Reply on Comments by Anonymous Referee #1:

Referee:
The manuscript by Klemme et al. presents a study explaining why tropical peat draining rivers are only a moderate source of CO2 to the atmosphere, which stands in contrast to what was assumed for global estimates. Klemme et al. test the hypothesis that decomposition and thus CO2 production in these organic C rich waters is limited by pH and O2 availability. For this, they use a comprehensive dataset of observations of DOC and CO2 concentrations, pH and other relevant physical and chemical parameters from SE Asian, peat draining rivers in combination with a conceptual model representing limitations of DOC decomposition by low pH and O2 concentrations. They find that DOC decomposition in those peat draining rivers is likely more limited by pH than by O2, and suggest that increased loads of carbonates due to agricultural liming or enhanced weathering could increase decomposition of DOC and thus CO2 emissions from those peat draining rivers.

The study is original and of great interest for the readership of Biogeosciences. The manuscript is well written, the methodology is clearly described, and results are clearly presented and support the main findings of this study. I suggest publication after minor revisions. Please, find my comments below.

Response:
We thank the reviewer for the work with our manuscript and are pleased about their positive response to the concept and findings of our study. The suggestions by the reviewer were very helpful and improved the manuscript.

Referee:
L15-17 : Other studies have shown that large amounts of CO2 evading rivers are actually put in as dissolved CO2 from soil respiration (both heterotrophic and root respiration) (Abril and Borges, 2019; Lauerwald et al., 2020). Maybe you should mention that source as well.

Response:
We included this suggestion in our manuscript. In the revised manuscript we state: *» … riverine CO2 is fed by decomposition of organic matter that is leached from soils (Wit et al., 2015) and by the leaching of dissolved CO2 from soil respiration (Abril and Borges, 2019; Lauerwald et al., 2020). «*

Referee:
L17-18: These are actually not model based studies that would represent peat soils. Those are more upscaling studies that lacked observations from these important systems

Response:
We realise that the use of the term "model-based studies" is imprecise. As the reviewer

points out these studies do not include soil models but are based on upscaling. We corrected this and in the updated manuscript we state: *» Despite scarcity in river CO2 measurements from Southeast Asia, studies suggest it as a hotspot for river CO2 emissions (Lauerwald et al., 2015; Raymond et al., 2013) due to the presence and degradation of carbon-rich peat soils. «*

Referee:
L42: In peat draining rivers, is there also less instream production by algae that would otherwise be a source of O2 to the water column?

Response:
Indeed, low nutrient concentrations (Baum and Rixen, 2014) as well as the dark water colour of peat-draining rivers that limit the light availability to algae (Wit et al., 2015) cause low rates of instream production. This further decreases O2 concentrations within those rivers that due to the high DOC and the concomitant high O2 consumption by decomposition exhibit low O2 concentrations. In the corrected manuscript we state: *» Due to high rates of decomposition caused by the carbon rich environment and low rates of photosynthesis caused by low nutrient concentrations and dark water colours that limit light availability to algae, peat-draining rivers are usually undersaturated with regard to atmospheric O2 (Wit et al., 2015, Baum and Rixen, 2014). «*

Referee:
L48-51: You should link these quite specific objectives here again to the more general research objective (or hypothesis to be tested): explain the moderate CO2 emissions from peat draining rivers by the effect of low pH and O2 limitation.

Response:
We included this as suggested. In the revised manuscript we state: *» This study aims at quantifying the impact of pH and O2 on the DOC decomposition in peat-draining rivers in order to explain the measured moderate CO2 emissions from those rivers by the limiting effect of these parameters. «*

Referee:
L95-97: I don't understand why you have used such a projection for determining areas. For that purpose, I would rather use an equal area projection, like an equal area projection after Lambert or the EckertIV projection.

Response:
Our phrasing at this point was misleading. We did not use the projection to determine catchment sizes but instead the Hydro-SHEDS data that our calculation of catchment sizes was based upon were provided in that geographical projection (Lehner et al., 2006). In the revised manuscript we rephrased this section to: *» Catchment sizes were derived from Hydro-SHEDS (Lehner et al., 2006) at 15s resolution in WGS 1984 Web Mercator Projection. Subbasins belonging to the catchments were identified using the HydroSHEDS 15s flow directions data set and added to the main basins. «*

Referee:
L110-112: The exponential limitation factor related to pH, which is defined as negative decadic logarithm of H+ activity - would that be comparable to a linear factor relating to the H+ activity? That might be worth discussing here in one or two sentences.

Response:
The logarithmic pH relation in the exponential limitation factor is indeed striking. Yet, it would not result in a linear correlation with the H+ activity but with this activity by the power of the exponential constant λ divided by ln(10), which for the rivers we studied results to approximately 0.2. We included this information in the revised manuscript. In the methods we state: *» Considering the definition of pH as negative decadic logarithm of H+ activity ({H+}), the exponential limitation factor is equivalent to a correlation with {H+}^(λ/ln(10)). «* and in the discussion we write: *» The exponential pH coefficient is λ = 0.5 ± 0.1. Thus, in terms of H+ activity the correlation is given by {H+}^(0.5/ln(10)), which roughly equals the fifth root of {H+}. «*

Referee:
L122-123: That would require that dissolved CO2 inputs via groundwater inputs and CO2 consumption by autotrophic production is negligible. These are strong assumptions that would be worth mentioning here explicitly and some discussion later on.

Response:
We included this suggestion. In the methods we state: *» This approximation assumes photosynthetic CO2 consumption and direct CO2 input from leaching to be negligible. «* and later on we include discussions in form of: *» We acknowledge that this approximation assumes photosynthetic CO2 consumption and direct CO2 input from leaching to be negligible, which might not be the case for all rivers and we discuss the impact of these processes later on. «*
In the discussion we state: *» As mentioned before, our results do neglect the direct leaching of CO2 from soils and the consumption of CO2 by autotrophic production within the rivers. Since CO2 leaching rates are likely higher for peat soils than for mineral soils (Kang et al., 2018) and autotropic production is limited in peat-draining rivers (Wit et al., 2015), both of these processes would work against the observed recession in CO2 growth. This indicates that exclusion of those processes could cause underestimation of the limitation factors rather than overestimation. «*

Referee:
L140: "spatially as well as temporally"

Response:
We changed this as suggested.

Referee:
Figure 3: The grey lines, are those regression fits or the 1:1 line, or both?

Response:
Those lines represent the 1:1 line. We included this information in the revised manuscript.

Referee:
For figures 3 and 4, it would be great if you could report in addition the RMSEs.

Response:
We included those as suggested.

Referee:
L184: There's a "c" missing in "concentration".

Response:
We changed this.

Referee:
L189-191: Do Borges et al. also report CO_2 emission rates or CO_2 concentrations which are comparable to those in your study?

Response:
Yes, the CO_2 and DOC concentrations by Borges et al are comparable to the concentrations measured in our study. In the revised manuscript we included this information and state: *» A similar pattern of stagnating CO_2 concentrations has been observed in river sections of high DOC at the Congo river (Borges et al., 2015). The CO_2 and DOC concentrations measured in these rivers are comparable to those measured in our study, indicating that the underlying process is valid not only for Southeast Asian rivers but for tropical peat-draining rivers in general. «*

Reply on Comments by Anonymous Referee #2:

Referee:
The contextualization and general justification of the paper could be revised. The authors justify their research to explain the discrepancy between estimates of CO_2 evasion by "global models" and those based on field measurements by their own group (for example Wit et al. 2015). The "global models" of Raymond et al. (2013) and Lauerwald et al. (2015) are not and not mechanistic models but in fact extrapolations of pCO_2 data calculated from pH and alkalinity measurements of unverified quality, that usually give results that are incorrect (Abril et al. 2015), and with a very coarse and extremely irregular spatial coverage. If you look at the maps of data point distribution of those two papers (in the supplements), for SE Asia there a handful of points in Thailand in the Raymond paper, and these data points did not meet the selection criteria of Lauerwald. In the Lauewarld paper that are in fact no data points at all for SE Asia.

Response:
We thank the reviewer for the work with the manuscript. The use of the term "model-based" was also criticised by the first reviewer and we changed the statement to: *» Despite scarcity in river CO_2 measurements from Southeast Asia, studies suggest it as a*

hotspot for river CO2 emissions (Lauerwald et al., 2015; Raymond et al., 2013) due to the presence and degradation of carbon-rich peat soils. «

The reviewer is right in that the mismatch between those studies and measured data is not surprising considering the data scarcity and consequential uncertainties. Furthermore, the results by Lauerwald et al. (2015) are within the range of measured CO2 concentrations (Wit at al., 2015). Thus, according to the reviewer's suggestion, we shift the motivation of our study from discrepancies between those upscaling studies and measurements towards the surprisingly low CO2 measurements in rivers of high DOC concentrations. In the revised manuscript we state: » *However, despite high leaching rates that cause DOC concentration which can be more than four times higher than those in temperate regions (Butman and Raymnond, 2011; Müller et al., 2015), measured CO2 fluxes from tropical peat-draining rivers (25.2 gC m^{-2} yr^{-1}) hardly exceed those measured for rivers in temperate regions (18.5 gC m^{-2} yr^{-1}; Butman and Raymond, 2011; Wit et al., 2015). «*

Referee:
In conclusion, the mismatch between field measurements and those predicted by Raymond et al. (2013) and Lauewarld et al. (2015) only shows that these "global models" are extremely unreliable, and does not reveal a hidden mechanism that lowers CO2 emissions.

Response:
As we state above, it is not only the mismatch between these specific studies and measurements that we want to explain. The question we want to answer is the cause for the rather moderate CO2 concentrations measured in tropical peat-draining rivers given the high DOC concentrations. The presence of carbon-rich peat soils and consequently high concentrations of DOC in peat-draining rivers should result in high CO2 concentrations, but the measurements show that the CO2 concentrations in these rivers are only insignificantly higher than emissions from temperate regions (Wit et al., 2015). In this study, we aim at explaining the process that is limiting the CO2 production given the high DOC concentrations.

Referee:
Conversely, the pCO2 values reported for SE Asian peatland rivers, ranging between 2000 and 8000 ppm according to figure 2 of Wit et al. (2015) are within the range of pCO2 reported in African tropical rivers (Borges et al. 2015) and also in rivers and streams of the Amazon River network (Abril et al. 2014). So the pCO2 values in SE Asian peatland rivers seem relatively "normal" for tropical rivers, and not abnormally low.

Response:
This is exactly what we want to explain. Despite high DOC concentrations in tropical rivers, the CO2 emissions are relatively moderate (Wit et al., 2015). It is not the aim of our study to discuss or explain that CO2 values in Southeast Asian rivers are abnormally low in contrast to other tropical rivers. What we refer to when mentioning

moderate CO_2 is the stagnating concentration in rivers of high peat coverage, in which DOC concentrations are extremely high. Yet, while DOC concentrations can be by a factor 5 higher than in temperate regions, CO_2 emissions are not even twice as high as those stated for temperate rivers. Similarly, for the rivers in our study, CO_2 concentrations do not change significantly for rivers with DOC concentrations between 2,000 and 4000 µmol L^{-1}. Since our dataset is specifically based on measurement campaigns in Southeast Asian rivers, we focus on quantifying the limitation factors for rivers within this area. However, we explicitly state that a similar limitation is likely present in tropical peat-draining rivers in general (line 190-191). According to a suggestion of reviewer #1, this section was adjusted to: *» A similar pattern of stagnating CO2 concentrations has been observed in river sections of high DOC at the Congo river (Borges et al., 2015). The CO2 and DOC concentrations measured in these rivers are comparable to those measured in our study, indicating that the underlying process is valid not only for Southeast Asian rivers but for tropical peat-draining rivers in general. «*

Referee:

The core topic of the paper is to look into the limitation of organic matter degradation (and subsequent CO_2 production) by low pH and low O_2. While it is intuitive that low O_2 and low pH might not be optimal to microbial growth, micro-organisms tend still to growth in sub-optimal conditions if there are substrates to metabolize. The correlations of CO_2 concentrations and pH/O_2 based on the data in Table 1 of the ms (see below) indicate on the contrary that the high CO_2 were associated to low pH and low O_2. And even if the conditions of pH and O_2 were sub-optimal, the micro-organisms were still able to degrade enough organic matter to produce large quantities of CO_2.

Response:

The correlation of CO_2 concentrations and pH/O_2 pointed out by the reviewer neglects the DOC concentration. The rivers of low pH and low O_2 are the rivers with a high peat coverage in the catchment and therefore high DOC. Obviously, the CO_2 concentration is high in these rivers, since the DOC decomposition increases with the amount of available DOC in the rivers. This is why we define the decomposition rate as produced CO_2 per available DOC. If this decomposition rate was not limited by parameters like pH or O_2, the CO_2 production would linearly increase with DOC concentrations, which would result in a fairly linear increase of CO_2 concentrations with DOC and therewith significantly higher CO_2 concentrations than observed in peat-draining rivers.

Referee:

Minor comments P1 L20: there could be a need to revise this statement in light of the work of Dargie et al. (2017).

Response:

It is a good suggestion to include the study by Dargie et al. in our manuscript. Their results increase the total tropical peat carbon store from approximately 89 PgC to 105 PgC. Southeast Asian peatlands are estimated to store more than 60 PgC (Page et al, 2011). Thus, these data conform with our original statement that more than half of the known tropical peatlands are located in Southeast Asia. In the revised manuscript we state: *» More than half of the known tropical peatlands are located in Southeast Asia (Dargie et al., 2017; Page et al., 2011), whereat 84 % of these are Indonesian peatlands, mainly on the islands of Sumatra, Borneo and Irian Jaya (Page et al., 2011). «*

References

Abril et al. 2014: Abril, G., Martinez, JM., Artigas, L. et al. Amazon River carbon dioxide outgassing fuelled by wetlands. Nature 505, 395–398 (2014).

Abril et al., 2015: Abril, G., Bouillon, S., Darchambeau, F., Teodoru, C. R., Marwick, T. R., Tamooh, F., Ochieng Omengo, F., Geeraert, N., Deirmendjian, L., Polsenaere, P., and Borges, A. V.: Technical Note: Large overestimation of pCO2 calculated from pH and alkalinity in acidic, organic-rich freshwaters. Biogeosciences 12, 67–78 (2015).

Abril and Borges, 2019: Abril, G. and Borges, A. V.: Ideas and perspectives: Carbon leaks from flooded land: do we need to replumb the inland water active pipe?. *Biogeosciences* 16, 769–754 (2019).

Baum and Rixen, 2014: Baum, A. and Rixen, T.: Dissolved inorganic nitrogen and phosphate in the human affected blackwater river Siak, central Sumatra, Indonesia. *Environment and Pollution* 11, 13-24 (2014).

Borges et al., 2015: Borges, A., Darchambeau, F., Teodoru, C. et al.: Globally significant greenhouse-gas emissions from African inland waters. Nature Geoscience 8, 637–642 (2015).

Butman and Raymnond, 2011: Butman, D. and Raymond, P.: Significant efflux of carbon dioxide from streams and rivers in the United States. Nature Geoscience 4 (2011).

Dargie et al., 2017: Dargie, G., Lewis, S., Lawson, I. et al.: Age, extent and carbon storage of the central Congo Basin peatland complex. Nature 542, 86–90 (2017).

Lauerwald et al., 2015: Lauerwald, R., Laruelle, G. G., Hartmann, J., Ciais, P., and Regnier, P. A.: Spatial patterns in CO2 evasion from the global river network. Global Biogeochem. Cycles 29, 534– 554 (2015).

Lauerwald et al., 2020: Lauerwald, R., Regnier, P., Guenet, B., Friedlingstein, P. and Ciais, P.: How Simulations of the Land Carbon Sink Are Biased by Ignoring Fluvial Carbon Transfers: A Case Study for the Amazon Basin. *One Earth* 3, 226-236 (2020).

Lehner et al., 2006: Lehner, B., Verdin, K., and Jarvis, A.: HydroSHEDS, Technical Documentation. Tech. rep., HydroSHEDS, version 1.0, 1-27, (2006).

Müller et al., 2015: Müller, D., Warneke, T., Rixen, T., Müller, M., Jamahari, S., Denis, N., Mujahid, A., and Notholt, J.: Lateral carbon fluxes and CO2 outgassing from a tropical peat-draining river. Biogeosciences 12, 5967–5979 (2015).

Page et al., 2011: Page, S. E., Rieley, J. O., and Banks, C. J.: Global and regional importance of the tropical peatland carbon pool. Global Change Biology 17, 798–818 (2011).

Raymond et al., 2013: Raymond, P. A., Hartmann, J., Sobek, S., Hoover, M., McDonald, C., Butman, D., Striegel, R., Mayorga, E., Humborg, C., Kortelainen, P., Dürr, H., Meybeck, M., Ciais, P., and Guth, P.: Global carbon dioxide emissions from inland waters. Nature 503, 355–359 (2013).

Wit et al., 2015: Wit, F., Müller, D., Baum, A., Warneke, T., Pranowo, W. S., and Müller, M.: The impact of disturbed peatlands on river outgassing in Southeast Asia. Nature Communications 6, (2015).