Understanding the balance between methane production and oxidation from wetlands: insights from a reduced process-based model

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We thank the Editor and the reviewers for their careful reading of the manuscript and for their constructive and insightful comments. We have addressed all points raised below, with corresponding revisions highlighted in red in the marked version of the manuscript. We believe these changes have strengthened the clarity of the work.

I have read the manuscript. I thought the paper was well written and followed a logical workflow. This study provides an excellent example of using extensive field data to parameterize a simplified, quasi-mechanistic modeling approach.

Response: We thank the reviewer for their positive feedback on our manuscript. We have carefully considered their revision points and provide detailed responses below to address each comment.

The paper could have provided more information on the data source, which fluxes were used? Each wetland had 5 wetland chambers and 3 upland chambers in each wetland. Were only wetland chambers used? Was there any averaging across chambers?

Response: We thank the reviewer for raising this point. For this study, we used flux data exclusively from the central chamber (Chamber 1) in each wetland. We did not include data from upland or peripheral chambers in order to maintain consistency and focus on the primary wetland methane dynamics at the wetland centre. Hence, there was also no averaging across multiple chambers in this analysis. We have clarified this point in the revised manuscript (pg. 11, lines 260–262):

"Given our focus on the wetland centre, we use flux measurements from a single chamber located near the centre of each wetland (Chamber 1 in the dataset). Measurements from other wetland or upland chambers are not included in the analysis."

I also questioned some assumptions in the notes below. The authors should mention the role of methylotrophic methanogenesis, particularly in PPR wetlands (Dalcin et al. https://doi.org/10.1111/gcb.13633, Bechtold et al. https://doi.org/10.1038/s41467-025-56133-0).

Response: We thank the reviewer for highlighting the potential importance of methylotrophic methanogenesis, particularly in PPR wetlands. Indeed, whilst traditional wetland methane models focus on hydrogenotrophic and acetoclastic pathways, recent studies demonstrate that methylotrophic methanogenesis can contribute substantially to methane emissions in wetlands with diverse organic inputs. Hence, we have updated the text (pg. 6, lines 133–142) to recognise this alternative pathway:

"Three methanogenic pathways contribute to CH_4 production in wetlands: hydrogenotrophic, whereby bacteria reduce CO_2 with hydrogen to form CH_4; acetoclastic, in which bacteria convert acetic acid from decomposing organic matter into both CH_4 and CO_2; and methylotrophic methanogenesis, in which specialised methanogens convert methylated compounds (e.g. methanol, methylamines, or methyl sulfides) into CH_4, and may be particularly important in PPR wetlands (Conrad, 1999; Bechtold et al., 2025, Dalcin Martins et al., 2017, Thauer et al., 2008). Biomass availability thus plays a crucial role in all three pathways: directly through litter input for acetoclastic methanogenesis, indirectly via CO_2 production for hydrogenotrophic methanogenesis, and by supplying methylated compounds for methylotrophic methanogenesis. Despite differences in substrates and microbial mechanisms, we combine these pathways into a single effective methanogenesis term for model simplicity. To represent this dependence, we use the Normalised Difference Vegetation Index (NDVI) as a proxy for available plant biomass."

There are also methane production in oxic water columns and anerobic conditions that support methanotrophy. These were not discussed.

Response: We thank the reviewer for raising this important point. Indeed, methane production has been observed in oxic water columns via non-canonical pathways such as demethylation of methylated compounds, and anaerobic methane oxidation can proceed using alternative electron acceptors like nitrate, iron, or sulphate. These processes are particularly relevant in redox transition zones and dynamic wetland environments.

In the present study, we focus on the dominant sedimentary methane production and aerobic oxidation processes most commonly invoked to explain wetland-scale CH_4 emissions. Oxic methane production and anaerobic methane oxidation are not represented explicitly, as incorporating them would require additional mechanistic detail and parameters beyond the scope of this reduced, zero-dimensional model framework. However, we acknowledge their role in the updated manuscript (pg. 6, lines 129–132; pg. 7, 172–175):

"Note that, whilst methanogenesis predominantly occurs in anoxic soil layers, small amounts of CH_4 may also be produced in oxic layers via micro-anoxic microsites within the soil column (Angle et al., 2017). These contributions are not explicitly resolved in our model, which focuses on bulk soil CH_4 production as the dominant source."

"Moreover, our model assumes that CH_4 oxidation occurs predominantly under aerobic conditions in the unsaturated soil zone. Anaerobic oxidation of CH_4 in saturated layers, which requires alternative electron acceptors (e.g. sulphate or nitrate, see Segarra et al., 2015), is not explicitly resolved and may slightly reduce net CH_4 flux in some wetlands."

We note that variation in these processes among wetlands is implicitly captured by calibrating methane production parameters (k_p, Q_p) and oxidation parameters (k_o, Q_o, p_2). For example, a shallower decline in oxidation rate (i.e. lower p_2) may reflect the influence of anaerobic methane oxidation.

Title: Minimalist emissions model is very jargony and will lose audience immediately.

Response: We thank the reviewer for this suggestion and have revised the title to:

"Understanding the balance between methane production and oxidation from wetlands: insights from a reduced process-based model",

to emphasise process-level insight and improve accessibility to a broad readership.

Find a more universal definition of wetlands. Bansal et al. 2023 methods review paper has a lot of basic wetland info and citations: https://doi.org/10.1007/s13157-023-01722-2

There are many other types of wetlands. The PPR wetlands are often less than 0.1 ha. Use a couple PPR-specific citations. newer citation on wetland loss. Fluet-Chouinard et al. https://www.nature.com/articles/s41586-022-05572-6

Response: We thank the reviewer for these these suggestions. To address these, we have included some extra PPR-specific references and have revised the opening paragraph of the manuscript (pgs. 1–2, line 15–27):

"Wetlands are soil-water ecosystems in which the persistent or recurring presence of water at or near the land surface strongly influences physical, chemical, and biological processes (

(Bansal et al., 2023a; Mitsch and Gosselink, 2015). Spanning a wide range of water depths and hydroperiods, wetlands occur in many forms, including marshes, swamps, bogs, fens, floodplain wetlands, tidal wetlands, and small, geographically isolated systems. Individual wetlands can range in size from well under 1 ha, as is typical for wetlands of the Prairie Pothole Region (PPR) of North America (Goldhaber et al., 2014), to expansive complexes covering hundreds or even thousands of square kilometres (Junk, 2024). Serving as a boundary between land and aquatic environments, these diverse and dynamic ecosystems provide a habitat for a variety of plants, animals, and microbes whilst also performing critical ecological functions such as water filtration, retention, and purification (Bridgham et al., 2006; Gleason et al., 2011; Zedler and Kercher, 2005). Given this wide array of functions, wetlands are often touted as a possible nature based solution (e.g. for flood prevention Ferreira et al., 2023) and there has been a recent push for their enhanced conservation given their previous loss due to anthropogenic activities, including widespread drainage, land conversion, and hydrological alteration associated with urbanisation and agricultural intensification (Bradford, 2016; Evenson et al., 2018; Fluet-Chouinard et al., 2023; Verhoeven and Setter, 2010)."

Or uptake GHGs Not clear in sentence that methane or all three gases are the focus.

Response: We thank the reviewer for highlighting this ambiguity. The text has been revised (pg. 2, lines 28–32) to clarify that wetlands may function as both sources and sinks of greenhouse gases, and that our analysis focuses specifically on methane dynamics:

"...sequestering substantial amounts of carbon in their soils and storing roughly one-third of global soil carbon despite covering only 5–8% of the land surface (Mitsch et al., 2013). Through active microbial processes, wetlands can both emit and uptake greenhouse gases (GHGs), including carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) (Bridgham et al., 2006; Salimi et al., 2021). In this study, we focus specifically on CH_4 dynamics, examining the balance between CH_4 production, oxidation, and emission from wetlands."

Fig. 1. Most of the abbreviations are not labeled. More labels/graphics to make this information and a conceptual figure would help.

Response: We thank the reviewer for this suggestion. Accordingly, we have revised Fig. 1 (pg. 5) to include a schematic representation of the wetland showing soil columns under varying hydrological conditions, indicated the modelled environmental drivers for CH_4 production, oxidation, and emissions, and added further details to the figure caption to improve clarity. We have also included conceptual plot (Fig. 1g), highlighting the non-linear dependence of methane emissions on water table depth.

Water in soils doesn't really dilute the DOC. If fresh water was moving through the soils, then maybe.

Response: We thank the reviewer for highlighting this issue. We agree that water in saturated soils does not inherently dilute dissolved organic carbon unless there is advective exchange with fresh water. We have therefore revised the manuscript (pg. 6, lines 119–122) to clarify that waterlogged conditions influence CH_4 production primarily through changes in redox conditions, substrate accessibility, and transport processes, rather than simple dilution effects:

"However, waterlogged conditions can reduce CH_4 production if the available carbon substrate becomes distributed over an increasingly large water column above the soil surface, effectively reducing substrate availability for methanogenesis depending on the degree of mixing."

There are three pathways. Methylotrophic methanogenesis may be very important in PPR wetlands

Response: In response to the reviewer's earlier comment, we have revised the manuscript to include a discussion of methylotrophic methanogenesis.

>30 degree days are more likely in the future. Impact?

Response: We appreciate the reviewer's comment on temperature dependence. Our model uses a simplified function (Eq. 5) in which methane production increases to 30°C and is held constant thereafter. This approach provides parsimony and captures typical saturation in production rates. In reality, microbial responses are complex, with thermal optima varying between pathways and communities; sustained temperatures above 30°C may either continue to increase production or suppress it if microbial activity declines beyond the optimum. The net effect is likely to vary across wetlands and warrants further investigation. We have added a brief discussion of this point in the manuscript (pg. 7, lines 156–159):

"Under future climate scenarios with more frequent extreme heat, CH_4 production may continue to increase above 30°C, in which case our current formulation would be conservative. Alternatively, enzymatic and microbial activity may decline above their thermal optimum due to heat stress, potentially suppressing production. The net effect will likely vary among wetlands with different thermal regimes and microbial communities, and warrants further modelling investigation."

Plant transport is very dependent on water table. If zw=zb, then plant transport will not be any different than diffusion in terms of methanotropy. When water table is higher, zw>zs, then plant transport allows methane to skip past methanotrophy (Bansal et al. 2020)

Response: We thank the reviewer for highlighting this point. We have clarified in the revised manuscript (pg. 8, lines 203–205) that plant-mediated methane transport is strongly dependent on water table depth:

"The effectiveness of this bypass increases with higher water tables, particularly when $z_w > z_s$, as plant-mediated transport can transport CH_4 directly from saturated soil to the atmosphere, thereby avoiding oxidation in near-surface oxic zones (Bansal et al., 2020)."

use a PPR citation

Response: We thank the reviewer for this suggestion. As the specific location for the PPR citation was not indicated, we have added appropriate PPR references to our discussion of precipitation and temperature variability in mid-latitude wetlands (pg. 9, line 232), as well as to our section on the role of ebullition in wetland emissions (pg. 8, line 208).

Variables could use more details, NDVI (from Landsat satellite imagery), soil temperature (or water temperature when zw>5 cm), water-filled pore space (top 5 cm soils). Do these detail affect model or interpretation?

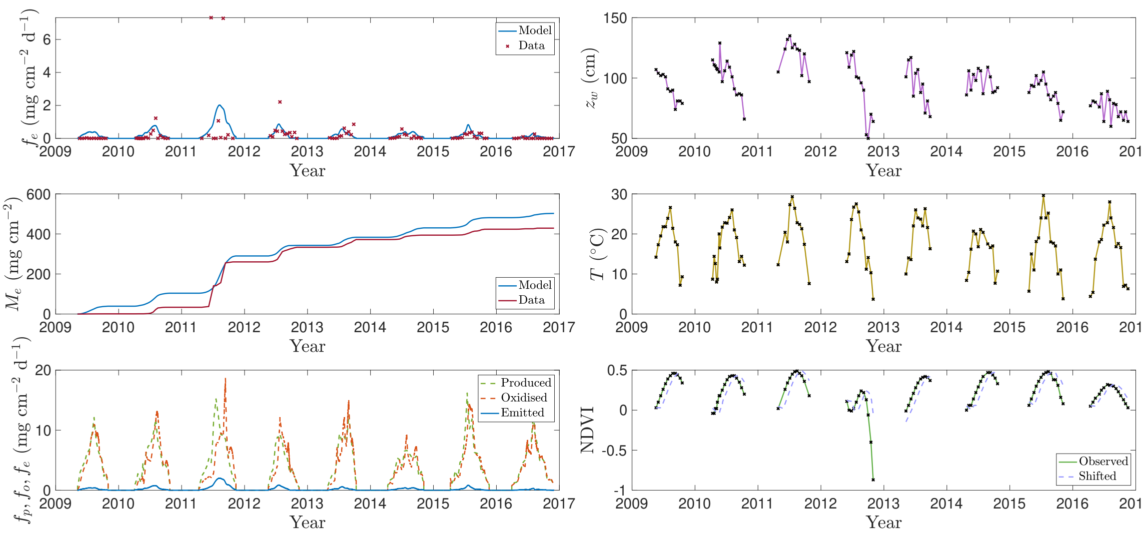
Response: We appreciate the reviewer's request for clarification. Full measurement details are provided by Bansal et al. (2023b), but we have added a brief summary in the revised manuscript (pg. 11, lines 278–287) to describe the key variables used to force the model:

"Full details on the measurements used to force the model are provided by Bansal et al. (2023b), but we summarise briefly here. Methane fluxes were measured in the wetland zone of undrained Prairie Pothole wetlands using static chambers deployed on sediment or floats along a single transect per wetland, with five wetland-zone sampling locations spaced from the edge to the centre. Measurements were collected approximately every two weeks during the growing season (May-November), between 10:00 h and 14:00 h, and included water depth, soil temperature (or water temperature when the water table exceeded 10 cm), air temperature, and soil volumetric water content (with WFPS calculated by dividing by soil porosity). NDVI corresponding to each sampling event was obtained from Landsat imagery to represent vegetation availability. These variables provide the spatially and temporally resolved forcing used in the chamber-scale model. As measurements are limited to the top 5–10 cm of soil (or water surface), daytime sampling, and relatively coarse NDVI (30 m), short-term heterogeneity may be smoothed or under-represented."

As measurements are limited to the top 5–10 cm of soil (or water surface), daytime sampling, and relatively coarse NDVI (30 m), short-term spatial or diurnal heterogeneity may be smoothed. These limitations could modestly affect model interpretation at fine temporal or spatial scales, but the overall seasonal and interannual patterns captured by the model are likely robust.

It is possible that removing those high emissions from the dataset is causing the poor performance in P8, which is driven by high rates of ebullition.

Response: We thank the reviewer for this suggestion and tested fitting the model without removing extreme outliers to assess whether this improves performance for wetland P8 (see figure below).



Model performance did not noticeably improve. The model still fails to capture the emissions peak in 2012 (present in both datasets) and cannot reproduce the extreme peaks in 2011 (removed in the outlier-filtered dataset). The model does, however, approximate similarly high cumulative annual emissions by smoothing these effects over the year. This limitation likely stems from our simplified assumption of constant ebullition throughout the year, which neglects hydrostatic, atmospheric pressure, and temperature effects, each of which can strongly influence ebullition rates (2011 was particularly hot, for example). As discussed in the manuscript, this represents an avenue for future model refinement.

Fig 5. Perhaps put area in hectares

Response: We thank the reviewer for this suggestion. To improve clarity, we have updated Fig. 5 (pg. 16) to report wetland area in hectares.

methylotrophic pathways too.

Response: We thank the reviewer for pointing this, and have updated the text (pg. 23, line 559) to acknowledge this pathway too:

"...hydrogenotrophic, acetoclastic, and methylotrophic methanogenesis pathways..."

Fig 6s. How did T9 have such high emissions (Me) but very low emissions in panel c?

Response: We thank the reviewer for raising this question. Wetland T9 exhibits very high methane production, reflected by a large methanogenesis scaling constant ($k_p = 7.55 \times 10^1$ mg CH_4 cm^{-2} d^{-1}), alongside a high oxidation rate constant ($k_o = 2.00 \times 10^2$ d^{-1}) with weak decay with water depth ($p_2 = 1.87 \times 10^{-2}$). This creates a dynamic balance in which intense methanotrophic oxidation substantially offsets the high methane production.

Production in T9 is strongly temperature-dependent and peaks during summer, particularly under inundated conditions (reflecting the weak decay of production with increasing water depth), whereas oxidation exhibits minimal temperature dependence and can persist outside the summer months. Although production rates are extreme, strong oxidation suppresses net emissions; nonetheless, the elevated production, combined with predicted ebullition and plant-mediated transport, still yields relatively high observed CH_4 fluxes. The model therefore captures T9's methane cycling as characterised by vigorous production coupled with efficient oxidation. This demonstrates the necessity of jointly considering both processes and their seasonal dynamics when interpreting emission patterns across wetlands.