Replies to Referee 2

Review of Satellite-based modeling of wetland methane emissions on a global scale (SatWetCH4 1.0). Bernard et al.

The authors use surface eddy covariance data for wetland methane fluxes from the global FLUXNET-CH4 Community Product v1.0 to calibrate an empirical model that is applied to produce a globally upscaled wetland methane emissions product. The study is at the forefront of global wetland methane modeling and responds to the scientific imperative to understand the global methane budget in a time of rapid change (accelerating growth of atmospheric methane concentrations since 2014). With revisions focused on reconciling findings of the author's study (SatWetCH4 1.0) with the first and only published global wetland methane upscaling product (UpCH4 v1.0; McNicol et al. 2023) and providing more justification of the model calibration approach, the study is likely to become an important contribution to wetland methane upscaling science.

McNicol, G., Fluet-Chouinard, E., Ouyang, Z., Knox, S., Zhang, Z., Aalto, T., et al. (2023). Upscaling wetland methane emissions from the FLUXNET-CH4 eddy covariance network (UpCH4 v1.0): Model development, network assessment, and budget comparison. AGU Advances, 4(5). https://doi.org/10.1029/2023av000956

I led the analysis and writing of the study referenced above which was published in October 2023. I am aware of the ethical considerations regarding promotion of one's own work during the review process, but I would like to explain why I consider referencing of my study as not merely justified, but essential.

We thank you for reading the manuscript, providing suggestions to improve it, and the positive feedback.

Most of the work on this paper was carried out in 2022 and early 2023, with completion of the submission then being delayed for various reasons. This explains, but does not excuse, the fact that we do not compare the results with UpCH4 study (McNicol, 2023) in this manuscript. We updated the citation r, and would like to state that it was an omission due to a combination of circumstances, and not a deliberate action.

We include some comparisons with UpCH4 along the manuscript, emphasizing the complementarity and differences of the two approaches. However, notice that, strictly speaking, UpCH4 is a data-driven empirical upscaling of wetland methane fluxes using machine learning techniques. SatWetCH4 is a model based on a process equation - extremely simplified - which is also data-driven in terms of its calibration and input data, but is not an empirical model. The authors would be interested in a future collaboration for a deeper inter-comparison study that could certainly improve our understanding of both product estimates.

Point by point replies to the comments are listed below.

The line numbers given hereafter refer to the tracking-changes PDF manuscript. Changes in the manuscript are given here in violet.

Given the lack of a true global wetland methane emissions benchmark dataset, our understanding advances via careful model/product inter-comparison. The absence of a comparison to our 2023 study greatly reduces the potential insights that could be gained. For instance, Bernard et al. estimate a global annual total wetland methane source of around 70-86 TgCH4 y-1. This is remarkably low; much lower than the spread of bottom up and top down models within the Global Carbon Project methane budget ensemble or WetCHARTS. I think the estimates may be different due to Bernard's inclusion of an explicit substrate availability term in the empirical function, over the temperature-dominated learned function in McNicol et al., or the inflexibility of the temperature response term (see section below), but this needs to be explored in some detail by the authors before a clear insight can be gained into the pros and cons of using this substrate dependent formulation.

The value of the SatWetCH4 total budget found by the independent calibration method presented in this manuscript is indeed remarkably low compared to the literature. We mentioned this several times in the manuscript, notably section 3.3.4.

*"SatWetCH4 is in the **lower** range of the GMB LSMs (grey areas), or even slightly below this range in the 30°S-30°N band. The total annual budget of SatWetCH4 wetland emission estimate averages 85.6Tg CH4 yr−1 with WAD2M (resp. 70.3 with TOPMODEL), which is **lower** than the range of the GMB LSMs estimates (102 to 181 Tg CH4 yr−1). This discrepancy is consistent with **the underestimation of methane fluxes by SatWetCH4** at tropical sites (discussed in section 3.2). Note that this difference in total emissions could be easily resolved by calibrating the k parameter to the total emissions of the mean GMB LSMs if we need to constrain total emissions, as it has been done previously by Bloom et al. (2017); Gedney et al. (2019)."*

We explained in the submitted manuscript that the global total estimate is not necessarily the value of interest in this approach, but rather the seasonal and inter-annual and spatial patterns. In fact, to be consistent with the literature mean global estimates, as we already mentioned in this manuscript, we could simply calibrate the k factor to match the commonly accepted total, as it has been done in several previous studies (e.g., Bloom et al. 2017). Even though the total amount diverges from the estimates established in the literature, we believe that this kind of independent process-based model can be useful for the community: the equation used here is a simplified process model, but with the advantage of being calibrated and constrained with independent data. We believe that the advantage of SatWetCH4 is its dependency on remote sensing observations rather than on modelling outputs, which allows looking at seasonal and inter-annual variations and spatial patterns.

The global total differences in methane emissions between UpcH4 and SatWetCH4 are due :

1. to the different nature of the models. Even though they are calibrated using the same eddy covariance data, UpCH4 is based on a data-driven empirical approach, while SatWetCH4 uses a simplified process-based equation.
2. SatWetCH4 tends to underestimate fluxes in the tropics due to the regression process used to optimize the parameters of the equation.

3. UpCH4 simulated very high values in Australia and subequatorial Africa (Sahel) compared to SatWetCH4 (and GMB), as shown in Fig. 5 of McNicol et al. (2023) and on Fig.6 of our revised manuscript. UpCH4 fluxes over Australia represent 20.5 TgCH4 yr-1 (14% of the global total) which seems huge knowing that these regions are a desert or semi-arid area. These high methane emissions over Australia result from the use of the WAD2M product for constraining the wetland extent, and its known discrepancies. WAD2M is based on the SWAMPS dataset (Jensen et al., 2019). In fact, the microwave signature of deserts has similar characteristics to water, and the SWAMPS dataset misidentifies desert, snow, and coastal regions as flooded areas (see Sect. 3.3.1 of the manuscript, Pham-Duc et al., 2017, Bernard et al., 2024). The same misinterpretation occurs over the Sahel, with emissions of 13.8 TgCH4 yr-1. Thus, these two regions alone explain 34 TgCH4 yr-1 of the 60 TgCH4 yr-1 difference between SatWetCH4 and UpCH4.

We can still discuss the low value of our global total estimate using SatWetCH4, as there are several possible reasons for it. Firstly, this extremely simplified equation does not take into account all processes (oxidation and transport to the atmosphere) and their related parameters (such as a water proxy, vegetation type). Soil moisture is indeed relevant at the site scale and improves the predictions at site-level. However, we found that available soil moisture or water table products do not provide any pertinent information when taken at a coarse resolution of 0.25°. So we decided to exclude this for the moment. This information, which is often used in land surface models (Wania et al., 2013) on a scale of 0.5° or 1°, does not in fact add any benefit at that scale. Another reason could be the underrepresentation of tropical sites, which have generally larger fluxes than temperate and boreal sites. More data in the tropic areas, as underlined in McNicol et al. (2023), would help to better represent tropical wetland emissions, and in the case of SatWetCH4 could allow a specific fit per latitudinal band, or per wetland class. Finally, the site level calibration method can also lead to underestimation, as the site fluxes are measured all year long, even if the site is unsaturated, and this can lead to an underestimation of flux intensity at the global scale. This is due to the fact that dynamic wetland mapping products account for saturated or inundated areas, whereas site-level measurements conducted during the dry season are likely to underrepresent the emission intensity of saturated areas. Consequently, the parameters calibrated from dry season measurements may underestimate emission intensity when multiplied by the area of saturated wetlands.

These points are deeper discussed in lines 366-381 of the tracking changes manuscript.

"Figure 7 shows the latitudinal distribution per season for SatWetCH4 run with WAD2M and TOPMODEL, as well as the GMB LSMs, WetCHARTs ensemble, and UpCH4 estimates. The monthly variation for emissions estimates and wetland extent per latitudinal band is shown in Fig. 8. Note that the WetCHARTs models are calibrated to the GMB annual budget and are therefore not independent in terms of methane emission amplitude. SatWetCH4 is in the lower range of the GMB LSMs (grey areas), or even slightly below this range in the 30°S-30°N band. The total annual budget of SatWetCH4 wetland emission estimate averages 85.6 Tg CH4 yr−1 with WAD2M (resp.

70.3 with TOPMODEL), which is lower than the range of the GMB LSMs estimates (102 to 181 Tg CH_4 yr^{-1}) and the UpCH4 estimates (146 Tg CH_4 yr^{-1}) even the same wetland extent is used.

This discrepancy can be explained by 1. an underestimation of methane fluxes by SatWetCH4 especially of tropical fluxes (discussed in Sect. 3.2 and in the following paragraph) and 2. the consideration by WAD2M of desert regions as inundated areas, leading to methane fluxes overestimation in Australia and Sahel in UpCH4 and some diagnostic LSMs (see discussion Sect. 3.3.3, Fig. 6, S3 and 7). Indeed, Sahel and Australia represent 33.4 out of the 146 Tg CH_4 yr^{-1} estimated by UpCH4 using WAD2M, while these regions represent 4.5 Tg CH_4 yr^{-1} in SatWetCH4 using WAD2M.

The scarcity of site-level data in tropical regions, coupled with the absence of tropical peatlands and floodplain sites, has undoubtedly contributed to the uncertainty associated with the calibration of parameters. Furthermore, the use of site-level calibration for tropical wetland emission may result in an underestimation at the regional or global scale. This is due to the fact that dynamic wetland mapping products account for saturated or inundated areas, whereas site-level measurements conducted during the dry season are likely to underrepresent the emission intensity of saturated areas. Consequently, the parameters calibrated from dry season measurements may underestimate emission intensity when multiplied by the area of saturated wetlands. This is a less significant issue in temperate and Arctic regions, where the wet seasons occur in summer and there is minimal emission in winter. As the number of tropical sites increases, future studies could consider refining the calibration for the tropics, for example, by only using wet season measurements for calibration.

Note that this difference in total emissions could be easily resolved by calibrating the k parameter to the total emissions of the mean GMB LSMs if we need to constrain total emissions, as it has been done previously by Bloom et al. (2017); Gedney et al. (2019).”

Another key distinction that would be valuable to explore via inter-comparison with the UpCH4 product is the choice to use an empirically defined model itself, rather than a purely data-driven (random forest) model as in UpCH4. As a community we are being encouraged to combine our ecosystem science knowledge of good process representation with a full utilization of flux observations, enabled with machine learning. I imagine this study could become a useful baseline study of a purely empirical model, which arrives at one calibrated parameter set (one model) from optimization on all ground surface methane flux data, much as UpCH4 is intended as a baseline for a purely data driven model, which optimizes on the same dataset to identify, in effect, an ensemble of highly conditional predictive models. Neither method is anywhere close to perfect, and future advances are most likely in uniting the two, yet Bernard et al. make no mention of this modeling issue within their limitations section. The behavior of the purely data driven models is of particular concern during expansive extrapolations where models may behave in an unconstrained (by data) manner, yet in McNicol et al. 2023, we arrived at a more plausible global total of 146 TgCH4 y-1. A discussion of model equifinality and extrapolation is entirely absent and would be readily facilitated by comparison to our published study.

We added some discussion about the complementarity of the two approaches (lines 477-487 of the tracking changes manuscript):

Despite the impossibility of analyzing temporal variation due to WAD2M issues, Fig. 9 informs us that the temporal variations of SatWetCH4 are more similar to GMB LSMs than UpCH4. This is consistent with the fact that SatWetCH4 is a - highly simplified - process-based equation, whereas UpCH4 relies on empirical flux upscaling using random forest. SatWetCH4 and UpCH4 approaches both provide new independent estimates of wetland emissions, while offering distinct perspectives. A deeper comparison of the fluxes modelled by SatWetCH4 and UpCH4 at the site level could serve understanding differences between the simplification of complex processes represented by a fixed process equation (SatWetCH4) versus a machine learning data-driven approach (UpCH4). In addition, running both SatWetCH4 and UpCH4 with another wetland extent database would also serve to assess uncertainties and errors associated with WAD2M product and a better comparison of global methane emissions trends estimated by SatWetCH4 and UpCH4. Both methods are currently limited by the scarcity of eddy covariance flux data (McNicol et al., 2023), especially over important wetland methane emitting regions of the world, e.g., in the tropics (Congo, Sudd, Amazon) and Russia (Siberian lowlands).

A more specific concern not considered by the present study related to this issue of empirical model calibration is that recent work has demonstrated that the temperate dependency of methane flux varies in space and time, such that a single temperature dependency is almost certainly an erroneous model framework assumption (Chang et al. 2021; Yuan et al. 2024). This is not addressed at all in the present study, nor are these two recent and high profile paper cited.

Chang, K.-Y., Riley, W. J., Knox, S. H., Jackson, R. B., McNicol, G., Poulter, B., et al. (2021). Substantial hysteresis in emergent temperature sensitivity of global wetland CH4 emissions. Nature Communications, 12(1), 2266. https://doi.org/10.1038/s41467-021-22452-1

Yuan, K., Li, F., McNicol, G., Chen, M., Hoyt, A., Knox, S., et al. (2024). Boreal-Arctic wetland methane emissions modulated by warming and vegetation activity. Nature Climate Change, 14(3), 282–288. https://doi.org/10.1038/s41558-024-01933-3

In our study, the $Q_{10}(T)$ value is not constant but depends on temperature ($Q_{10}(T) = Q_{0\ 10}^{T0\ /T}$). Ideally, we could adjust Q_{10} to better match the observations, which would indeed be an improvement. Nonetheless, it is clear that Q_{10} is one of, but not the primary, sources of uncertainty in our results. We conducted tests by latitude band or wetland types to explore this further. Unfortunately, fitting Q_{10} on such groups is not reliable due to currently insufficient data.

We added some discussion about the $Q_{10}(T)$ simplification in the discussion lines 466 and 474-476, along with citation of the suggested literature:

“Indeed, Q10 was found to depend on ecosystems (Chang et al., 2021)”

“Some refinement of the Q10 function (here $Q_{10}(T) = Q^0{}_{10}{}^{T0/T}$ according to Gedney (2004)) could be envisioned, such as the incorporation of a temperature hysteresis (Chang et al., 2021).”

I am also concerned that the concept, structural elements, and visualization choices are remarkably similar to our 2023 study, despite no citation being present.

Although we agree that we should have cited your study and compared the results of SatWetCH4 with UpCH4, we disagree with this comment. Indeed, we were surprised by this remark implying a copy of your work.

First, as explained in the preamble to this document, almost all the study and the Figures were produced in 2022 / first part of 2023 before the publication of your paper.

The present SatWetCH4 study was also presented in June 2023 at the NCGG9 conference. If needed, we can provide versioning of the scripts used and of manuscripts, even if this suspicion is absurd given the classic structure of our manuscript and of the Figures.

Out of the ten figures in our study, only two are similar to yours: the flux towers localization maps and the flux visualization map. These are standard figures also used in several papers, e.g., the Global Methane Budget (Saunois et al., 2020) or FluxNet-CH4 paper (Delwiche et al., 2021) as shown below.

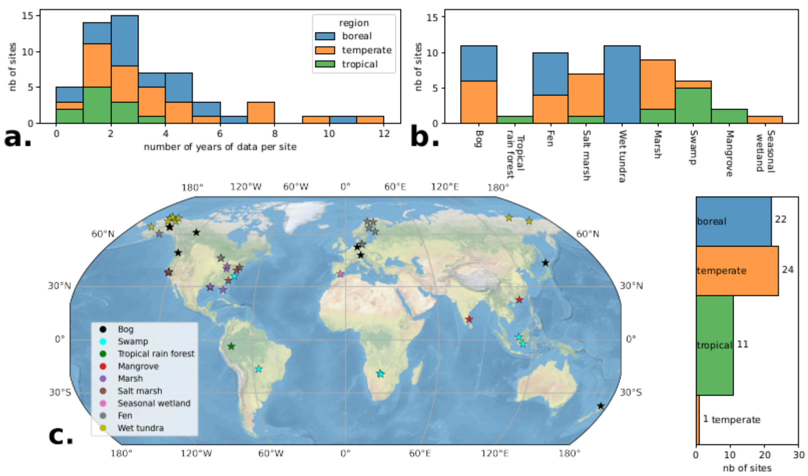

Figure 1 of our manuscript

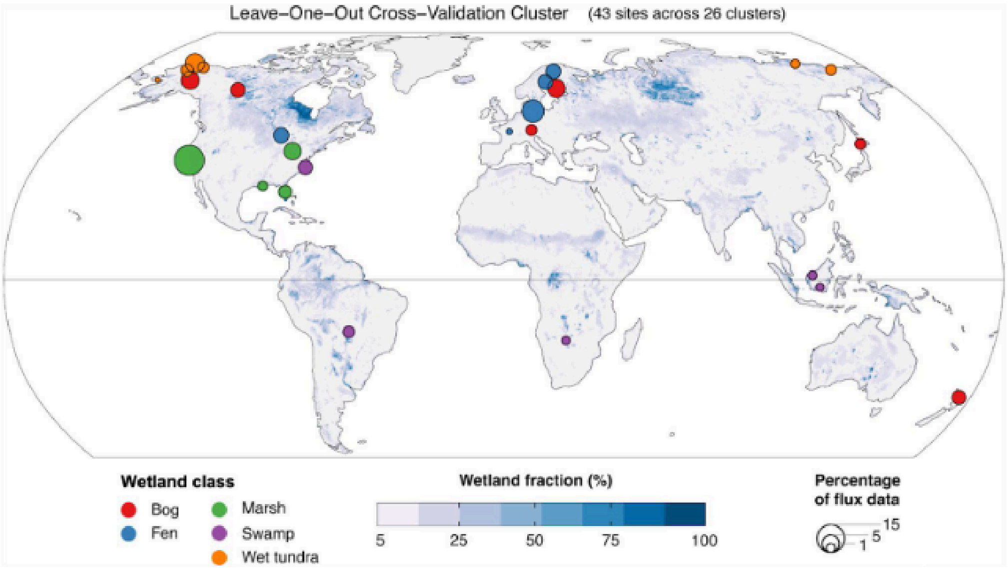

Figure 2 of McNicol et al., 2023

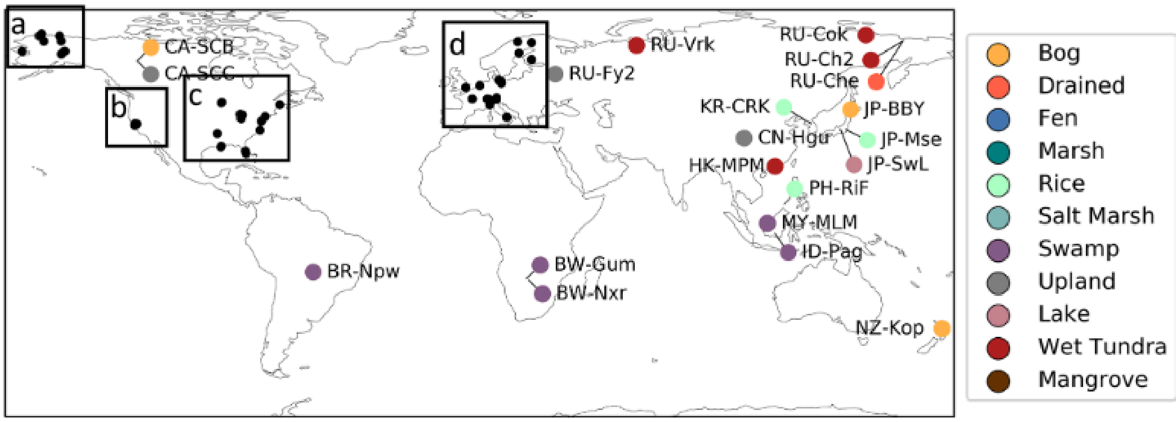

Figure 3.a of Delwiche et al. (2021)

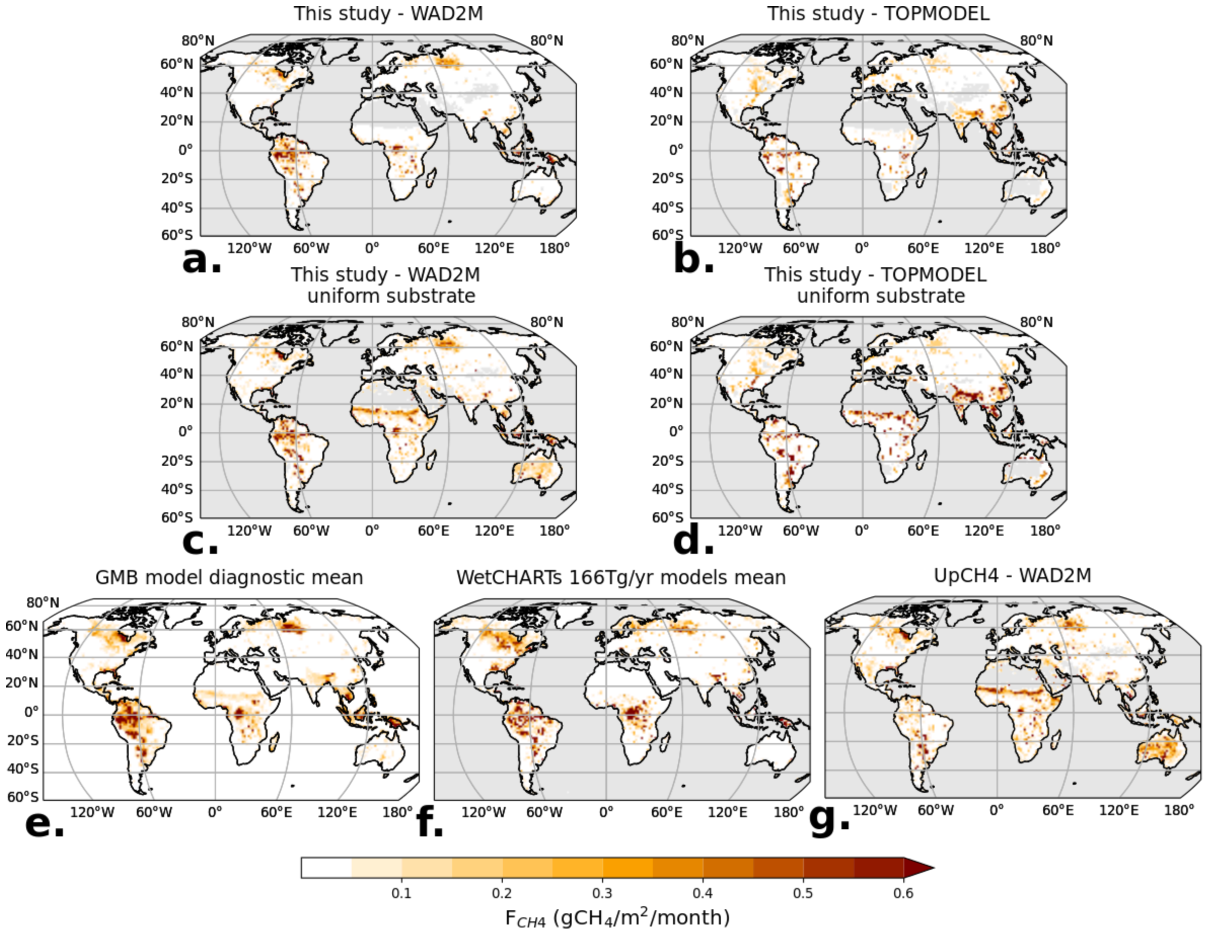

Figure 6 of our manuscript

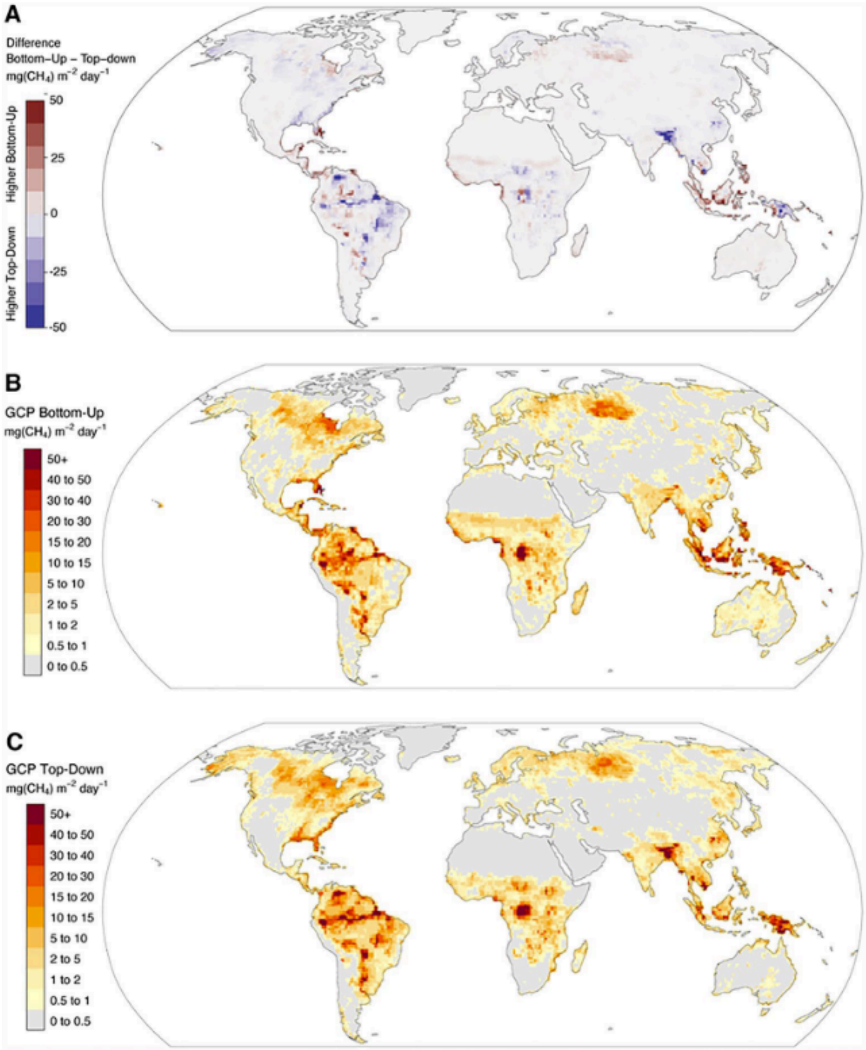

Figure 1 of McNicol et al. (2023)

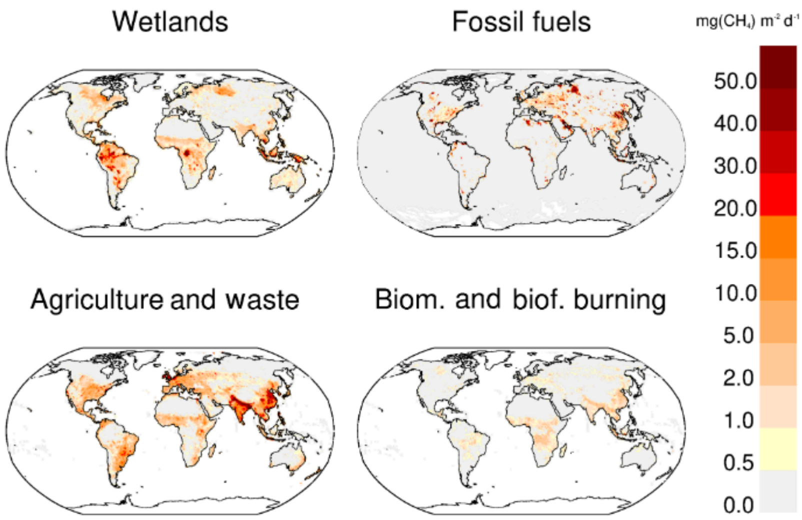

Figure 3 of Global Methane Budget, Saunois et al., 2020.

In addition to our project leads, our study included over 50 co-authors to honor the terms and spirit of a data policy agreement designed to provide fair credit to a large and growing international community of eddy covariance scientists. I was heavily involved in the acquisition of data in FLUXNET-CH4 v1.0 and a common concern voiced by international investigators outside Europe and North America, whose contributions would do much to address the data and community biases present across the global contributor network, was that their data may be used in high profile global synthesis studies for which they would not receive fair credit. While Bernard et al. do cite Delwiche et al. 2021, which is the dataset release paper, citing our study would ensure that the spirit of the data policy of the original FLUXNET-CH4 synthesis was not undermined by omission on downstream FLUXNET-CH4 upscaling work. The authors should also include, as indicated on the FLUXNET website, the second of the following to CC-BY data attribution requirements to include the DOIs of the sites contributing data:

Data use should follow these attribution guidelines for CC-BY-4.0:

- Cite the data-collection paper, for example, for FLUXNET2015, cite Pastorello et al. 2020[1]
- *List each site used by its FLUXNET ID and/or per-site DOIs in the paper (these DOIs are provided with download)*

Fluxnet.org/data/data-policy/ accessed July 6, 2024

We are fully aware of and grateful for the collaborative efforts of all the PIs of the EC Flux Tower and have acknowledged them in the Acknowledgements section:
Acknowledgements. [...] The authors would like to thank the managers of the 55 out of 58 eddy covariance flux towers who made their data available as open source. These data play a crucial role in improving our understanding of methane emissions from wetlands and in calibrating the models more accurately.

We have tried to follow the legacy statement carefully by 1. citing the reference papers of the databases we used and 2. citing all DOIs of the 58 EC flux tower data used in the supplementary material attached to the manuscript (Table S2). We only used CC-BY-4.0 data from the FluxNET-CH4 and AmeriFlux datasets. For Euroflux, as some sites were not under CC-BY-4.0, we contacted the site PI to ask for permission to use their data and proposed co-authorship for non-legacy sites.

We believe that we are following the legacy terms fairly. We understand why you included all sites PI in your paper, as your upscaling approach relies heavily on FluxNET-CH4 fluxes, which is not the case in your study.