± 24% (wet/dry) is in agreement with the average for Southeast Asian rivers of 54 ± 7% (Wit et al., 2015).~~

The Asia-Pacific region is known for its high sediment yields, especially where rivers drain Cenozoic sedimentary and volcanic rock (Milliman and Farnsworth, 2011). Therefore, the high suspended sediment load in the Rajang River is not surprising. However, SPM concentrations during our expeditions were substantially lower (187.2 ± 75.7 mg L^{-1} and 51.5 ± 12.1 mg L^{-1}) ~~(179.2 mg L^{-1} and 47.8 mg L^{-1})~~ than in July 1992 (613 mg L^{-1}, Staub and Esterle, 1993). This could be an effect of upstream dams (operational since 2011 and 2015), which trap sediment in their reservoirs, thereby reducing downstream sediment loads (Vörösmarty et al., 2003, Snoussi et al., 2002). In support of this, SPM concentrations were intermediate in the upper Rajang River in 2014/2015 (218.3 mg L^{-1}; Ling et al., 2017). These measurements were taken before, and the measurements in the current study were taken after, the Murum dam began full operation in the second quarter of 2015. Furthermore, SPM and POC concentrations (2.6 mg L^{-1} and 1.1 mg L^{-1}, wet/dry) ~~(2.9 mg L^{-1} and 1.1 mg L^{-1})~~ in the Rajang River were similar to those in the Pearl River, China, (SPM: 70 mg L^{-1} -247 mg L^{-1}, POC: 1.0 mg L^{-1} -3.8 mg L^{-1}, Ni et al., 2008) and the Red River, Vietnam, (SPM: 294 ± 569 mg L^{-1} (wet) and 113 ± 428 mg L^{-1} (dry), POC: 3.7 ± 2.0 mg L^{-1} (wet) and 1.1 ± 1.1 mg L^{-1} (dry), Le et al., 2017), both of which are also affected by damming.

SPM was higher during the wet season than during the dry season in agreement with observations at the Kinabatangan River, Malaysia (Harun et al., 2014). This can be attributed to enhanced erosion during the wet season. In logged-over forest, as found in most of the Rajang River basin, the energy impact of rain drops on the soil is higher than in densely vegetated areas, where rain ~~drops are~~is intercepted by the canopy before falling on the ground (Ling Lee et al., 2004). In agreement with this line of reasoning, Ling et al. (2016) showed that the amount of suspended solids in Malaysian streams draining areas with logging activities increased significantly after rain events. The decreased organic carbon content observed during the wet season further supports this, as it indicates a higher contribution of eroded mineral soil to SPM. This pattern is observed in many rivers in this region (Huang et al., 2017). Despite the changing carbon content, most POC was still exported during the wet season, as in other Southeast Asian rivers (Ni et al., 2008; Moore et al., 2011). The proportion of laterally transported carbon in the Rajang River that is in organic form (57 ± 12 % and 60 ± 18%, wet/dry) is similar to that reported for the carbon flux to the South China Sea (50 ± 14%, Huang et al., 2017).

4.2 Inorganic carbon load

4.2.1 DIC concentrations and sources

DIC concentrations in the Rajang River (203.9 µmol L^{-1} in the dry season and 301.1 µmol L^{-1} in the wet season) were comparable to those reported by Huang et al. (2017) for the Rajang River (201 µmol L^{-1} and 487 µmol L^{-1}), but substantially lower than reported for the Mekong River (1173-2027 µmol L^{-1}, Li et al., 2013) and the Pearl River (1740 µmol L^{-1}, Huang et al., 2017). DIC concentrations in the Rajang are similar to those in the Musi River, Indonesia (250 µmol L^{-1}, Huang et al., 2017), suggesting that the Rajang River compares better to the equatorial Indonesian rivers than to rivers draining mainland Southeast Asia, probably because of the scarcity of carbonate rock, which has the highest weathering rate and is thus responsible for high DIC in rivers (Huang et al., 2012).

The source of DIC varied along the length of the Rajang River. In the estuarine part, the positive linear relationship between DIC and salinity (Fig. 4a) suggests that the main source of DIC in the estuary is marine. This is also supported by the relatively high δ^{13}C-DIC of estuarine samples, as ocean DIC is more enriched with δ^{13}C-DIC between 0 and 2.5 ‰ (Rózanski et al., 2003). The positive relationship correlation between DIC and δ^{13}C in the delta thus implies an increasing contribution of marine DIC.

In the freshwater part of the Rajang River, δ^{13}C values were more depleted (-7.0 ± 1.5 ‰, Table 2) than downstream(-8.1 ‰ on average), but higher were more enriched than δ^{13}C-DIC values reported for other rivers in the region than those reported for the (Lupar and Saribas Rivers in Sarawak, (-15.7 ‰ to -11.4 ‰, Müller et al., 2016;) or for the Musi, Indragiri and Siak Rivers in Indonesia, (-22.5 ‰ to -9.0 ‰, Wit, 2017).

Multiple sources and processes are likely to influence δ^{13}C-DIC in the Rajang River. To start with, the y-intercept of the Keeling plot for freshwater samples suggests that the initial freshwater source has a δ^{13}C-DIC of -18.6 ‰, which is consistent with δ^{13}C values of bicarbonate from silicate weathering with soil CO_2 from C3 plants (-22.1 to -16.1 ‰, Das et al., 2005). This is consistent with the assumption that only minor amounts of carbonates, which yield ^{13}C-enriched DIC (Das et al., 2005), are present in the catchment (Staub et al., 2000). Another relevant source is rainwater DIC with a typical δ^{13}C of -9.3 ‰ (Das et al., 2005). In a river with relatively low DIC (177.9 µmol L^{-1}) and large surface runoff due to heavy rain, this source term is presumably non-negligible, and a significant contribution would partially explain the relatively high δ^{13}C-DIC values.

With regard to in-stream processes, photosynthesis increases and respiration decreases δ^{13}C-DIC (Campeau et al., 2017). Due to the high turbidity, it can be assumed that photosynthesis in the Rajang River is negligible. In contrast, the correlation of DO and pCO_2 (Fig. 5) suggests that respiration is important. This assumption is supported by the negative correlation of δ^{13}C and DIC for freshwater samples, because with increasing DIC, δ^{13}C values get more depleted, suggesting that organic carbon (with a δ^{13}C of around -26 ‰ for C3 plants, Rózanski et al., 2003) is respired to CO_2 within the river. However, we observed overall relatively high δ^{13}C values. Two processes are likely to be responsible for the downstream increase in δ^{13}C: (1) Methanogenesis and (2) evasion of CO_2. (1) Campeau et al. (2018) observed a strong relationship between CH_4 concentration and δ^{13}C-DIC in a boreal stream draining a nutrient-poor fen, suggesting that fractionation during methanogenesis leads to an increase in δ^{13}C-DIC. As the peat soils in the Rajang delta are also anaerobic and nutrient-poor, it is likely that methanogenesis plays a role there as well. This is consistent with high reported soil CH_4 concentrations of up to 1465 ppm in a peat under an oil palm plantation in Sarawak (Melling et al., 2005). It would therefore be of high interest to investigate CH_4 concentrations in the Rajang River in the future. (2) CO_2 evasion is also known to lead to a gradual increase of δ^{13}C-DIC values until in equilibrium with the atmosphere (with δ^{13}C-DIC around +1 ‰, Polsenare and Abril, 2012; Venkiteswaran et al., 2014; Campeau et al., 2018). Due to intracarbonate equilibrium fractionation, dissolved CO_2 is more depleted in δ^{13}C than the other carbonate species. Thus, if it is removed, δ^{13}C of the remaining DIC increases. This effect depends on pH and is more pronounced in near-neutral waters and less strong in very acidic water (Campeau et al., 2018). We sampled the lower river reaches downstream of Kapit, which corresponds to approximately the last 200 kilometers of the river. In addition, the terrain is much steeper upstream of Kapit than in the lower river reaches, so that CO_2 fluxes to the atmosphere are presumably much higher due to higher turbulence. This means that a large fraction of CO_2 had likely already been emitted from the river surface before reaching Kapit, leading to the observed high δ^{13}C-DIC values. Groundwater DIC usually has a δ^{13}C of -16 ‰ to -11 ‰ (Rózanski et al., 2003), depending on the soil CO_2 and the weathered rock material. While DIC from silicate weathering is more depleted, DIC from carbonate weathering is more enriched due to the contribution of carbonate-C to DIC (Das et al., 2005). Atmospheric CO_2, as present in rain water, has a δ^{13}C of around -8.3 ‰ (at Bukit Kototabang, Indonesia, in 2014, White et al., 2018). In-stream processes affect δ^{13}C-DIC as well: respiration of DOC decreases δ^{13}C, while photosynthesis increases δ^{13}C (Rozanski et al., 2003; Campeau et al., 2017). CO_2 evasion gradually leads to higher δ^{13}C values until in equilibrium with the atmosphere (with δ^{13}C-DIC around +1 ‰, Polsenaere and Abril, 2012).

It can be assumed that DIC in the Rajang River stems from a combination of these sources. The relatively high δ^{13}C in our samples suggests that carbonate weathering could play a role; however, only minor amounts of carbonates are present in the catchment (Staub et al., 2000). The contribution of rain-DIC to total DIC is non-negligible for a river with relatively low DIC (203.9 µmol L^{-1}), particularly in a catchment with heavy rainfall that leads to surface runoff, diluting DIC and enhancing δ^{13}C-DIC. With regard to in-stream processes, photosynthesis can be assumed to be negligible in the Rajang River due to its high turbidity, while respiration seems to be important due to the correlation of DO and pCO_2 (Fig. 5). This assumption is also supported by the negative correlation of δ^{13}C and DIC for freshwater samples, because with increasing DIC, δ^{13}C values get more depleted, suggesting that organic carbon (with a δ^{13}C of around -26 ‰ for C3 plants, Rózanski et al., 2003) is respired to CO_2 within the river. The overall relatively high δ^{13}C values can be explained by enrichment due to evasion of CO_2. Since we sampled the lower river reaches, it can be assumed that a large fraction of CO_2 had already been emitted from the river surface, leading to gradually higher δ^{13}C-DIC.

4.2.2 *p*CO_2

pCO_2 in the Rajang River (2919 µatm and 2732 µatm (wet/dry)) was higher than in most Southeast Asian rivers without peat influence, such as the Mekong River (*p*CO_2= 1090 µatm, Li et al., 2013), the Red River (*p*CO_2= 1589 µatm, Le et al., 2017) or the freshwater parts of the Lupar and Saribas Rivers (*p*CO_2= 1274 µatm and 1159 µatm, Müller et al., 2016, Table 4, Fig. 6). This could be attributed to the peat influence. However, the Rajang River has a *p*CO_2 at the low end of values reported for peat-draining rivers (Fig. 6): Wit et al. (2015) report values between 2400 µatm in the Batang Hari (peat coverage = 5%) and 8555 µatm in the Siak River (peat coverage = 22%).

A meaningful comparison is also the one between the Rajang River and the Indragiri River, Indonesia, because they have a similar peat coverage (Rajang: 11%, Indragiri: 12%) and peat coverage has previously been considered as a good predictor of river CO_2 emissions (Wit et al., 2015). However, *p*CO_2 in the Indragiri (5777 µatm) was significantly higher than in the Rajang, which can be attributed to a lower pH (6.3, numbers from Wit et al., 2015). To illustrate this, we ran a simple exercise using CO_2Sys. At the given temperature, salinity and pH, the *p*CO_2 of 5777 µatm in the Indragiri corresponds to a DIC value of 327 µmol L^{-1}. At a hypothetical pH of 6.8, as measured in the Rajang River, this DIC value corresponds, under otherwise unchanged conditions, to a *p*CO_2 of 2814 µatm – which is very close to the average values measured in the peat area ofmeasured in the Rajang River. This shows that pH is a major determinant for a river's *p*CO_2 (Ruiz-Halpern et al., 2015), and that the peat coverage in a river basin is insufficient as sole predictor of CO_2 fluxes. Rather, pH must be taken into account as well, and its drivers must be considered. δ^{13}C-DIC in the Indragiri was lower (-16.8 ‰, Wit, 2017) than in the Rajang (-8.17.0 ‰), implying that respiratory CO_2 is more dominant in the Indragiri, while the Rajang might be more strongly influenced by weathering, which could explain the higher pH. Note also that peat coverage is usually reported for the entire catchment (e.g., Wit et al, 2015; Rixen et al., 2016) and does not reveal how much peat is found in estuarine vs. freshwater reaches, which makes comparisons more difficult.

While DOC and *p*CO_2 are positively related to discharge in most rivers (e.g., Bouillon et al., 2012), this pattern is sometimes reversed in peat-draining rivers. This is due to dilution, when rainfall exceeds the infiltration capacity of the wet soil and water runs off at the surface (Clark et al., 2008; Rixen et al., 2016). In the Rajang River, *p*CO_2 was slightly higher in the non-peat area during the wet season in agreement with many non-peat-draining tropical rivers (Bouillon et al., 2012; Teodoru et al., 2014; Scofield et al., 2016). However, the seasonality of *p*CO_2 was very small, similar to other Malaysian rivers (Müller et al., 2016) and in line with the small seasonal variability of DOC concentrations in the Rajang River (Martin et al., 2018). Note that since our data was collected during two single surveys, they represent only a snapshot and do not allow strong claims about seasonality.

Due to an El Nino event, temperatures in Southeast Asia were unusually high in late 2015 and 2016, with a temperature extreme in April 2016 prevailing in most of Southeast Asia (Thirumalai et al., 2017) and unusually hot conditions also recorded in Sibu (Fig. 2b). Given that weathering rates increase at elevated temperatures, DIC from weathering could have been enhanced over other years, although this seems unlikely because DIC was relatively low and in agreement with previous studies. Another factor to be taken into account is that decomposition in the dry upper soil layer is more intense at higher temperatures, and with incipient rainfall, all the resultant DOC is flushed out to the river. Therefore, it is possible that during the year of our measurements, DOC concentrations were higher than usual, and respiratory CO_2 may therefore have been enhanced compared to other years.

4.2.3 Impact of the peatlands on the CO_2 emissions from the Rajang River

The fact that pCO_2 was significantly higher in the peat area than in the non-peat area implies, at first glance, that the peat areas are a source of CO_2 to the river. However, ~~the~~ this difference ~~between peat and non-peat pCO_2~~ has to be interpreted with caution, as the entire peat area is under tidal influence (Fig. 1b). In the following, we will present several arguments that suggest that the peatlands exert only a small influence on the CO_2 emissions from the Rajang River.

a) DOC

One indicator of peatland influence on a river's carbon budget is DOC. DOC concentrations in the Rajang River delta were reported to range between 1.4 mg L^{-1} and 3 mg L^{-1} (Martin et al., 2018). This is at the low end of the range of DOC concentrations reported for peat-draining rivers in Indonesia: These range from 2.9 mg L^{-1} in the Musi River (peat coverage = 3.5%) up to 21.9 mg L^{-1} in the Siak River (peat coverage = 22%; Wit et al., 2015). Rivers whose catchment area is entirely covered by peat exhibit even higher DOC concentrations, with 52 mg L^{-1} (wet season) and 44 mg L^{-1} (dry season) in the Sebangau River, Indonesia (Moore et al., 2011), and 44 mg L^{-1} in the Maludam River, Sarawak, Malaysia (Müller et al., 2015). The Rajang River compares rather to rivers like Lupar and Saribas, Malaysia, which exhibit DOC concentrations of 1.8 mg L^{-1} and 3.7 mg L^{-1} in their freshwater parts (no peat influence, Müller et al., 2016). Consequently, DOC concentrations imply that the peatlands' influence on the Rajang's DOC is rather small.

~~**b) Non-peat contribution**~~

~~The non-peat contribution (as calculated according to Eq. (6) and (7)) is a measure of the fraction of delta CO_2 emissions that can be explained by upstream (non-peat) sources alone. This means that the non-peat contribution provides an indication of how important CO_2 sources within the delta (i.e., peat) are compared to upstream sources. During the wet season, the non-peat contribution was >100% (126 ± 66%), suggesting that upstream sources are sufficiently strong to explain all the CO_2 emissions in the delta, and that part of the upstream CO_2 was even transported to the ocean. However, this does not necessarily mean that there were no additional sources in the delta, as it is unknown how much CO_2 was exported to the ocean. During the dry season, the contribution of non-peat CO_2 was <100% (54 ± 52%) suggesting that upstream sources cannot explain all of the CO_2 emissions in the delta and that the remainder is derived from within the delta, i.e. net heterotrophy in the peat area and estuary.~~

~~Note that the calculated non-peat contributions have relatively large uncertainties, so these statements cannot be made with certainty.~~

b~~c~~) Mixing model

An alternative approach is to theoretically calculate the increase in Rajang River pCO_2 that would result from the influx from peatlands. For this, we created a simple model to simulate the mixing of two water masses (see Supplement), one with a pH of 6.8 and a pCO_2 of 2434 µatm (designed to resemble the Rajang River, non-peat area) and the other with a pH of 3.8 and a pCO_2 of 8100 µatm (designed to resemble peat-draining tributaries, based on values for the peat-draining Maludam River in Sarawak, Müller et al., 2015). For simplicity, we assumed that mixing occurs at salinity = 0 and that the temperature in both water bodies is the same (28.4°C). From these values, DIC and total alkalinity (TA) of the two water bodies were calculated using CO_2Sys. Since they can be assumed to be conservative, we simply calculated DIC and TA of the mixture as

$$DIC_{S=0} = (1 - pc) \cdot DIC_1 + pc \cdot DIC_2 \text{ and } TA_{S=0} = (1 - pc) \cdot TA_1 + pc \cdot TA_2 \qquad (8) \text{ and } (9),$$

where pc is the peat coverage in the basin (pc=0.11). From DIC and TA, the pCO_2 of the mixture was computed (pCO_2 = 3058 µatm). This means that if all peat-draining tributaries in the Rajang River basin had a pCO_2 of 8100 µatm and a pH of 3.8, the pCO_2 in the peat area would be enhanced by around 600 µatm. However, this increase in pCO_2 is obviously gradual. For example, at the city of Sibu, peat coverage was estimated at around 2%, for which the described mixing model yields a pCO_2 of 2548 µatm (Fig. S3). In most parts of the delta~~In the estuary~~, dilution with sea water already plays a role. Therefore, the mixing model was extended, assuming that at pc=3%, salinity is still zero and then linearly increases until pc=11%, S = 32, $DIC_{S=32}$ = 2347 µmol L^{-1} and $TA_{S=32}$ = 2324 µmol L^{-1} (two end-member mixing model, see Supplement). As a result, pCO_2 would theoretically not exceed 2605 µatm if the peat-draining tributaries were the only source of CO_2 ~~in the delta~~downstream of Kanowit (Fig. S3).

However, pCO_2 in the peat area was ~~3472~~ 2990 µatm (wet) and ~~3053~~ 2994 µatm (dry) and 3005 µatm (wet) and 2783 µatm (dry) in the delta, so there must be another source of CO_2. Since pCO_2 in Sarikei varied 2-fold with the tidal cycle, it seems likely that a large part of the difference in pCO_2 between non-peat area and peat area is actually a difference between river and tidal river. Tidal variability is often seen in estuaries (e.g., Bouillon et al., 2007, Oliveira et al., 2017), largely due to conservative mixing. However, during rising tide in Sarikei, we observed pCO_2 values of almost 6000 µatm, which is higher than the freshwater end-member, suggesting that other effects also play a role. Among those are decomposition of organic matter in intertidal sediments (Alongi et al., 1999, Cai et al., 1999) and subsequent transport of the produced CO_2 to the river, as well as groundwater input (Rosentreter et al., 2018).

c~~d~~) δ^{13}C-DIC

If the peatlands acted as a significant source of CO_2 to the Rajang River, this would also have to be visible in the δ^{13}C-DIC values. In the peat-draining Maludam River, δ^{13}C-DIC averaged -28.55 ‰ (Müller et al., 2015). Thus, it would be expected that the influx of peat-draining tributaries to the Rajang River would decrease δ^{13}C-DIC. This was not observed. ~~Although δ^{13}C-DIC in the Rajang River appeared lower in the peat area than in the non-peat area (Fig. 4b), this difference was not significant.~~ We were therefore unable to discern a large impact of peatlands on the DIC budget of the Rajang River. It is possible that, because the peatlands are located close to the coast in this system, mixing with sea water occurs before significant effects on the pCO_2 are theoretically possible. This means that not only the peat coverage in the catchment is relevant, but also how much of this peat is found in ~~the~~ estuarine reaches. These findings support the arguments of Müller et al. (2015) and Wit et al. (2015) that material derived from coastal peatlands is swiftly transported to the ocean, explaining why peat-draining rivers may not necessarily be strong sources of CO_2 to the atmosphere.

5. Conclusions

The Rajang River is a typical Southeast Asian river, transporting large amounts of terrestrial material to the South China Sea. ~~The derived fractions of evaded versus laterally transported carbon are in agreement with other rivers draining into the South China Sea.~~ In contrast to other Southeast Asian rivers with similar peat coverage, the impact of the peatlands on the Rajang River's pCO_2 appeared to be rather small, probably due to the proximity of the peatlands to the coast. As a consequence, CO_2 emissions from the Rajang River were moderate compared to other Southeast Asian rivers and low if compared to Southeast Asian peat-draining rivers.

Data availability

Calibrated data used in this manuscript are available as a Supplementary Table to this manuscript. Raw data are available at the Institute of Environmental Physics, University of Bremen, Bremen, Germany.

Author contribution

DMD, TW, TR and MM designed this study. DMD performed all measurements and sample preparations during the first survey, AC, AB and MM performed the measurements and sample preparations during the second survey. JO and BE analyzed the DIC and isotopic data, DMD analyzed all other data. All co-authors contributed to the interpretation and discussion of the results. DMD prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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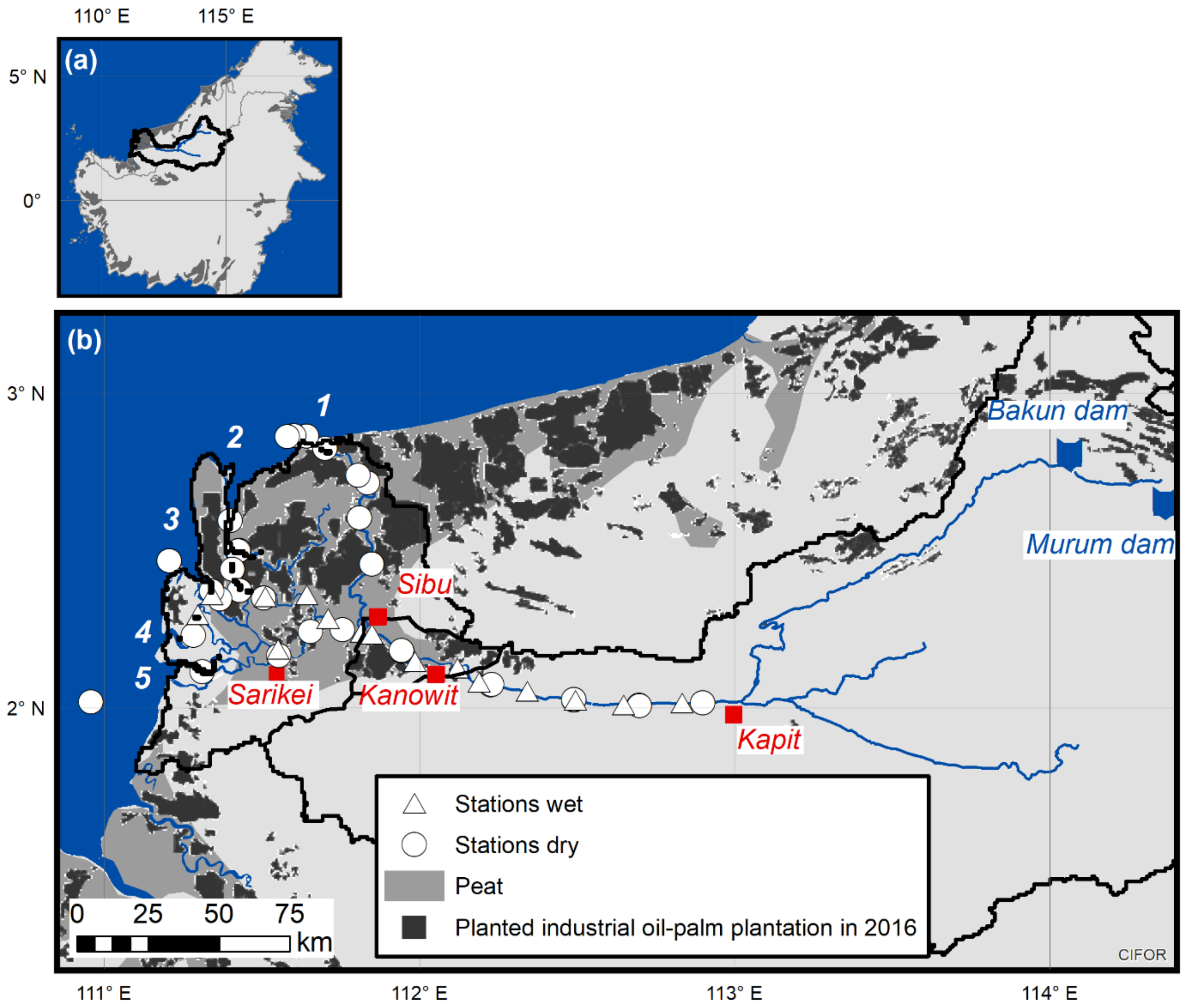
110° E
115° E
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(a)
(b)
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1
2
3
4
5
Sibu
Sarikei
Kanowit
Kapit
Bakun dam
Murum dam
Stations wet
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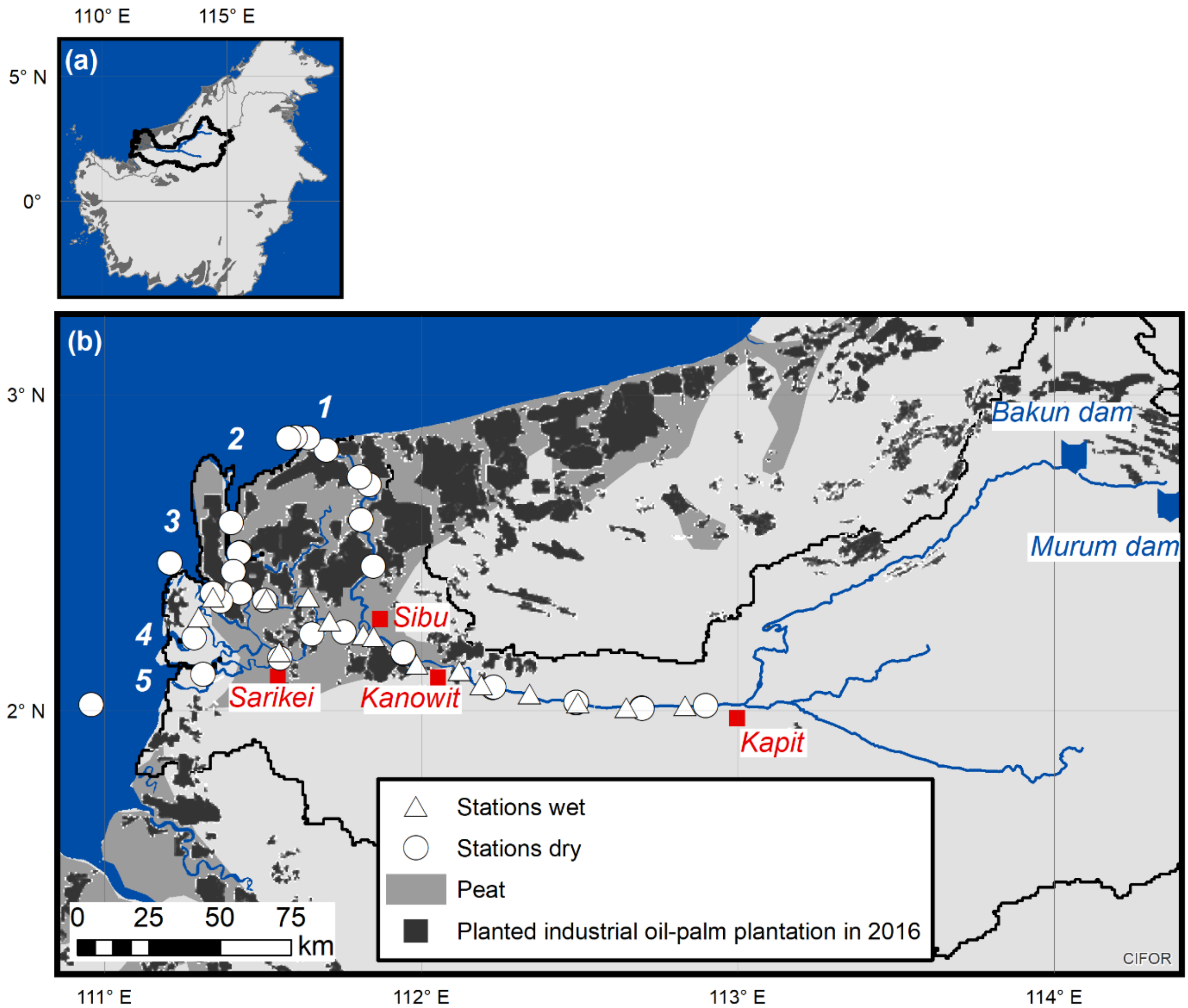
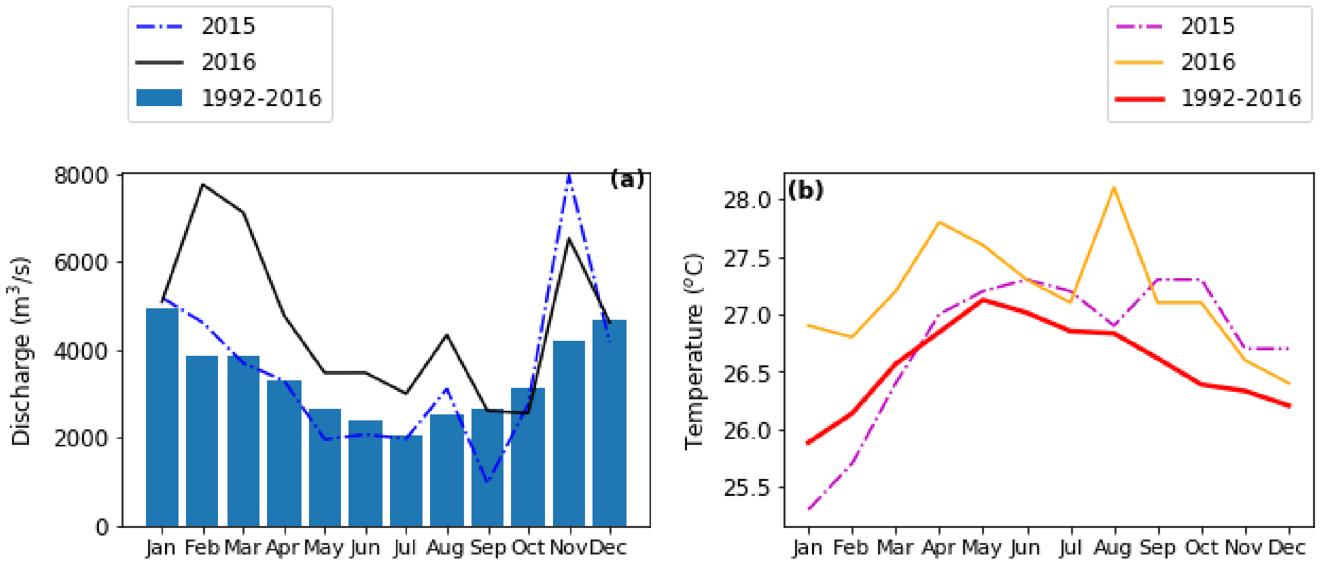


Figure 1: Map of the Rajang basin on the island of Borneo (a) and a close-up of the basin (b) including the location of the peatlands (Nachtergaele et al., 2009), industrial oil palm plantations (Gaveau et al., 2016) and the stations during the cruise. The distributaries are marked with numbers: 1-Igan, 2-Lassa, 3-Paloh, 4-Belawai, 5-Rajang.



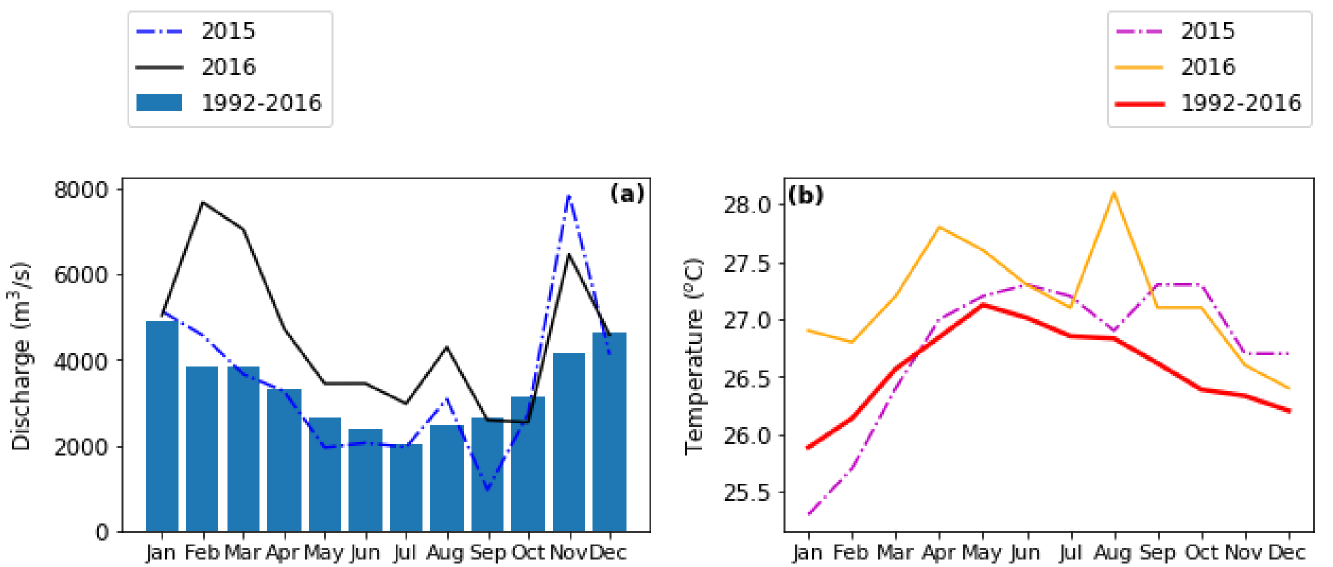


Figure 2: Monthly discharge calculated for the Rajang River (a) and average temperatures (b) for the city of Sibu (2° 20' N, 111° 50' E) for the years 2015, 2016 and the long-term average from 1992-2016. Data from DWD (2018).

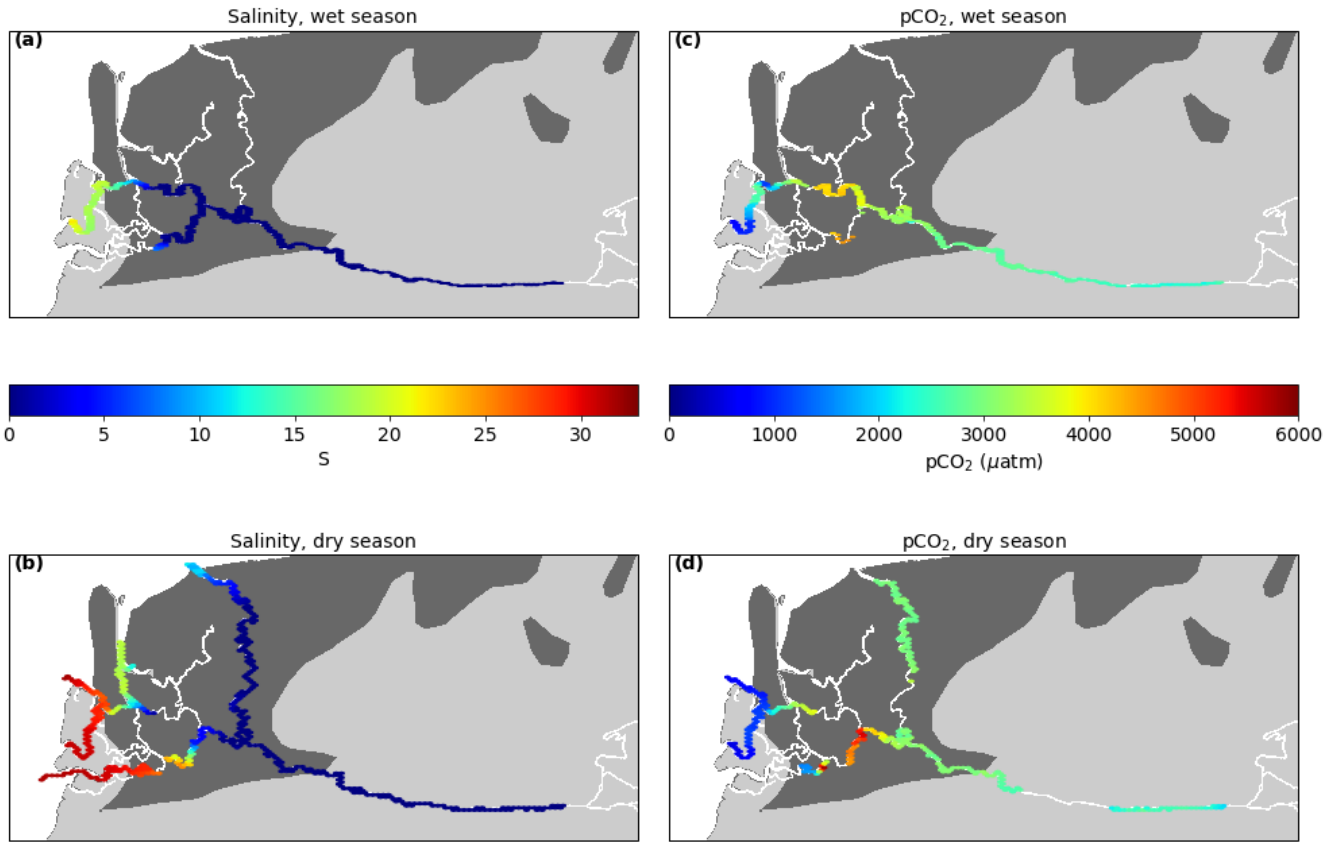


Figure 3: Salinity (interpolated) and *p*CO_2 distribution in the Rajang River and delta during the wet season survey (a,c) and dry season survey (b,d).

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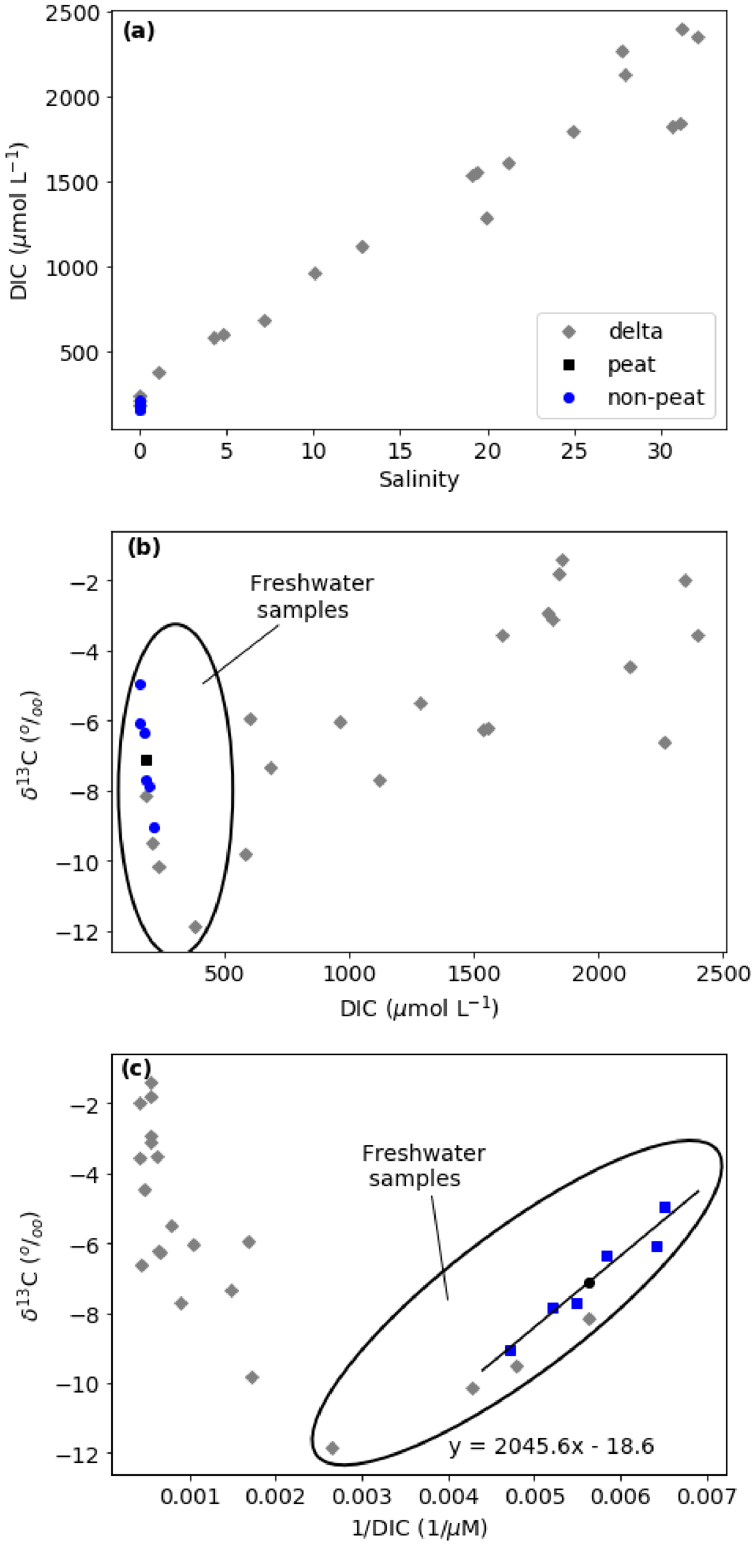

(a)
DIC (μmol L⁻¹)
Salinity
delta
peat
non-peat
(b)
Freshwater samples
δ13C (‰)
DIC (μmol L⁻¹)
(c)
Freshwater samples
y = 2045.6x - 18.6
δ13C (‰)
1/DIC (1/μM)

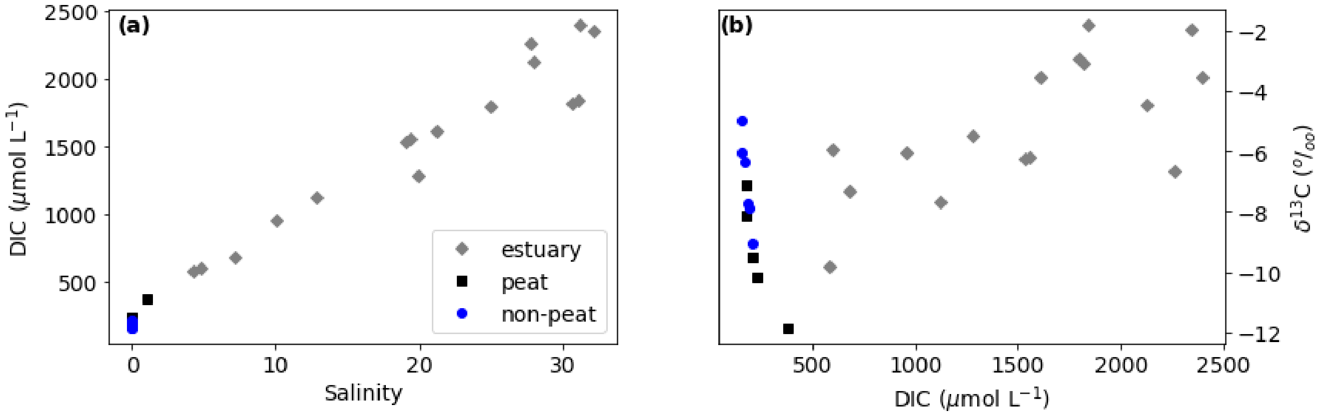


Figure 4: DIC versus salinity (a),– δ^{13}C versus DIC (b) and a Keeling plot of δ^{13}C versus 1/DIC for non-peat, peat and delta samplesand δ^{13}C versus DIC for the estuary and freshwater (=peat + non-peat) samples, respectively. Freshwater samples, including those from the delta region, are circled in in panel b and c. All data refer to dry season samples.

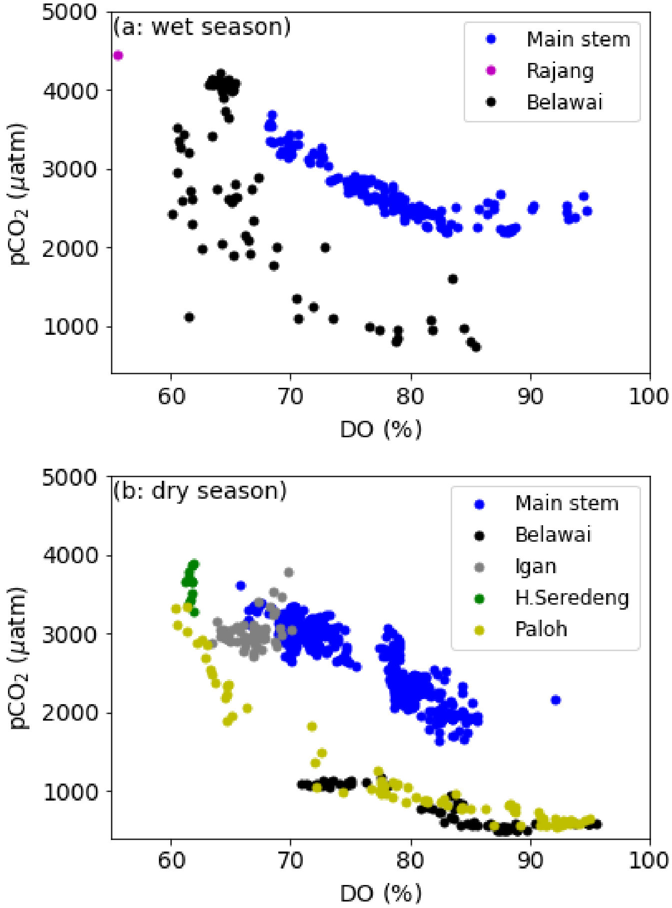
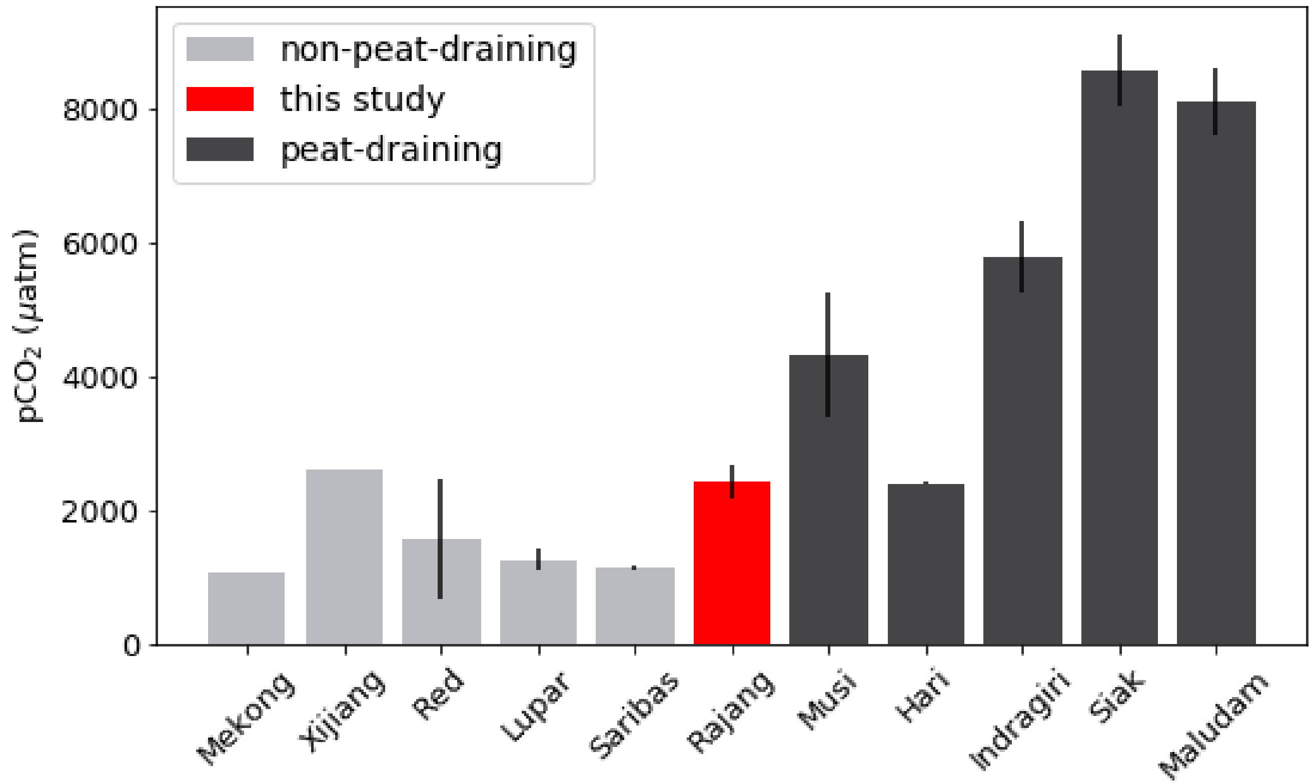


Figure 5: Correlation of *p*CO_2 versus dissolved oxygen (DO) in the wet and dry season for individual distributaries.



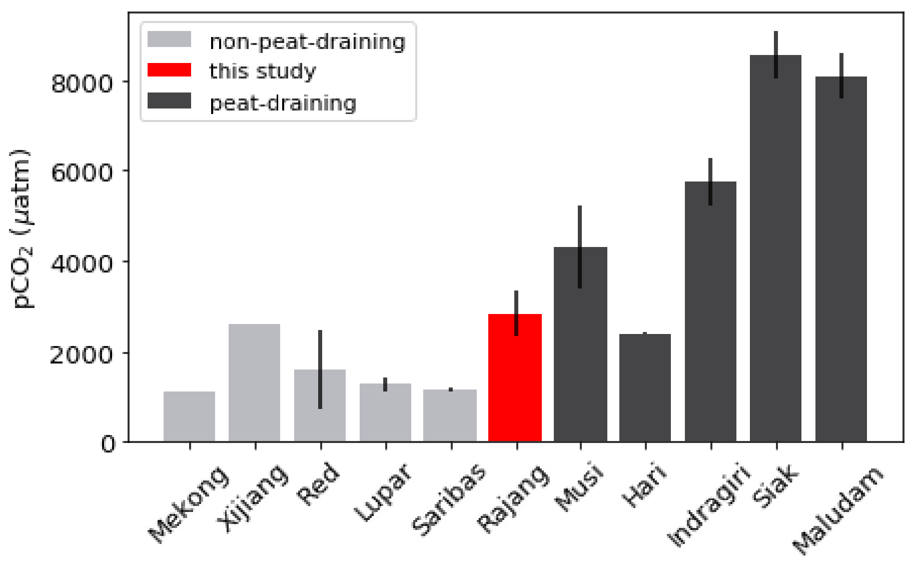


Figure 6: Comparison of average *p*CO_2 values in Southeast Asian rivers. Colors distinguish peat-draining rivers from non-peat-draining rivers. The Rajang River (this study) is highlighted in red.

Table 1: Definition of the different areas considered in this study.

	Non-peat	**Peat**	**Delta**
Description of geographical extent	Source to Kanowit	Kanowit to Sibu	Sibu to coast
Definition of geographical extent	lon >112.1000	112.1000 ≥lon ≥111.8193, lat ≤2.2831	lon <111.8193 or lat >2.2831
Water surface area (km^2)	167.5	34.3	553.0
Corresponding catchment area (km^2)	43550.5	899.6	7559.5
Tidal influence	None	Tidal	Tidal
Influence of salinity	Freshwater	Freshwater	Brackish

Table 1: Average values for the freshwater part of the Rajang River (salinity ≤2) ± 1 standard error (SE). Results for k_{600} and FCO_2 are based on the B04 *k*-parameterization. *denotes a calculated, not measured value.

	Wet	**Dry**
DO (%)	76.8 ± 9.9	75.0 ± 7.0
pH	6.7 ± 0.1	6.8 ± 0.1
T (°C)	27.5 ± 0.3	29.2 ± 0.9
SPM (mg L^{-1})	179.2 ± 74.7	47.8 ± 17.1
POC (mg L^{-1})	2.9 ± 1.9	1.1 ± 0.4
%OC in SPM	1.6 ± 0.5	2.3 ± 0.5
pCO_2 (µatm)	2919 ± 573	2732 ± 443
DIC (µmol L^{-1})	301.3 ± 44.4*	203.9 ± 59.6
δ^{13}C-DIC (‰)	n.d.	-8.06 ± 1.90
u_{10} (m s^{-1})	0.57	1.09
k_{600} (cm h^{-1})	8.23	9.57
FCO_2 (gC m^{-2} d^{-1})	2.28 ± 0.52	2.45 ± 0.45

Table 2: Average values of measured parameters for different river reaches (mean ± 1SE) for all parameters except FCO2, which is reported as mean (minimum – maximum).

		Non-peat	Peat	Weighted mean peat/non-peat	Delta
Average salinity	**Wet**	0	0	0	7.1± 8.6 (n=566)
	Dry	0	0	0	16.0 ± 13.5 (n=2510)
Temperature (°C)	**Wet**	27.4 ± 0.4 (n=152)	28.7 ± 1.2 (n=89)	27.4 ± 0.4	28.6 ± 1.0 (n=126)
	Dry	28.4 ± 0.6 (n=628)	29.6 ± 0.2 (n=130)	28.4 ± 0.6	30.3 ± 2.6 (n=787)
SPM (mg L^{-1})	**Wet**	188.9 ±76.9 (n=6)	104.5 ± 16.7 (n=2)	187.2 ± 75.7	162.4 ± 88.3 (n=7)
	Dry	51.9 ± 12.3 (n=7)	33.1 ± 2.5 (n=2)	51.5 ± 12.1	68.3 ± 31.6 (n=22)
POC (mg L^{-1})	**Wet**	2.6 ± 0.6 (n=6)	1.8 ± 0.0 (n=2)	2.6 ± 0.6	2.9 ± 2.8 (n=7)
	Dry	1.1 ± 0.4 (n=7)	0.8 ± 0.0 (n=2)	1.1 ± 0.4	1.0 ± 0.4 (n=22)
OC content in SPM (%)	**Wet**	1.5 ± 0.4 (n=6)	1.7 ± 0.3 (n=2)	1.5 ± 0.4	1.6 ± 0.6 (n=7)
	Dry	2.1 ± 0.6 (n=7)	2.5 ± 0.0 (n=2)	2.1 ± 0.6	1.5 ± 0.7 (n=22)
O_2 (%)	**Wet**	81.1 ± 5.4 (n=152)	80.8 ± 9.2 (n=89)	81.1 ± 5.5	66.0 ± 6.9 (n=126)
	Dry	79.8 ± 3.5 (n=628)	71.6 ± 1.3 (n=130)	79.6 ± 3.5	71.2 ± 11.1 (n=787)
pH	**Wet**	6.7 ± 0.1 (n=6)	6.6 ± 0.1 (n=2)	6.7 ± 0.1	6.9 ± 0.5 (n=7)
	Dry	6.8 ± 0.0 (n=7)	6.8 ± 0.0 (n=2)	6.8 ± 0.0	7.3 ± 0.5 (n=24)
DIC (µmol L^{-1})	**Wet***	290.8 ± 32.8* (n=5)	243.6* (n=1)	289.8 ± 32.1	338.1 ± 41.9* (n=7)
	Dry	177.9 ± 22.4 (n=6)	177.6 (n=1)	177.9 ± 22.4	1302.3 ± 749.2 (n=21)
δ^{13}C-DIC (‰)	**Dry**	-6.99 ± 1.47 (n=6)	-7.11 (n=1)	-7.0 ± 1.47	-5.90 ± 2.96 (n=21)
pCO_2 (uatm)	**Wet**	2531 ± 188 (n=703)	2990 ± 239 (n=170)	2540 ± 189	3005 ± 1039 (n=566)
	Dry	2337 ± 304 (n=1259)	2994 ± 141 (n=644)	2350 ± 301	2783 ± 1437 (n=2510)
FCO_2 (gC m^{-2} d^{-1})	**Wet**	1.5 (0.5-2.0)	1.8 (0.7-2.4)	1.5 (0.5-2.0)	1.8 (0.7-2.4)
	Dry	1.7 (0.6-2.6)	2.3 (0.8-3.5)	1.7 (0.6-2.6)	2.0 (0.7-3.0)

~~**Table 2: Differences between peat, non-peat and estuary samples (mean ± SE).**~~

	~~pCO_2 (µatm)~~		~~FCO_2 (gC m^{-2} d^{-1})~~		~~O_2 (%)~~		~~DIC (µmol L^{-1})~~
	~~Wet~~	~~Dry~~	~~Wet~~	~~Dry~~	~~Wet~~	~~Dry~~	~~Dry~~

~~Non-peat~~	~~2531 ± 188~~	~~2337 ± 304~~	~~1.93 ± 0.17~~	~~2.05 ± 0.32~~	~~81.1 ± 5.4~~	~~79.8 ± 3.5~~	~~177.9 ± 20.4~~
~~Peat~~	~~3472 ± 477~~	~~3053 ± 224~~	~~2.78 ± 0.43~~	~~2.78 ± 0.22~~	~~73.0 ± 11.3~~	~~68.9 ± 7.9~~	~~235.1 ± 74.3~~
~~Estuary~~	~~2046 ± 856~~	~~2607 ± 1763~~	~~1.38 ± 0.75~~	~~2.04 ± 1.64~~	~~68.9 ± 7.9~~	~~74.3 ± 12.9~~	~~1531.1 ± 593.1~~

Table 3: Average discharge and calculated carbon loads and emissions to the atmosphere, estimated for the months of the two surveys and ~~annually~~the whole year 2016.

	Jan 2016	August 2016	Annual estimate 2016
	Peat and non-peat area		
Discharge	4347 $m^3 s^{-1}$	3706 $m^3 s^{-1}$	3942 $m^3 s^{-1}$
DOC load	24 ± 4 GgC/month	21 ± 6 GgC/month	269 ± 60 GgC/year
POC load	30 ± 7 GgC/month	11 ± 4 GgC/month	246 ± 64 GgC/year
DIC load	41 ± 5 GgC/month	21 ± 3 GgC/month	371 ± 46 GgC/year
CO_2 emissions	10 (3-13) GgC/month	11 (4-17) GgC/month	126 (44-181) GgC/year
	Delta		
Discharge ($m^3 s^{-1}$)	739 $m^3 s^{-1}$	630 $m^3 s^{-1}$	670 $m^3 s^{-1}$
CO_2 emissions	31 (12-41) GgC/month	34 (12-51) GgC/month	391 (144-555) GgC/year
	~~Jan 2016~~	~~August 2016~~	~~Annual estimate~~
~~**Discharge ($m^3 s^{-1}$)**~~	~~4964~~	~~4232~~	~~3404~~
	~~C fluxes (GgC/month)~~	~~C fluxes (GgC/month)~~	~~C fluxes (GgC/year)~~
~~**DOC load**~~	~~27 ± 5~~	~~24 ± 6~~	~~307 ± 68~~
~~**POC load**~~	~~38 ± 26~~	~~12 ± 5~~	~~301 ± 182~~
~~**DIC load**~~	~~48 ± 7~~	~~28 ± 8~~	~~455 ± 92~~
~~**CO_2 emissions**~~	~~32 ± 7~~	~~35 ± 6~~	~~402 ± 82~~

Table 4: *p*CO_2, pH and CO_2 evasion of several Southeast Asian rivers flowing into the South China Sea. *The sampling points were located outside of the peat area, so the actual peat coverage at that point was zero.

	Country	Catchment size (km^2)	Discharge (m^3 s^{-1})	Peat coverage (%)	pH	*p*CO_2 (μatm)	CO_2 evasion ($g\ m^{-2}\ d^{-1}$)	Reference
Mekong	Vietnam/Myanmar/Laos/Thailand/Cambodia	795,000	15,000	-	7.4-7.9	1090	2.3	Li et al., 2013
Xijiang	China	350,000	7,290	-	7.6 ± 0.2	2600	2.2-4.2	Yao et al., 2007
Rajang	*Malaysia*	*~~51,500~~52,010*	*3,~~300~~350*	*11*	*6.8 ± 0.1*	*~~2825~~ 2445 ± ~~508~~245*	*~~2.4 ± 0.5~~1.6 (0.5-2.6)*	*This study*
Musi	Indonesia	56,931	3,050	3.5	6.9 ± 0.3	4316 ± 928	7.6 ± 3.2	Wit et al., 2015
Red	China/Vietnam/Laos	156,450	2,640	-	8.1	1589 ± 885	6.4 ± 0.2	Le et al., 2018
Batang Hari	Indonesia	44,890	2,560	5	7.1	2400 ± 18	3.9 ± 0.8	Wit et al., 2015
Indragiri	Indonesia	17,968	1,180	11.9	6.3 ± 0.1	5777 ± 527	10.2 ± 2.7	Wit et al., 2015
Siak	Indonesia	10,423	684	21.9	5.1 ± 0.5	8555 ± 528	14.1 ± 2.7	Wit et al., 2015
Lupar	Malaysia	6,558	490	30.5*	6.9 ± 0.3	1274 ± 148	2.0 ± 0.5	Müller et al., 2016
Saribas	Malaysia	1,943	160	35.5*	7.3	1159 ± 29	1.1 ± 0.9	Müller et al., 2016
Maludam	Malaysia	91	4	100	3.8 ± 0.2	8100 ± 500	9.1 ± 4.7	Müller et al., 2015

1 Pressure correction

1.1 Failure of the Internal Pressure Sensor

The Li-820 maintains a stable cell temperature and corrects the absorptance of CO_2 based on a measurement of the pressure in the cell. During the cruise in August 2016, a failure of the internal pressure sensor occurred on August 25, 2016 at 22:53 GMT. The failure was evident, because the cell pressure reading dropped from a relatively stable value of 102 kPa to 62.57 kPa within 10 seconds. Even when all tubes and pumps were removed and the Li-820 cell pressure was allowed to adjust to ambient pressure, the reading did not change. The internal pressure correction that the Li-820 performs was thus based on the false reading of a cell pressure of 62.57 kPa. The setup had not been changed, and the cell pressure before the failure had been at a stable level of approximately 102.2 kPa. Consequently, the pressure correction done by the Li-820 was reversed and performed again assuming an internal cell pressure of 102.2 kPa for the time after the failure of the pressure sensor.

1.2 Pressure Correction in the Li-820

The CO_2 mole fraction in the Li-820 is computed from a pressure-corrected measurement of absorptance. The pressure correction is performed by multiplication of the absorptance α_c with an empirically determined correction function (Li-820 Manual, Eq. 4-4):

$$\alpha_{pc} = \alpha_c g_c(\alpha_c, P) \tag{1}$$

$$g_c(\alpha_c, P) = \begin{cases} X for P < P_0 \\ 1 for P = P_0 \\ \frac{1}{X} for P > P_0 \end{cases} \tag{2}$$

with $P_0 = 99kPa$ and $X = \frac{1}{\frac{1}{b_1(p-1)} + \frac{(\frac{1}{b_5-\alpha_c} - \frac{1}{b_5})}{\frac{1}{b_2+b_3p} + b_4}} + 1$ (Li-820 manual, Eq. 4-6). In this equation, $p = \frac{P_0}{P}$ or $\frac{P}{P_0}$, with $p > 1$.

So

$$\alpha_{pc} = \begin{cases} \alpha_c \cdot X for P < P_0 \\ \frac{\alpha_c}{X} for P > P_0 \\ \alpha_c for P = P_0 \end{cases} \tag{3}$$

1.3 Correction for false cell pressure

In order to correct for the false cell pressure P_{meas}, the absorptance α_c has to be computed. Then, the pressure-corrected absorptance α_{pc} has to be calculated using the corrected pressure P_c. P_c was taken to be the average cell pressure during the measurements before the pressure sensor failed, which was 102.18

kPa. This value was considered a good approximation, as the cell pressure in the Li-820 was fairly stable during the time of measurements while the pressure sensor was still functioning.

The inverse function which allows calculation of the pressure-corrected absorptance from the mole fraction is given as

$$\alpha_{pc} = \frac{a_1 C}{a_2 + C} + \frac{a_3 C}{a_4 + C} \tag{4}$$

with $a_1 = 0.3989974$, $a_2 = 5897.2804$, $a_3 = 0.097101982$, $a_4 = 596.49981$ (Li-820 Manual, Eq. 4-7).

In order to calculate the absorptance α_c from α_{pc}, Equation 3 has to be rearranged and solved for α_c. The solutions are:

$$\alpha_c = \begin{cases} -\frac{P_1}{2} - \sqrt{(\frac{P_1}{2})^2 - Q_1} for P < P_0 \\ -\frac{P_2}{2} - \sqrt{(\frac{P_2}{2})^2 - Q_2} for P > P_0 \\ \alpha_c \end{cases} \tag{5}$$

whereas
$P_1 = \frac{\alpha_{pc} m b_5 (n+b_4) - \alpha_{pc} + b_5^2 (n+b_4)(m+1)}{-b_5 (n+b_4)(m+1)+1}$
$Q_1 = -\frac{\alpha_{pc} m b_5^2 (n+b4)}{-b_5 (n+b_4)(m+1)+1}$
$P_2 = \frac{b_5^2 m (n+b_4) - \alpha_{pc} + \alpha_{pc} b_5 (1+m)(n+b_4)}{1-b_5 m (n+b_4)}$
$Q_2 = -\frac{\alpha_{pc} b_5^2 (1+m)(n+b_4)}{1-b_5 m (n+b4)}$
with $m = \frac{1}{b_1 (p-1)}$ and $n = \frac{1}{b_2 + b_3 p}$.

From α_c and P_c, the corrected $\alpha_{pc,c}$ is calculated according to Equation 1. C_c is calculated according to the manual:

$$C_c = \frac{D - (a_2 + a_4)\alpha_{pc,c} - \sqrt{A^2 \alpha_{pc,c}^2 + B\alpha_{pc,c} + D^2}}{2(\alpha_{pc,c} - a_1 - a_3)} \tag{6}$$

whereas $A = a_2 - a_4$, $B = 2A(a_1 a_4 - a_2 a_3)$ and $D = a_3 a_2 + a_1 a_4$ (Li-820 Manual, Eq. 4-10 and 4-11).

2 Salinity Interpolation

Salinity was only available at the stations (15 in the wet season, 34 in the dry season). However, in order to be able to interpret O_2 and CO_2 data, it is useful to know their distribution along a salinity gradient. Therefore, salinity in the estuary was spatially interpolated. Since the saltwater intrusion limit was presumably different between wet and dry season, interpolation was performed for the entire area under tidal influence (downstream of Kanowit). Beyond that point, salinity was measured to be zero.

Since some points for which interpolation was desired lay outside the area covered by our measurements, we added three reference points to better constrain the grid to be interpolated. The coordinates of these points were:

$$(2.0, 2.5, 3.5), (111.0, 111.0, 111.8) \quad (7)$$

These reference points all lie within the South China Sea off the coast of Sarawak. The salinity value ascribed to them was 33 according to our own measurements and those of Wang et al. (2014) for the Southern South China Sea. Interpolation was achieved with the Scipy Interpolation package for Python (scipy.interpolate.griddata) using linear interpolation. Figure 1a shows the points used for interpolation, Figures 1b and c show the results for the wet and dry season, respectively.

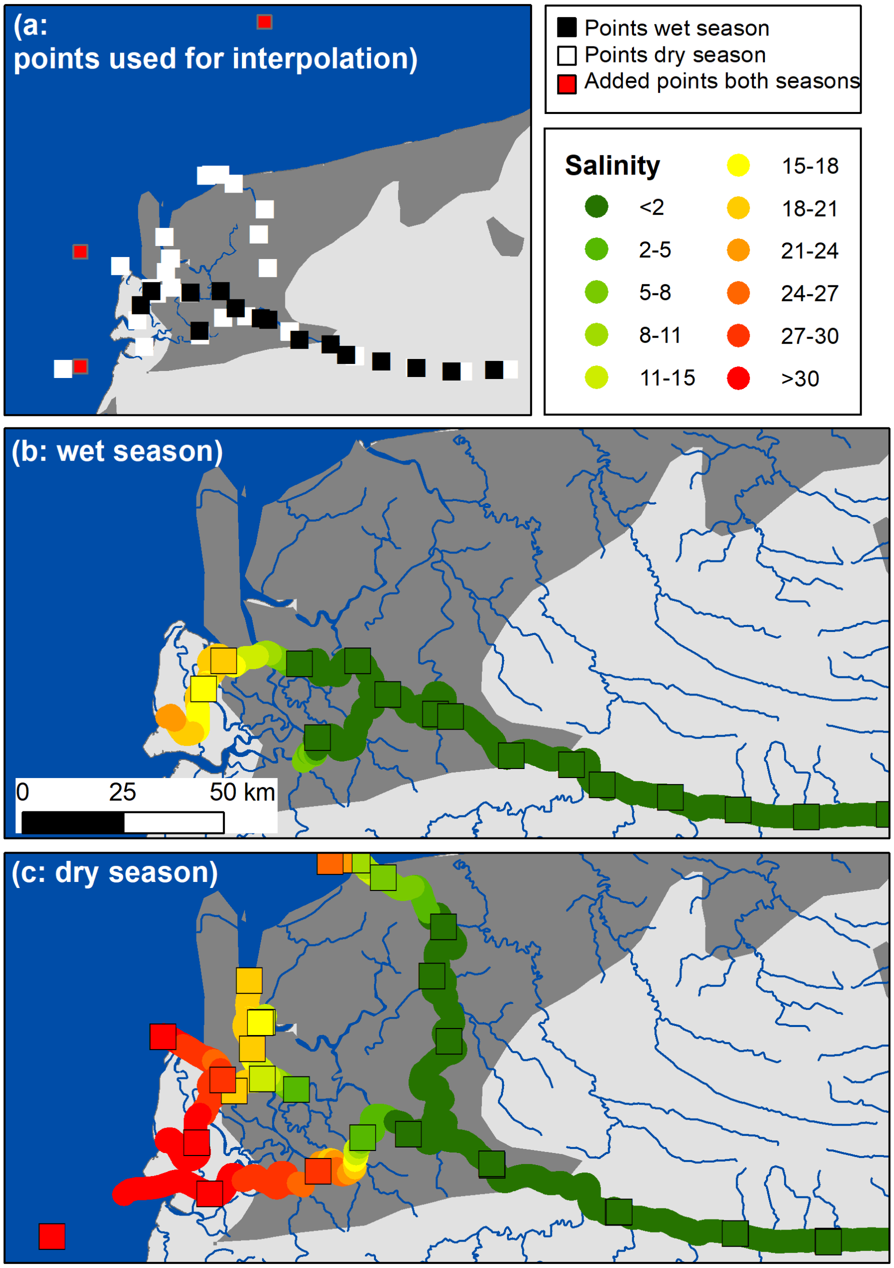


Figure 1: Data points used for interpolation (a), results for the wet (b) and dry (c) season. Interpolated salinity is shown in graduated colors, actual measurements are shown as squares.

3 Water surface area in the delta

We used stream widths for the Rajang River from the GRWL (Global River Widths from Landsat) Database (Allen and Pavelsky, 2018). The length of the river segments was determined using ArcMap 10.5 and multiplied by the mean river width. Missing parts were manually delineated using a georeferenced Landsat satellite image (Fig. 2, source of the Landsat image: `https://landsat.visibleearth.nasa.gov/view.php?id=91787` (last access: Oct 9th, 2018)). The total water surface area in the Rajang catchment was calculated at 755 km^2 or 1.5% of the catchment area.

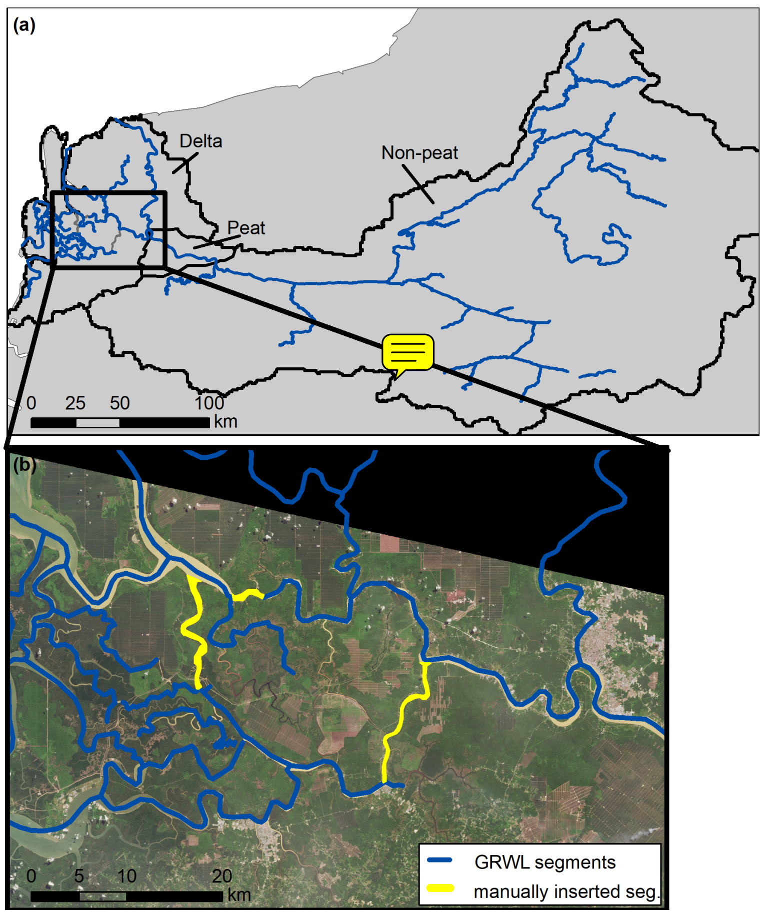


Figure 2: River segments used to determine the water surface area of the Rajang River. The close-up shows manually delineated segments in the delta using a georeferenced satellite image.

4 Tides

Tidal variability was only observed at the river mouth. The Figure shows water level from close-by stations and the measured pCO_2. The rectangle marks the only stationary measurement, which was performed in Sarikei overnight and covers one tidal cycle. For all other data, spatial and temporal variations are overlapping, because the ship was moving. Tidal variability in pCO_2 cannot be observed at all upstream of Sibu or in the Igan distributary. In the Paloh and Rajang distributary, variability in pCO_2 is high, but this is partly attributed to mixing with sea water.

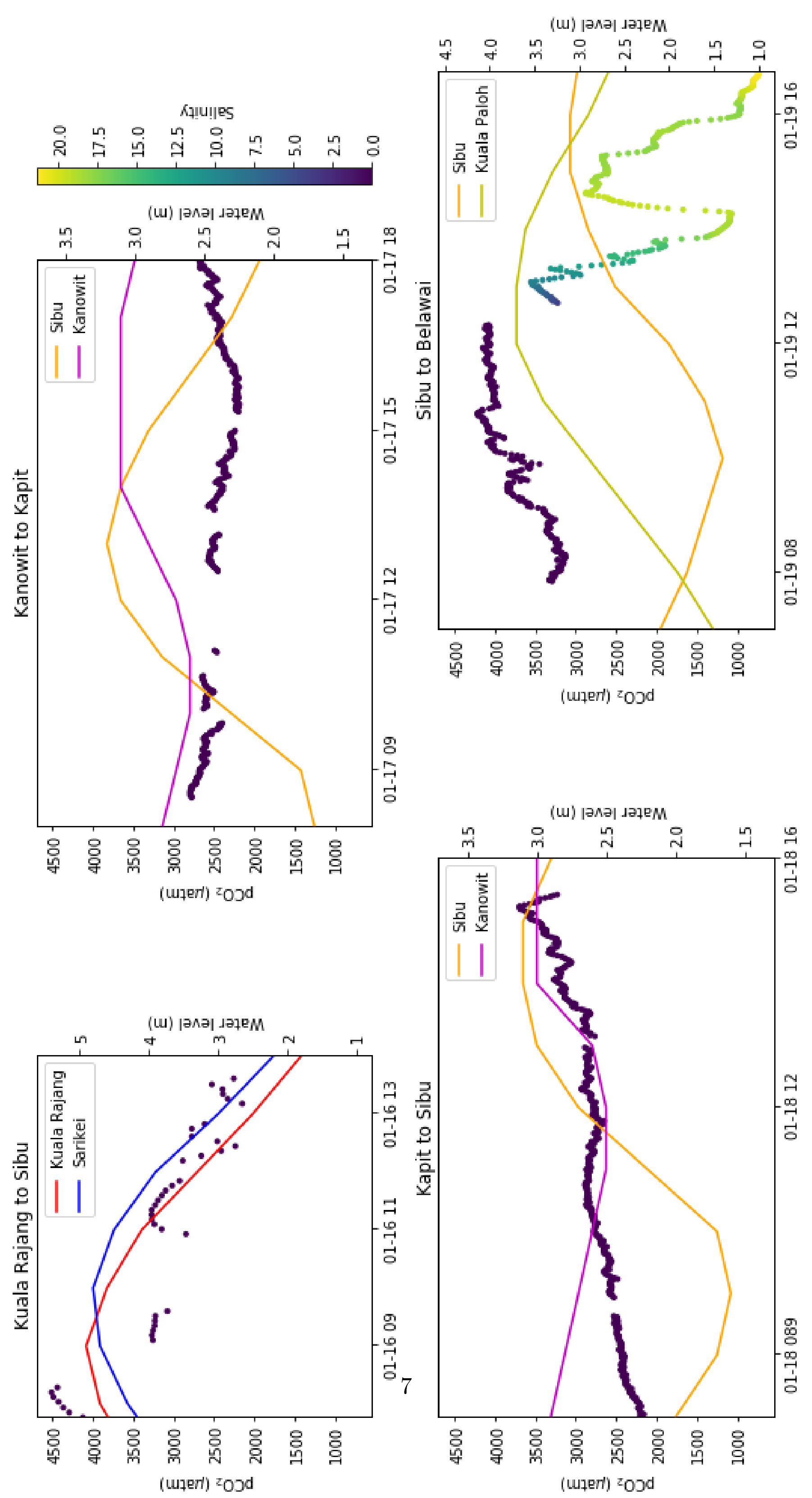


Figure 3: Measured pCO$_2$ in January 2016 and water level in different river reaches.

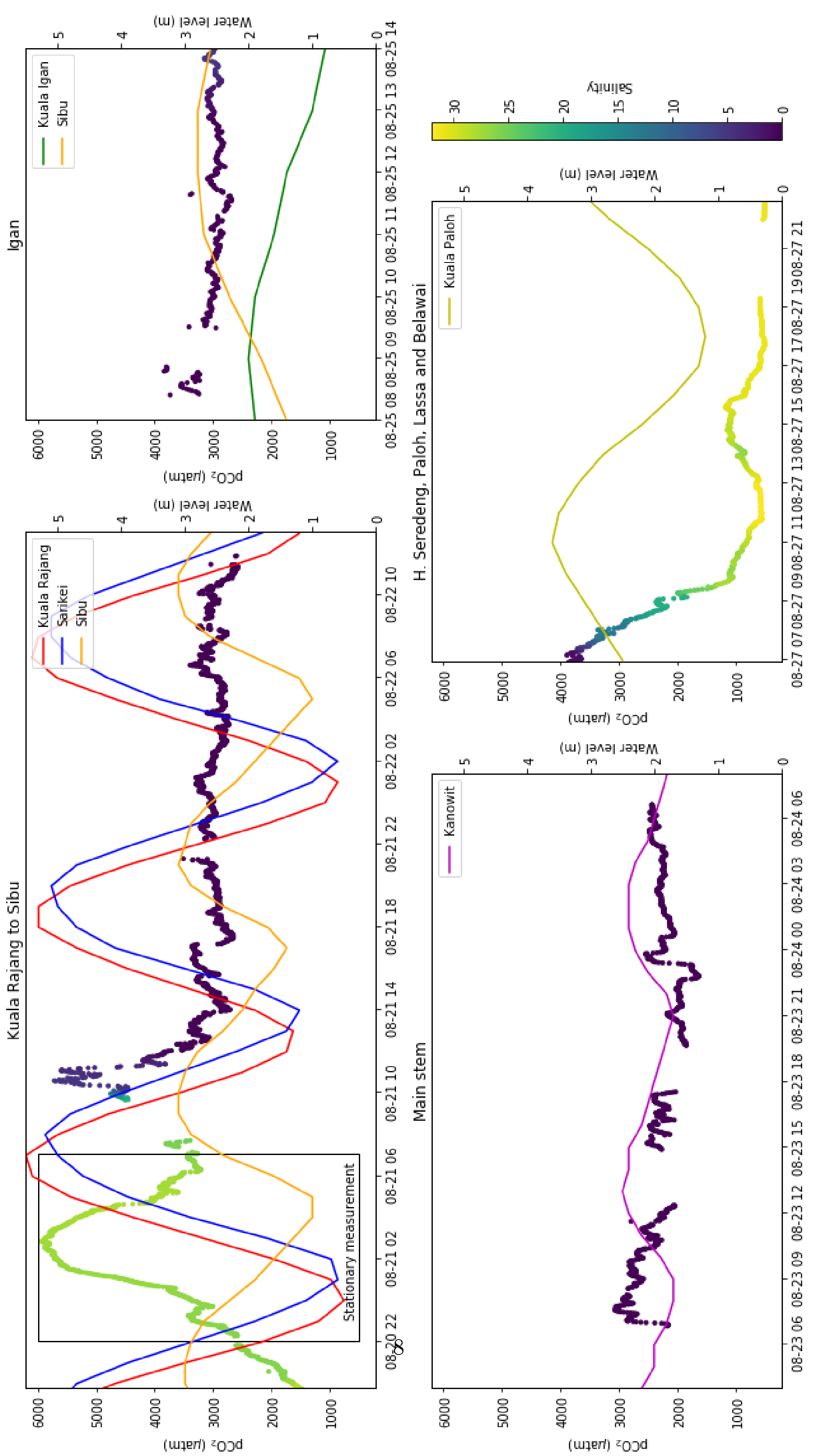


Figure 4: Measured pCO_2 in August 2016 and water level in different river reaches.

5 Gas transfer velocity considerations

The choice of a k-model has a big impact on the calculated CO_2 fluxes. Therefore, three different models are compared (Table 1). Additional uncertainty arises from the input data. Those models depend on wind speed and water flow velocity. In the absence of in-situ wind speed data, we had to use the NOAA NCEP Reanalysis product; however, wind speed on-site might differ from these values, which would impact our results for k. Secondly, we used two literature values for the Rajang River's water flow velocity w, that is, one fixed value for both seasons. According to Raymond et al. (2012), w scales with discharge $Q^{0.29\pm0.01}$. During the peak of the monsoon season in January, Q is approximately 50 % higher than average discharge, which would mean that w would be enhanced by 12 %. If we consider this the variability in w ($w = 0.9 \pm 0.1$ m s^{-1}), it would add an uncertainty of 4 % to $k_{600,B04}$. However, the deviation among the different k-models is much larger than that (Table 1), so the biggest source of uncertainty isn't the input data, but the choice of a k-model. Table 1 presents a comparison of three different k-parameterizations.

		k_{600}			FCO_2		
		B04	A11	R01	B04	A11	R01
non-peat	wet	8.23	8.51	2.32	1.9 ± 0.2	2.0 ± 0.2	0.5 ± 0.0
	dry	9.57	12.19	2.79	2.0 ± 0.3	2.6 ± 0.4	0.6 ± 0.1
peat	wet	8.23	8.51	2.32	2.3 ± 0.2	2.4 ± 0.2	0.7 ± 0.1
	dry	9.57	12.19	2.79	2.7 ± 0.1	3.5 ± 0.2	0.8 ± 0.0
delta	wet	8.23	8.51	2.32	2.3 ± 1.0	2.4 ± 1.0	0.7 ± 0.3
	dry	9.57	12.19	2.79	2.3 ± 1.4	3.0 ± 1.7	0.7 ± 0.4

Table 1: Comparison of the results for different k-parameterizations. B04: Borges et al. (2004), A11: Alin et al. (2011), R01: Raymond & Cole (2001). ± represents the spread of the data (derived from the spread of the pCO_2). In the main manuscript, the average of the three values is used, minimum and maximum are reported alongside.

6 Mixing model

We used a simple mixing model to estimate the theoretically possible contribution of the peatlands to river pCO_2. The model consists of two subsequent steps. First, the mixing of two water bodies was simulated, one with a pCO_2 of 2434 μatm and a pH of 6.8 (Rajang River), and the other with a pCO_2 of 8100 μatm and a pH of 3.8 (representing peat-draining rivers according to Müller et al., 2015). The DIC and TA of these water bodies were calculated using CO_2Sys. DIC and TA of the mixture were calculated as

$$DIC_{S=0} = (1 - pc) \cdot DIC_1 + pc \cdot DIC_2 \quad (8)$$

and

$$TA_{S=0} = (1 - pc) \cdot TA_1 + pc \cdot TA_2, \tag{9}$$

whereas pc is the peat coverage in the basin as the river flows downstream and passes through more and more peat areas (pc=0...0.11). As a next step, for pc>0.03, mixing with saltwater was taken into account. It was assumed that pc=0.03 correpsonds to S=0 and that pc=0.11 corresponds to S=32 and within this range, salinity increased linearly with increasing peat coverage. This is obviously a simplification, but since the model has only illustrative purposes, it seemed sufficient. DIC and TA were then calculated with a normal end-member mixing model:

$$DIC = \frac{DIC_{S=32} - DIC_{S=0}}{32} \cdot S + DIC_{S=0} \tag{10}$$

and

$$TA = \frac{TA_{S=32} - TA_{S=0}}{32} \cdot S + TA_{S=0}, \tag{11}$$

whereas $TA_{S=32} = 2324 \mu mol L^{-1}$ and$DIC_{S=32} = 2347 \mu mol L^{-1}$ according to our measurements. pCO_2 was calculated from TA and DIC using CO_2Sys. The mixing model and the results are shown in Figure 4.

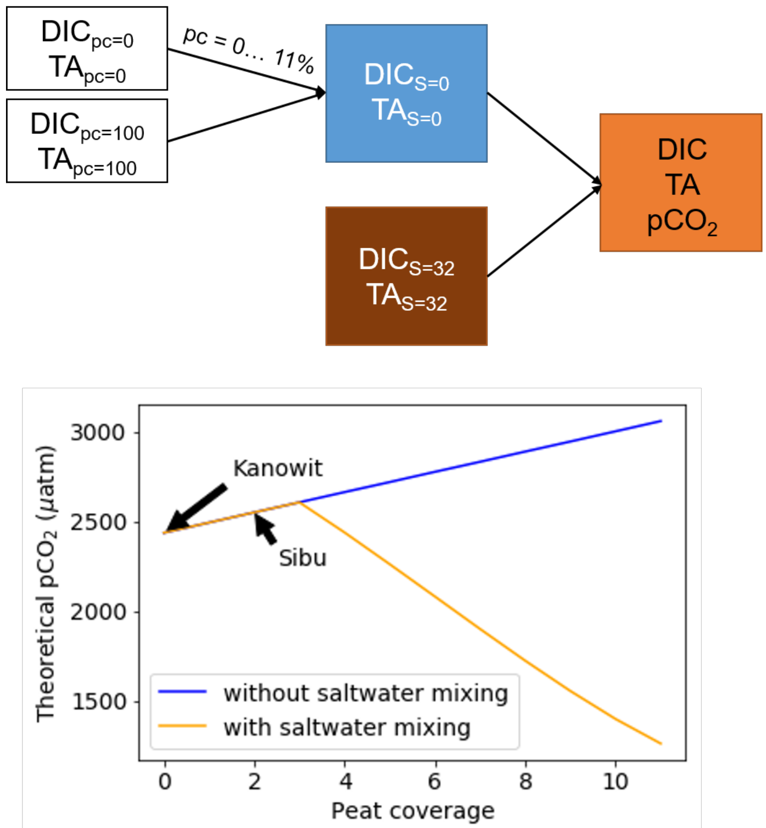


Figure 5: Mixing model flow chart and plot of the results for theoretically possible pCO_2 if peat is the only source of CO_2 in the delta.

7 Supplementary Data

The data used in this manuscript are available as a separate excel workbook.

8 References

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