

# Reply to Anonymous Referee #2 for “Underestimation of Anaerobic Decomposition Rates in Sphagnum Litterbag Experiments by the Holocene Peatland Model Depends on Initial Leaching Losses”

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Comments made by the reviewer start with a bold **Q** while our reply starts with a bold **A**. In section “Additional changes” we list additional changes we would like to incorporate in an updated version of the manuscript.

## 1 Reply to comments

1. **Q:** This manuscript describes a study in which Sphagnum moss litterbag data was used to evaluate whether the decomposition module of the Holocene Peatland Model (HPM) can predict correctly Sphagnum litter decomposition rates. In between the experimental data and HPM, there was a litterbag model (hereafter I’ll use my own acronym LBM) that was used to estimate decomposition rates from the data. The LBM is described by the authors in another manuscript that is also under review in Egusphere.

Several different versions of the model test set-up were used. Firstly, decomposition rates from HPM ran with the standard parameter values were compared against decomposition rates from standard LBM. In addition to this, the decomposition rates were estimated with Bayesian statistics by letting different parameter sets of HPM vary. The authors found that the standard HPM underestimates anaerobic decomposition rates for many moss species and predicts too steep decrease of decomposition rates from oxic to anoxic conditions.

The topic is useful and relevant, and the authors seem to have done lots of work, but the methods and materials should be described in more detail and clarifications are needed in the manuscript. In my opinion, in its present form, it is difficult to follow the text, and some information is missing - although I have to admit I'm not especially familiar with the Bayesian methods. In particular, I find the role of the LBM and the Bayesian modelling unclear. Below are my specific comments and questions. I focused on the Methods section since I think it is important to modify it first.

**A:** We thank the reviewer for their helpful comments. We agree that we should have described in more detail which equations of the HPM are considered as HPM decomposition module, how we modified them, and how we linked them to the LBM. We hope that our changes suggested below address the issues. In particular, we suggest an extensive re-write of all sections of the manuscript to address the reviewer comments and have attached an updated version to show how this manuscript would look like.

2. **Q:** The abstract text does not mention the LBM (=the litterbag model) at all

**A:** We thank the reviewer for this suggestion. We suggest to change the second sentence of the abstract (l. 2 to 3) from

“Here, we test whether the HPM decomposition module can predict decomposition of available *Sphagnum* litterbag data along a gradient from oxic to anoxic conditions and estimate parameter values from the litterbag data.”

to

“Here, we estimate parameter values of the HPM decomposition module from available *Sphagnum* litterbag experiments included in the Peatland Decomposition Database and with a litterbag decomposition model that considers initial leaching losses. Using either these estimates or the standard parameter values, we test whether the HPM decomposition module fits decomposition rates ( $k_0$ ) in *Sphagnum* litterbag experiments along a gradient from oxic to anoxic conditions.”

Please also see our reply to comment 8 of reviewer 2 for more information about the purpose of the LBM in our study here.

3. **Q:** l. 3: Please correct “conditionsand”

**A:** We will correct this typo as suggested.

4. **Q:** l. 13-14: Is this a correct sentence?

**A:** We think that this is a correct sentence, but we re-wrote the entire abstract section to consider the comments of all reviewers and this part of the abstract was changed completely and should be more readable now.

5. **Q:** l. 29-30: An unclear sentence (do the equations cause observed discrepancies less reliably, or do the tests identify things less reliably?)

**A:** We agree that this sentence can be improved. We suggest to change it from

“First, they test entire peatland models against observed data and thus can identify the parameter values or model equations that cause observed discrepancies less reliably.”

to

“First, they cannot reliably identify the parameter values or model equations that cause discrepancies between model predictions and measurements because they test entire peatland models against observed data.”

6. **Q:** l. 50: Please clarify what you mean with “HPM uses litterbag data”. Were the standard parameters derived from litterbag data?

**A:** Froelking et al. (2010) states that  $k_0$  values in the HPM were defined based on litterbag experiments, but the study does not explicitly mention data sources (except Moore et al. (2007)) or modeling (parameter estimation) approaches.

To avoid ambiguities, we suggest to replace “The HPM uses litterbag data to define average decomposition rates of moss plant functional types ...” by “The HPM derives initial decomposition rates of moss plant functional types from litterbag data ...”.

Here are the passages from Froelking et al. (2010) that describe how litterbag data were used: “Litter bag decomposition rates are determined by fitting mass loss data [from litterbag experiments] to an exponential function,  $m(t) = m_0 \exp(-kt)$ , under the assumption that  $k$  is a constant ( $\frac{dm}{dt} = -km$ ); since HPM represents litter/peat decomposition as an initial rate  $k_0$ , that declines linearly with mass loss (i.e.,  $\frac{dm}{dt} = -\frac{m}{m_0}k_0m$ ), the litter bag  $k$ -values need to be modified to  $k_0$  values. We have modified these so that, after 5 years of decomposition they have approximately the same mass loss (see Table 1).”

In the footnote to the referenced table, Froelking et al. (2010) states: “ $k_0$  are the tissue initial decomposition rates, determined by  $k_0 = k(1 + 3k)$ , where  $k$  is first order exponential decay rate, i.e.,  $m(t) = m_0 \exp(-kt)$  (e.g., Moore et al. (2007)), and  $k_0$  is the value that gives similar  $m(t)$  at  $t \sim 5$  years (i.e., near the end of reliable values from a litter bag field decomposition study) when  $m(t) = m_0/(1 + k_0t)$  (e.g. Froelking et al., 2002), the formulation used in HPM., E.g., if  $k = 0.15 \text{ y}^{-1}$ ,  $k_0 = 0.22 \text{ y}^{-1}$ ,  $\exp(-5k) = 0.47$ ;  $1/(1 + 5k_0) = 0.48$ .”

7. **Q:** l. 66-68: Are you referring to your own LBM, or are there many models compatible with HPM? Please clarify.

**A:** The sentence starting in l. 65 is: “Remaining masses in litterbag experiments are often very variable, even under controlled environmental conditions (e.g. Bengtsson et al. (2018)), and for many litterbag experiments, a range of decomposition rates may produce similar predictions for remaining masses if a litterbag decomposition model compatible with the HPM is used (Teickner et al., 2024).”

A model that is compatible with the HPM is one that uses equation (7) in Froelking et al. (2010) to describe mass losses in dependency of  $k_0$ . To our knowledge, the formula for remaining masses used in the HPM (equation (7) in Froelking et al. (2010)) has not been used by any litterbag study so far, except our modified version (equation (1) in our manuscript) that we used in Teickner et al. (2024) to estimate decomposition rates and initial leaching losses from *Sphagnum* litterbag experiments.

That a “range of decomposition rates may produce similar predictions for remaining masses” is due to large errors in estimates for initial leaching losses that can be derived

from available litterbag data and not because of using equation (7) in Frolking et al. (2010) to analyze litterbag data.

Thus, we just wanted to state that even a test of only the decomposition module has uncertainties because initial leaching losses of not well constrained magnitude cause errors in decomposition rate estimates and this also happens when the litterbag decomposition is analyzed with the equation for mass loss used in the HPM.

To clarify this sentence, we suggest to change it to:

“Remaining masses in litterbag experiments are often very variable, even under controlled environmental conditions (e.g., Bengtsson et al., 2018), and for many litterbag experiments, a range of decomposition rates may produce similar predictions for remaining masses (e.g., Yu et al., 2001), also if a litterbag decomposition model compatible with the HPM is used (Teickner et al., 2024).”

If the reviewer thinks that this does not address the issue, we would be grateful for further suggestions.

8. **Q:** l. 87-88: In my opinion, you need to tell here, and especially in the Methods section, more about your LBM. It remains unclear what kind of it is and what is its purpose. Why is a separate model needed to derive the decomposition rates from the litterbag data?

**A:** We thank the reviewer for this suggestion and apologize that we did not provide a more detailed description of the purpose of the LBM.

Our LBM has two purposes: First, as described in our reply to the previous comment by reviewer 2, it makes equation (7) in Frolking et al. (2010) compatible with litterbag experiments by including initial leaching losses; however this can also be seen as a simple modification of the HPM decomposition module and not a separate LBM. Second, there are many litterbag studies that do not provide the necessary data (water table depth) to make predictions with the HPM decomposition module, but they still provide information on initial leaching losses and average decomposition rates for individual species that are useful to constrain decomposition rate and initial leaching loss estimates. Our LBM is a hierarchical model that pools information of these experiments and experiments that provide data to make predictions with the HPM decomposition module and therefore helps to constrain estimates of the HPM parameters. We agree that it is necessary to make this clear in the introduction, but we now also think that we gave our LBM a too prominent place in the introduction which may be more confusing than helpful at this place.

We suggest to rewrite the entire paragraph (ll. 87 to 91) from

“To address these aims, we developed a model that combines the HPM decomposition module and our previous *Sphagnum* litterbag decomposition model, which estimates decomposition rates in available litterbag experiments while considering initial leaching losses (Teickner et al., 2024). Estimated decomposition rates of this model can be directly compared to decomposition rates predicted by the HPM decomposition module because the formula to compute remaining masses from decomposition rates is the same.”

to

“To address these aims, we used the HPM decomposition module to predict decomposition rates in available litterbag experiments and compared these to decomposition rates estimated for the same litterbag experiments with a litterbag decomposition model that considers initial leaching losses (Teickner et al., 2024) (Fig. 1). These predictions require the peat degree of saturation, which we estimate with the modified Granberg model (Granberg et al., 1999; Kettridge and Baird, 2007) from water table depth data reported in these studies. Furthermore, some *Sphagnum* litterbag experiments do not report water table depths and therefore cannot be used to test the HPM, but they still provide information on initial leaching losses and decomposition rates and therefore help to constrain parameter estimates. We therefore include these data via Bayesian hierarchical modeling in the litterbag decomposition model. In summary, our approach combines the HPM decomposition module, the modified Granberg model, and a *Sphagnum* litterbag decomposition model that allows to consider initial leaching losses and to pool information across litterbag experiments (Teickner et al., 2024). While this approach has its limitations, it exploits available data as far as possible, while considering known confounders and propagating relevant uncertainties.”

Please note that “Fig. 1” refers to the new figure suggested by reviewer 2 in comment 12.

9. **Q:** l. 89: Please define what is “initial leaching loss”.

**A:** We agree that it is a good idea to define “initial leaching loss” and to describe its relevance. We define “initial leaching losses” as losses of soluble compounds during the first days to weeks of decomposition that do not originate from microbial depolymerization due to leaching (Teickner et al., 2024). We suggest to introduce “initial leaching loss” already earlier by changing the part starting in l. 59 from

“Since decomposition rates have been estimated with different litterbag decomposition models in previous studies, their values are not directly comparable and therefore raw data are necessary to obtain estimates directly comparable to predictions from a certain peatland model (Yu et al., 2001; Teickner et al., 2024). Recently, we used available *Sphagnum* litterbag data to estimate decomposition rates which can be directly compared to decomposition rates predicted by the HPM (Teickner et al., 2024).”

to

“Since decomposition rates have been estimated with different litterbag decomposition models in previous studies, their values are not directly comparable. Moreover, initial leaching losses (losses of soluble compounds, which do not originate from microbial depolymerization, due to leaching during the first days to weeks of incubation) can bias decomposition rate estimates if they are not explicitly considered and can vary between species and experiments (Yu et al., 2001; Teickner et al., 2024). Therefore, raw data (remaining masses) are necessary for any meaningful test of decomposition modules with litterbag data. The recently published Peatland Decomposition Database (Teickner and Knorr, 2024) contains raw data from available *Sphagnum* litterbag experiments

and therefore allows to estimate parameters with any mass loss-based decomposition model and therefore also allows to consider initial leaching losses.”

10. **Q:** l. 94-95: What do you mean by “Our test”: this current work or an earlier study?

**A:** We mean the current work. To avoid misunderstandings, we suggest to change

“Our test identified discrepancies between the HPM and litterbag data that could give novel insights into processes controlling anaerobic decomposition rates in future litterbag experiments”

to

“Similarly, the parameter discrepancies identified here suggest future litterbag experiments that would provide novel insights into oxic and anoxic controls of *Sphagnum* decomposition rates and our study therefore suggests a strategy to improve decomposition modules in general.”

11. **Q:** Table 1: Can you please add here also the other parameters that you are optimizing, alpha and  $l_0$ . It would make it easier to follow the text, if all the parameters could be checked from here.

**A:** We suggest not to add  $\alpha$  and  $l_0$  to Tab. 1 because we did not aim to estimate  $\alpha$  from the litterbag data and because  $l_0$  is no parameter of the HPM, but a parameter we defined in our previous study (Teickner and Knorr, 2024) (implicitly, the HPM assumes  $l_0 = 0$ ).

We understand that it may be useful to have a list of all model parameters with their definitions, but we fear that such a list may be cause confusion about which parameters we intended to test. We therefore think that it is more useful after all to only show parameters of the HPM decomposition module we actually tested in Tab. 1.

We did not try to test  $\alpha$  with the litterbag data because previous studies (e.g., Frohling et al. (2001)) suggest that litterbag data are too short and (currently) have too large errors to estimate  $\alpha$  correctly and also our previous study (Teickner and Knorr, 2024) suggests this. We estimate  $\alpha$  only to propagate an approximate error estimate for this parameter.

Please note that the models include many more parameters than shown in Tab. 1. These parameters are now defined throughout the text and will be listed in supporting Tab. S1 in the updated version of the supporting information.

12. **Q:** It would be great to have a schematic picture that illustrates the relationship between the different models and data that you use. If possible, it could include some more general information of the HPM. There apparently are also other parts in the model, as you focus only on a small part of it (the decomposition module). Are there other PFT’s than *Sphagnum*?

**A:** We think that this is a good idea and we suggest to include the picture below as new Fig. 1 in our manuscript. Yes, the HPM includes additional PFT: brown mosses, feather mosses, minerotrophic and ombrotrophic sedges, shrubs, and forbs, but the Peatland Decomposition Database currently focuses on *Sphagnum*.

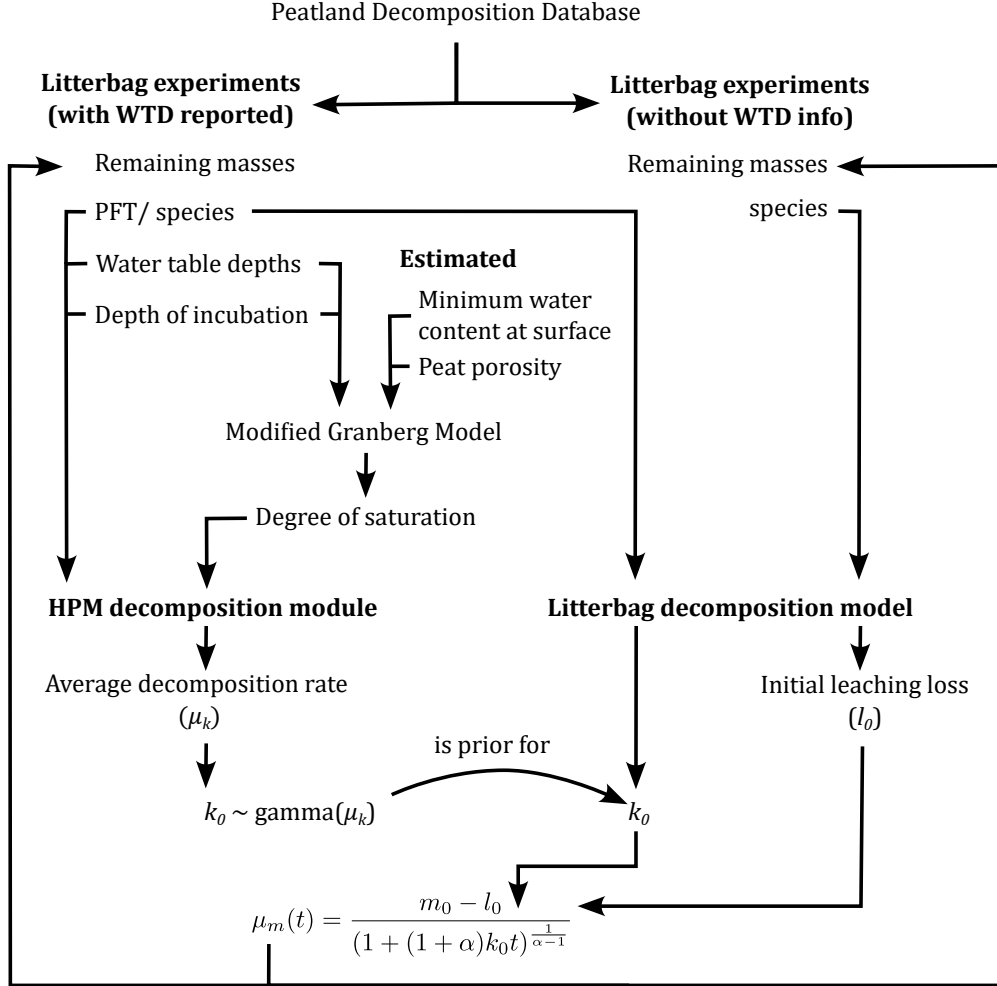


Figure 1: Conceptual representation of the modeling approach. Arrows represent flows of information. Litterbag data that have information on water table depths (WTD) and incubation depths are used to estimate average decomposition rates with the HPM decomposition module ( $\mu_k$ ). The HPM decomposition module needs plant functional type identity, peat degree of saturation, WTD, and incubation depth to predict decomposition rates. The modified Granberg model is used to estimate peat degree of saturation at incubation depths from WTD, minimum water content at the surface, and porosity, of which the latter two are estimated from the remaining masses. The litterbag decomposition model is used to estimate decomposition rates ( $k_0$ ) for all litterbag studies, including those that have information on WTD and those that have not. A gamma distribution with  $\mu_k$  as average is used as prior distribution for  $k_0$  for the litterbag experiments that have information on WTD (curved arrow). This helps to constrain initial leaching loss and decomposition rate estimates for studies that can be predicted with the HPM decomposition module. The Litterbag decomposition module also estimates initial leaching losses ( $l_0$ ) for all litterbag experiments. The equation at the bottom uses these to estimate remaining masses in the litterbag experiments. The litterbag decomposition model is described in more detail in section 2.2.1. See the text for further details.

13. **Q:** Please add a section describing the LBM, there’s no information about it now.

**A:** We suggest to modify section 2.2.2. to provide a more detailed description of our modeling approach. Please see the attached version of the manuscript to see how the text would look like with the suggested changes.

14. **Q:** l. 99-105: Please divide this sentence into smaller pieces, it is difficult to read. I do not completely understand what you did and for what you used only the data of the latter reference list. Did you compare the results to the same data into which you had fitted the models?

**A:** We suggest to split the sentence as follows:

“To test the HPM decomposition module against litterbag data, we used the Peatland Decomposition Database (Teickner and Knorr, 2024). In this study, we use data from Bartsch and Moore (1985), Vitt (1990), Johnson and Damman (1991), Szumigalski and Bayley (1996), Prevost et al. (1997), Scheffer et al. (2001), Thormann et al. (2001), Asada and Warner (2005), Trinder et al. (2008), Breeuwer et al. (2008), Straková et al. (2010), Hagemann and Moroni (2015), Golovatskaya and Nikonova (2017), and Mäkilä et al. (2018) to estimate  $k_0$  using the litterbag decomposition model. Data from Johnson and Damman (1991), Szumigalski and Bayley (1996), Prevost et al. (1997), Straková et al. (2010), Golovatskaya and Nikonova (2017), and Mäkilä et al. (2018) reported water table depths and therefore only these data were used to predict  $k_0$  also with the HPM decomposition module.”

We hope that the conceptual figure (Fig. 1) and our reply to comment 13 of reviewer 2 clarify how we used the litterbag data in our modeling approach.

15. **Q:** l. 109-111: Is this now the same list of input as in the Introduction l. 38-39? Porosity is missing here. Also, is “the fraction of mass already lost” the same as “initial leaching loss”?

**A:** Yes, this is supposed to be the same list as in the Introduction l(1. 38-39). The reason why we did not mention peat porosity here is that the degree of saturation can be computed from the water content (mentioned in ll. 38-39) and peat porosity and the HPM decomposition module only needs the degree of saturation to make predictions. We also missed “the depth of the litter below the peat surface” in the list in the Introduction. To avoid confusion, we suggest to change ll. 38-39 from:

“For example, in the Holocene Peatland Model (HPM) (Frolking et al., 2010), we only need to know litter species, peat water content, peat porosity, water table depth, and only five parameters to predict decomposition rates.”

to

“For example, in the Holocene Peatland Model (HPM) (Frolking et al., 2010), we only need to know litter species, peat degree of saturation, the depth of the litter below the peat surface, water table depth, and only five parameters to predict decomposition rates.”

“the fraction of mass already lost” is one minus the fraction of initial mass remaining ( $1 - \frac{m(t)}{m_0}$ ), i.e., the fraction of the mass of the litterbag before the incubation that has



been lost during the incubation. It is not the “initial leaching loss”. The HPM assumes that the decomposition rate slows down as mass gets lost during the decomposition. Equation (2) (in the attached version of the manuscript) already considers this slow down of the decomposition rate, but assumes that the litter has not been decomposed yet. If this is not the case,  $k_0$  needs to be adjusted for the fraction of initial mass already lost, as described in equations (3) and (6) in Frolking et al. (2001). We mention this here because samples from Prevost et al. (1997) are already decomposed *Sphagnum* samples. However, the fraction of initial mass already lost is not known which is why we assign them to dummy PFT and therefore estimate their initial decomposition rate ( $k_{0,i}$ ) separately to account for this unknown fraction of initial mass lost.

16. **Q:** l. 112-115: Please divide this sentence into two, it’s slightly complicated.

**A:** We thank the reviewer for this suggestion. We suggest to change the sentence from “Predicting decomposition rates for the available litterbag data is not straightforward because the HPM decomposition module does not consider specific features of litterbag experiments, because it does not specify how to assign species to plant functional types, and because required variables such as the degree of saturation are not reported in the litterbag studies and therefore need to be estimated.”

to

“Predicting decomposition rates for the available litterbag data is not straightforward because the HPM decomposition module does not consider specific features of available litterbag experiments. The HPM does not specify how to assign species to plant functional types. Moreover, none of the available litterbag studies reported the degree of saturation which therefore needs to be estimated in order to make predictions with the HPM decomposition module.”

17. **Q:** l. 115-116: The logic of this sentence is not clear. Do you mean that one can’t directly use litterbag data as a comparison for the HPM, because HPM doesn’t predict masses but decomposition rates?

**A:** We agree that this sentence is confusing at this place and therefore suggest to remove it. We hope that the new Fig. 1 and our reply to comment 13 of reviewer 2 explain how we link litterbag data to the HPM decomposition module.

18. **Q:** Section 2.2.2: Please report how many replicates/data points there were for each species, niches, etc. It is relevant information but not clearly mentioned anywhere.

**A:** We agree that this is useful information. We suggest to include a new table at the end of section 2.1. and make appropriate references throughout the text. The table is:

Table 1: Overview on litterbag experiments included for each *Sphagnum* taxon in this study. “HPM microhabitat” is the HPM microhabitat assigned to each taxon. Taxa without value are not considered in Johnson et al. (2015) (see section 2.2.2). “Number of experiments” is the number of litterbag experiments available from the Peatland Decomposition Database (these are either individual replicates or average values of replicates, depending on what data were reported in the studies). “Number of experiments with WTD data” is the number of litterbag experiments that also report water table depths and for which we therefore could make predictions with the HPM decomposition module. “Depth range” are the maximum and minimum depth below the peat surface at which litterbags were placed [cm]. Missing values mean that no study reported depths.

Taxon	HPM microhabitat	Number of studies	Number of experiments	Number of experiments with WTD data	Depth range
<i>Sphagnum spec.</i>		2	16	10	10, 30
<i>S. angustifolium</i>	Hummock	4	14	8	1, 30
<i>S. auriculatum</i>		1	3	0	0, 6
<i>S. balticum</i>	Lawn	3	12	3	1, 30
<i>S. cuspidatum</i>	Hollow	1	5	5	10, 50
<i>S. fallax</i>	Lawn	1	4	1	1, 1
<i>S. fuscum</i>	Hummock	9	32	13	1, 50
<i>S. lindbergii</i>	Lawn	1	2	0	
<i>S. magellanicum aggr.</i>	Hummock	3	7	5	1, 50
<i>S. majus</i>	Hollow	1	2	2	10, 30
<i>S. papillosum</i>	Lawn	2	6	1	0, 1
<i>S. rubellum</i>	Hummock	1	2	2	10, 30
<i>S. russowii</i>	Hummock	1	3	2	1, 1
<i>S. russowii</i> and <i>capillifolium</i>		1	18	0	5, 5
<i>S. squarrosum</i>	Lawn	1	2	0	0, 0
<i>S. teres</i>	Lawn	1	1	1	2, 2

20. **Q:** l. 145: Why did you estimate  $k_{i,0}$  only in these two set-ups?

**A:** The reviewer is correct that we omitted model HPMe-LE-peat-l0-outlier (new model name: HPM-outlier) from this list. We suggest to correct this. For all other model variants, all HPM decomposition module parameters were kept constant and we therefore did not estimate  $k_{0,i}$  for them.

21. **Q:** Section 2.2.3: Where was this information (degree of saturation) needed, was it input for the HPM?

**A:** Yes, the degree of saturation is an input of the HPM decomposition module. We hope that our new Fig. 1 (see our reply to comment 12 of reviewer 2) and our reply to comment 13 of reviewer 2 address this issue.

22. **Q:** l. 154: Does this mean you set the mass loss to zero in the model?

**A:** This means that  $m_0 = 1$  (equation (2) (attached manuscript)), i.e. all of the mass when the *Sphagnum* plants died is still available at the start of the incubation. To avoid misunderstandings, we suggest to modify ll. 153 to 155 from

“All litterbag data we use here, except samples from Prevost et al. (1997), are from *Sphagnum* samples collected from the surface of peatlands and therefore can be expected to have not experienced mass loss due to decomposition at the start of the experiments.”

to

“All litterbag data we use here, except samples from Prevost et al. (1997), are from *Sphagnum* samples collected from the surface of peatlands and therefore can be expected to have not experienced mass loss due to decomposition at the start of the experiments ( $m(t = 0) = 1$  in equation (2)).”

23. **Q:** l. 163: “Minimum water content at the surface” appears here for the first time. Is it an additional input parameter for HPM?

**A:** We thank the reviewer for this question. We forgot to mention that the minimum water content at the surface is an input required by the modified Granberg model. We suggest to add this in section 2.2.3. The section then reads (with other additions due to comment 27 of reviewer 3):

“We estimated the degree of saturation with the modified Granberg model (ModGberg model) (Granberg et al., 1999; Kettridge and Baird, 2007) from minimum water content at the surface ( $\theta_{0,\min}$ ), total porosity ( $P$ ), the water table depth below the peat surface ( $z_{\text{wt}}$ ), and the positions of the litterbags during the incubation ( $z$ ):

$$\theta(z) = \min \left( P, \theta_0 + (P - \theta_0) \left( \frac{z}{z_{\text{wt}}} \right)^2 \right) \quad (1)$$
$$\theta_0 = \max \left( \theta_{0,\min}, 0.15z_{\text{wt}}^{-0.28} \right),$$

where  $\theta_0$  is the water content at the surface and  $0.15z_{\text{wt}}^{-0.28}$  is an empirical relation of  $\theta_0$  with the WTD (Kettridge and Baird, 2007).

The minimum water content at the surface was not reported in any study and we therefore assumed a minimum water content at the surface of  $0.05 L_{\text{water}} L_{\text{sample}}^{-1}$  with a standard deviation of  $0.05 L_{\text{water}} L_{\text{sample}}^{-1}$ , based on measurements from Hayward and Clymo (1982). The total porosity was not reported in any study and therefore we assumed an average value of 80% with a standard deviation of 10%, roughly based on values reported for low-density *Sphagnum* peat (Liu and Lennartz, 2019). An improved test of the HPM decomposition module would require litterbag experiments with direct measurements of the degree of saturation at sufficient temporal resolution.”

24. **Q:** l. 166-168: So how did you determine the litterbag decomposition rates in this case?

**A:** We hope that our new Fig. 1 (see our reply to comment 12 of reviewer 1) and our reply to comment 13 of reviewer 2 address this issue. Specifically, in this case the standard parameter values of the HPM decomposition module were used to predict decomposition rates ( $\mu_k$  in Fig. 1, this reply document), and decomposition rates were estimated from the litterbag experiments using only the litterbag decomposition model. We think that our text may be ambiguous here and we suggest a complete re-write of the Methods section, where we improve our description of the different models. Please see section 2.3.1 in the attached version of the manuscript with the suggested changes.

25. **Q:** l. 169-173: I was trying to think how to name the model versions so that one doesn't need to always check the differences from the table. Perhaps it would help if you explained here why you named the models like this. E.g. where does the LE part come from?

**A:** We thank the reviewer for this suggestion. We suggest to change all model names as suggested in comment 7 of reviewer 3 and also update Tab. 2 to clarify how the models differ. In addition, we introduce the name “LDM-standard” for only the litterbag decomposition model, without the HPM decomposition module as prior. Please see the attached manuscript with the suggested changes.

26. **Q:** l. 172: Please show the formulas you used for  $l_0$ .

**A:** We suggest to add after l. 192:

“Specifically, we use the following logistic regression model to describe an average initial leaching loss per sample, in dependency of the degree of saturation:

$$\begin{aligned} \mu_l &= \text{logit}^{-1}(\beta_{l,1} + \beta_{l,2}W) \\ l_0 &\sim \text{beta}(\mu_l\phi_l, (1 - \mu_l)\phi_l), \end{aligned} \tag{2}$$

where  $\mu_l$  is the average initial leaching loss for a sample,  $\beta_{l,1}$  is the (hypothetical) average initial leaching loss at a degree of saturation 0 for each taxon,  $\beta_{l,2}$  is the coefficient that describes the relation to the degree of saturation ( $W$ ), and  $\phi_l$  transforms  $\mu_l$  and  $(1 - \mu_l)$  into the shape and rate parameters of a beta distribution. This beta distribution has the same function as the gamma distribution (equation 8) for  $k_0$  (compare also with Fig. 1): it is a prior for  $l_0$  estimated with the litterbag decomposition model, where the average of this prior is  $\mu_l$ .

27. **Q:** l. 174-178: Please explain this part more thoroughly. What did the Bayesian model do exactly? I assume you optimized different parameter sets of HPM, using the default parameters of HPM as priors. But what was the role of the LBM here? Did you simultaneously optimize parameters of the LBM, and if yes, which parameters were they? Why did you assume that the default parameters of HPM are better priors than something based on the litterbag data? Could you also have used some standard parameters of the LBM as the starting point?

**A:** We apologize that we have omitted these information. We hope that our new Fig. 1 (see our reply to comment 12 of reviewer 1) and our reply to comment 13 of reviewer 2 address all aspects of this comment.

To help clarify possible misunderstandings, here are brief replies to the questions:

- “Did you simultaneously optimize parameters of the LBM, and if yes, which parameters were they?” Yes, the LBM estimates  $k_0$ ,  $l_0$ , and  $\alpha$  for each litterbag experiment. The HPM decomposition module estimates  $\mu_k$  which is assumed to be the average of the gamma distribution that also estimates  $k_0$  (equation (8), in the updated section 2.2.1).
- “Why did you assume that the default parameters of HPM are better priors than something based on the litterbag data? Could you also have used some standard parameters of the LBM as the starting point?” In a Bayesian data analysis, you have to assume a prior to estimate a parameter. There are no prior estimates for the HPM decomposition module parameters based on litterbag data, except for the standard parameter values. We therefore constructed our priors based on these standard values.

28. **Q:** l. 180: How did you obtain the uncertainties?

**A:** The referenced sentence is: “If HPM parameter estimates from the combined model are not compatible with standard values used in the original model (Tab. 1) even if we adjust them to the HPM within the range allowed by the uncertainties, this is a discrepancy worth testing in future experiments.”

The uncertainties we mean here are the uncertainties of the HPM decomposition module parameters implied by our priors and the litterbag data, as represented by the joint posterior distribution for each model. To avoid misunderstandings, we suggest to change this sentence to:

“If HPM decomposition module parameter estimates from the combined model are different from the standard values used in the original model (Tab. 1), even if we consider these uncertainties and use the HPM decomposition module as prior for the litterbag data, this is a discrepancy worth testing in future experiments.”

29. **Q:** l. 182-183: How do you estimate the uncertain peat properties? Do you mean you assumed the decomposition rates from the LBM are correct and the HPM parameters are correct, and then analyzed what kind of peat properties were needed to achieve these?

**A:** By Bayes theorem, the posterior probability distribution of some parameter  $\theta$  conditional on some data  $y$  is proportional to the product of the likelihood and the prior distribution:  $p(\theta|y) \propto p(y|\theta)p(\theta)$ .

In this case, the data are the measured remaining masses in the litterbag experiments. This means that if we put a prior on a variable in a model, it can be estimated from the data conditional on the prior and the model. Not in all cases are the data informative with respect to a parameter, and, as expected, the marginal posterior distribution of the peat properties is dominated by the prior in our case (as mentioned in supporting information S3 (supporting information S2 in the updated version of the supporting information)).

If the reviewer thinks this should be mentioned more explicitly in the text, we would be grateful for further comments how we could do this most appropriately.

30. **Q:** l. 184: Only parameters or also the peat properties?

**A:** Model HPMe-LE-peat (now HPM-all) estimates peat properties and HPM decomposition module parameters. We hope that our reply to comment 25 of reviewer 2 addresses this issue.

31. **Q:** l. 189-190: I would have thought this was vice versa: weren't the leaching losses estimated more independently in the l0 version?

**A:** We apologize that we may have caused confusion by not fully explaining our modeling approach. In the  $l_0$  version, we introduce an additional model for initial leaching losses in dependency of the degree of saturation (see our reply to comment 26 of reviewer 2) and this potentially constrains  $l_0$  estimates because it is an additional prior. Without this model,  $l_0$  is only estimated by the LBM which simply estimates  $l_0$  from each individual litterbag experiment without assuming any specific relation to the degree of saturation. We hope that our reply to comment 26 of reviewer 2 also addresses this question.

32. **Q:** l. 200-201: The message of this sentence is unclear.

**A:** The sentence is "Results for HPMe-LE-peat-l0-outlier are shown in supporting information S10 and HPM parameter estimates agree with the other models where HPM parameters were estimated."

To avoid misunderstandings, we suggest to change this sentence to: "Results for HPM-outlier are shown in supporting information S9 and HPM decomposition module parameter estimates agree with estimates of HPM-leaching and HPM-all."

We would be thankful if the reviewer lets us know whether this clarifies the sentence.

33. **Q:** l. 202-203: Is it so that the Granberg model was not included in the Bayesian system, it had some fixed parameters? Is the minimum peat water content at the surface is from Granberg?

**A:** Yes, this is correct. We did estimate only the minimum water content at the surface to keep the model computationally manageable. We hope that we emphasized sufficiently throughout the manuscript that not having measurements for the degree

of saturation is a limitation and that the modified Granberg model is only an approximation we use since such data are not available.

Our prior for the minimum water content at the surface was defined as described in our reply to comment 23 of reviewer 2.

In the updated version of the manuscript, we suggest to include a detailed description of the modified Granberg model (see section 2.2.3 in the attached version of the manuscript with the suggested changes).

34. **Q:** l. 209-210: Again I'm a little bit lost with what the Bayesian model did. Can you please explain if the estimates from HPM and LBM were somehow optimized together, or if they were separate. I suppose that estimation of the decomposition rates from the litterbag data was done with the LBM?

**A:** We hope that our new Fig. 1 (see our reply to comment 12 of reviewer 1) and our reply to comment 13 of reviewer 2 addresses this comment. We also suggest to completely re-write the referenced part of the Methods section and hope that it is more understandable now.

35. **Q:** l. 211: Should it be “large probability indicates...”?

**A:** We thank the reviewer for reporting this error. We suggest to correct it as suggested.

36. **Q:** l. 218-219: Please define what is a one-pool decomposition rate? What pool?

**A:** We suggest to remove “one-pool”. We mean  $k_0$  here.

37. **Q:** l. 224-225: Is it possible to re-formulate this. E.g. it might be clearer to say that in the folds, you included only data of those species for which there was data from several sites.

**A:** We agree that this sentence should be improved. We suggest to change

“Each fold consists of the data from one study, except those values that were measured for *Sphagnum* species for which only this study had data (we want to estimate the predictive accuracy not for new species). Data for species with data from one study only were always used for model training and not part of the testing folds.”

to

“Each fold represents the data from one study, but only if there were still data for the same *Sphagnum* species left in the remaining data (we want to estimate the predictive accuracy not for new species). Species with data from one study only were always used for model training and not part of the testing folds.”

38. **Q:** l. 232: This kind of prior knowledge sounds relevant - were there many this kind of restrictions? Perhaps they need to be listed.

**A:** In Bayesian data analysis one always includes some sort of prior knowledge. All prior distributions are listed in supporting Tab. S1, as mentioned at the end of the same paragraph (l. 238).

39. **Q:** l. 239: Where was this priorsense package?

**A:** Unfortunately, we do not understand this question.

40. **Q:** l. 250 and Table 3: To me it looks like the  $\text{RMSE}_{\text{test}}$  is smaller for HPMe-LE-peat\_10.

**A:** The average  $\text{RMSE}_{\text{test}}$  is smaller for HPMe-LE-peat-10, but our estimates have large errors (as in indicated in Tab. 3) and therefore one can neither conclude that HPM-leaching makes better, nor that it makes worse predictions. We currently think that the confidence intervals given in Tab. 3 make this clear.

41. **Q:** l. 257: Didn't you also adjust the peat parameters in HPMf-LE-peat?

**A:** Yes, this is described in Tab. 2. However, the peat properties are no parameters of the HPM decomposition module. This confusion was probably caused by our omission of details of our modeling approach. We hope that our new Fig. 1 (see our reply to comment 12 of reviewer 1) and our reply to comment 13 of reviewer 2 address this comment.

42. **Q:** l. 263-264: Where are the estimates of initial leaching losses needed?

**A:** As now shown in our new Fig. 1 and in equation (2) (in the new version of the manuscript),  $l_0$  is needed to predict remaining masses in the litterbag experiment. Our point here is that mass losses in litterbag experiments can be explained both by initial leaching losses and by decomposition, but there is uncertainty about the relative magnitude of both processes (because the design of available litterbag experiments is not ideal, see Teickner et al. (2024)). For this reason, the model can — within the range of uncertainty implied by the posterior distribution — adjust the decomposition rate so that it agrees with the HPM decomposition module and then change initial leaching losses accordingly to fit the remaining mass data from the litterbag experiments.

To clarify this point, we completely re-wrote the referenced part of the Results section. Please see the attached manuscript for how the suggested changes would look like (sections 3.1 and 3.2).

43. **Q:** l. 271-272: Could this result be affected by the priors? Also, to me it seems (Fig. 2) that especially for *S. angustifolium*, these estimates are very similar - but perhaps I misunderstood the plot.

**A:** The referenced sentences (ll. 269 to 272) are: “HPMe-LE-peat estimated larger initial leaching losses and smaller decomposition rates than the litterbag decomposition model from Teickner et al. (2024) alone, similar to HPMf-LE-peat (Fig. 3). This is particularly the case for *S. angustifolium*, for which the separate litterbag decomposition model estimated much larger average decomposition rates and smaller initial leaching losses than the litterbag decomposition model in HPMe-LE-peat (Fig. 2).”

We think that this is a misunderstanding. We state that average decomposition rate estimates for *S. angustifolium* by the LBM alone (without using the HPM decomposition module as prior) are larger than when the HPM decomposition module is used as prior for  $k_0$ . Thus, we here refer to the black line in the first column in Fig. 2



compared to the grey lines in the first three columns for *S. angustifolium*. The black line in the first column clearly is above the grey lines, indicating that when the HPM decomposition module is used as prior for  $k_0$ ,  $k_0$  estimates are smaller.

We now think that the figure may be more confusing than helpful. We therefore suggest to remove it and replace it by a better presentation of our results and two new figures that more appropriately illustrate the differences between HPM-standard and LDM-standard on the one hand and between HPM-standard and the modifications of the HPM decomposition module on the other hand. Please see section 3.4 in the attached version of the manuscript with the suggested changes.

Regarding “Could this result be affected by the priors?”: In the companion manuscript, Teickner et al. (2024), we analyzed whether initial leaching losses and decomposition rates of different magnitude in simulated data can be recovered by the LBM and this was the case. Therefore, priors for parameters of the LBM are unlikely to strongly bias our results, but of course, they can have some influence, which is why we suggest future experiments to test our hypotheses.

As mentioned above, when the HPM is used as prior, estimates change and therefore, the smaller  $k_0$  and larger  $l_0$  estimates compared to the LBM alone are caused by the HPM decomposition module.

44. **Q:** l. 258: Relations of  $l_0$  and what?

**A:** We think the reviewer refers to l. 286, where we omitted to mention the degree of saturation, and not l. 258. We thank the reviewer for this suggestion and correct the sentence as suggested.

45. **Q:** Figure 2: I don’t understand why the “HPM=No” values are different for different model versions, if they were not predicted by the different versions of HPM but just estimated from the litterbag data. What are the error bars?

**A:** We think this misunderstanding is caused because we did not appropriately describe our modeling approach. We hope that our new Fig. 1 (see our reply to comment 12 of reviewer 1) and our reply to comment 13 of reviewer 2 address this comment.

Specifically, decomposition rate estimates shown for “HPM=No” are  $k_0$  and for “HPM=No” are  $\mu_k$  as shown in Fig. 1. Thus,  $k_0$  values (“HPM=No”) for different versions of the HPM decomposition module are different because the prior implied by the modified HPM is different in each case. We re-wrote the entire Results section and hope that this point is clarified now. Please see the attached version of the manuscript with the suggested changes.

46. **Q:** Figure 3: Why especially HPMf vs. the LBM is on the 1:1 line although these were not from the same Bayesian model? Why weren’t the Hagemann and Moroni estimates tested against the HPM? What are the error bars?

**A:** In HPMf, the HPM decomposition module is not used as prior for  $k_0$  estimated by the LBM. Therefore, the LBM in HPMf is the same as the LBM without the HPM decomposition module.

Litterbag experiments in Hagemann and Moroni (2015) were reported without WTD

and therefore no predictions of decomposition rates with the HPM decomposition module could be made for these samples. Therefore, data from these experiments contributed to the prior implied by the HPM decomposition module only indirectly.

Points represent average estimates and error bars 95% posterior intervals.

We thank the reviewer for these questions and agree that the figure is more confusing than helpful. We decided to remove the figure and replace it by a hopefully more understandable description. Please see sections 3.1 and 3.2 in the attached version of the manuscript with the suggested changes.

47. **Q:** Figure 4b: Are these results for one species or some kind of summary?

**A:** These are marginal posterior distributions for parameters that are valid for all species. We also hope that the updated section 2.2.1 clarifies the role of these parameters in the HPM decomposition module (please also refer to our reply to comment 13 of reviewer 2).

48. **Q:** l. 315-316: How significant is it to estimate the initial leaching loss, considering the long-term HPM results about peat accumulation?

**A:** As suggested in our companion manuscript (Teickner et al., 2024), neglecting initial leaching losses biases decomposition rate estimates and this bias amplifies when these decomposition rate estimates are used for long-term predictions. We suggest to completely re-write this part of the Discussion section and to summarize limitations in a separate section (section 4.4, point 4 in the attached version of the manuscript with the suggested changes).

49. **Q:** l. 340: I would think it is possible that a more accurate fitting of these parameters to litterbag data is not the only key to better understanding of the C accumulation, but there are other factors affecting the processes and differences between different litterbag experiments.

**A:** The referenced sentence is: “Explaining the discrepancies and finding ways to test them more accurately than possible with available litterbag data should therefore improve our understanding of peat C accumulation.”

We therefore do not state that “more accurate fitting of these parameters to litterbag data is not the *only* key to better understanding of the C accumulation” [our emphasis] and agree that this is only one of the necessary steps.

In the updated version of the manuscript, we suggest to remove this section because of the suggested re-structuration of the Results and Discussion sections.

50. **Q:** l. 343: How do you conclude this?  $W_{opt}$  was related only to aerobic respiration (Table 1).

**A:** The referenced sentence is: “The discrepancies in  $c_2$  and  $W_{opt}$  together imply smaller aerobic and larger anaerobic decomposition rates and therefore a less steep decrease of decomposition rates from oxic to anoxic conditions (Fig. 2).”

It is true that  $W_{opt}$  is the degree of saturation where the aerobic decomposition rate is maximal. However, in the HPM decomposition module, the anaerobic decomposition rate is computed by transforming the hypothetical aerobic decomposition rate

computed at a degree of saturation of 100% (see equations (5) and (6) in the attached version of the manuscript with the suggested changes). Therefore, the magnitude of anaerobic decomposition rates in the HPM decomposition module depends on  $W_{opt}$ . We hope that our more detailed description of the HPM decomposition module (see our reply to comment 13 of reviewer 2) addresses this issue, and the re-formulation of the Results and Discussion section, where we now hopefully describe better how the gradient in decomposition rates from oxic to anoxic conditions is controlled by the HPM decomposition parameters (section 3.4 in the attached version of the manuscript with the suggested changes)

51. **Q:** l. 344 and 347: there's perhaps a bit repetition.

**A:** We did include this part on purpose because the differences in  $W_{opt}$  and  $c_2$  only imply relative differences between aerobic and anaerobic decomposition rates, but it will depend on the value of  $k_{0,i}$  whether absolute decomposition rates are larger or smaller than implied by the standard parameter values.

In the updated version of the manuscript, this part is removed.

52. **Q:** l. 351-354: This explanation is complicated. Can you please write it more clearly. How many different runs did you do exactly?

**A:** We suggest to change the text (ll. 351 to 353) from:

“We predicted average  $k_0$  of *S. fuscum* with HPMe-LE-peat-10 ( $k_{0,modified}(HPMe-LE-peat-10)$ ) and with HPMe-LE-peat-10 setting either  $c_1$ ,  $W_{opt}$ ,  $f_{min}$ , or  $c_2$  to the standard value ( $k_{0,standard}(HPMe-LE-peat-10)$ ) and computed their differences.”

to

“With these settings, we predicted five sets of average  $k_0$ : (1) with HPM-leaching ( $k_{0,modified}(HPM-leaching)$ ). The remaining four sets were also predicted with HPM-leaching, but each time setting one of the HPM decomposition module parameters to their standard value ( $k_{0,standard}(HPM-leaching)$ ): (2)  $c_1$ , (3)  $W_{opt}$ , (4)  $f_{min}$ , (5)  $c_2$ . We then computed the difference of  $k_0$  from set (1) and (2) to analyze the effect of the new  $c_1$  estimate, from set (1) and (3) to analyze the effect of the new  $W_{opt}$  estimate, and so on for sets (4) and (5).”

In addition, we suggest to move this part to the Methods section.

53. **Q:** Figure 6: Please explain the confidence levels.

**A:** We suggest to add to the caption of Fig. 6 (and also Fig. 7):

“Shaded areas are central confidence intervals with probabilities given in the figure legend.”

54. **Q:** l. 370: What do you mean by the “same study”?

**A.** The referenced phrase is: “The less pronounced gradient in measured decomposition rates above the water table depth is, however, also visible for *S. fuscum* replicates within the same study ...”

With “same study” we mean litterbag experiments that were described within the same

publication and often were performed with the same original litter material. In these cases, the differences could be explained by differences in sample pre-treatment, litter chemistry, etc. Currently, we think that it is clear from the previous paragraph what is meant by “same study”, but if the reviewer disagrees here, we would be grateful for recommendations how to improve our text here.

55. **Q:** One question about Supporting information. You write:

“The litterbag decomposition model combined with each modification of the HPM is obtained from Teickner et al. (2024) (model 1-4, see the supporting information to Teickner et al. (2024) for details). Here, we describe the modules which were added to this model in the different modifications of the HPM”

- Do you mean that you added some modules in this study, which you didn’t have in the other work? Please add also this piece of information in the main text, when describing the LBM.

**A:** We hope that the conceptual figure (Fig. 1) and our reply to comment 13 of reviewer 2 address this issue.

## 2 Additional changes

1. We suggest a complete re-write of large parts of the manuscript to address the reviewer comments. Specific aspects of this re-write are listed in the comments of the reviewers, others are too numerous for a list of them to be useful without knowing the context of these changes. Please see the attached manuscript with the suggested changes.
2. We suggest to include Quillet et al. (2015) as reference for studies estimating  $c_2$  from peat cores. We suggest the following changes:

We suggest to change l. 392 to 393 from

“Larger and smaller  $c_2$  than the standard value have been estimated for several permafrost peatland cores with a modified version of the HPM with monthly time step (Treat et al., 2021, 2022).”

to

“Larger and smaller  $c_2$  than the standard value have been estimated for several peatland cores with the HPM and a modified version with monthly time step (Quillet et al., 2015; Treat et al., 2021, 2022).”

3. Frohking et al. (2010) also mention that peat accumulation as predicted by the HPM is sensitive to  $c_2$  and a site-specific parameter. We therefore add Frohking et al. (2010) as reference at l. 47 and 422.
4. In l. 77 we will correct “decmposition” to “decomposition”.

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# Peat Oxic and Anoxic Controls of *Sphagnum* Decomposition Rates in the Holocene Peatland Model Decomposition Module Estimated from Litterbag Data

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**Abstract.** The Holocene Peatland Model (HPM) is a widely applied model to understand and predict long-term peat accumulation, but it is difficult to test due to its complexity, measurement errors, and lack of data. Instead of testing the complete model, tests of individual modules may avoid some of these problems. In particular, the HPM decomposition module can be tested with litterbag data, but no such test has been conducted yet.

5 Here, we estimate parameter values of the HPM decomposition module from available *Sphagnum* litterbag experiments included in the Peatland Decomposition Database and with a litterbag decomposition model that considers initial leaching losses. Using either these estimates or the standard parameter values, we test whether the HPM decomposition module fits decomposition rates ( $k_0$ ) in *Sphagnum* litterbag experiments along a gradient from oxic to anoxic conditions.

Both Litterbag data and model versions where HPM decomposition module parameters were estimated suggest a less steep  
10 gradient of decomposition rates from oxic to anoxic conditions and larger anaerobic decomposition rates for several species than the standard parameter values. This discrepancy may be caused by ignoring effects of water table fluctuations on aerobic and anaerobic decomposition rates. Moreover, our analysis suggests that maximum possible decomposition rates of individual species ( $k_{0,i}$ ) vary more than suggested by the standard parameter values of the HPM plant functional types. Based on previous sensitivity analyses of the HPM, the estimated differences to the standard parameter values can cause differences in predicted  
15 5000 year C accumulation up to 100 kg m<sup>-2</sup>.

The HPM decomposition module with standard parameter values fits  $k_0$  estimated from *Sphagnum* litterbag data, but model versions where HPM decomposition module parameters were estimated and differ significantly have an equivalent fit. The reason why models with different parameter values have equivalent fit is that errors in remaining masses and the design of available litterbag experiments support a range of initial leaching loss and  $k_0$  estimates. Consequently, applications of the HPM  
20 and any other peatland model should consider that a broad range of decomposition module parameter values is compatible with available litterbag experiments.

Improved litterbag experiments are needed for more accurate tests of any peatland decomposition module and for obtaining parameter estimates accurate enough to allow even only approximate predictions of long-term peat accumulation. The modeling approach used here can be combined with different data sources (for example measured degree of saturation) and decomposition  
25 modules. In light of the large differences in long-term peat accumulation suggested by the parameter estimates, we conclude

that it is worth to conduct such experiments, not only to improve the decomposition module of the HPM, but to improve peatland models in general.

## 1 Introduction

Decomposition is one of the major controls of how much carbon (C) peatlands can store. Compared to other ecosystems, northern peatlands usually have small decomposition rates because of cold temperatures, high water table levels, acidic pH value, and litter that does not decompose fast even under environmental conditions favorable for decomposition (van Breemen, 1995; Rydin et al., 2013). These slow decomposition rates caused northern peatlands to accumulate at least 400 Gt C (Yu, 2012; Nichols and Peteet, 2019) during the Holocene and changes in the controls of decomposition rates may cause them to loose considerable amounts of C to the atmosphere under climate and land use changes (Frolking et al., 2011; Loisel et al., 2017).

Peatland models are used to better understand past C accumulation and to predict future changes in peat C stocks, but because of the long time scales which have to be considered, they are difficult to test. Past studies have compared site-adapted simulations of peat height, age, C and N stocks, macrofossil composition, and water table level predicted by peatland models against peat core data (e.g., Frolking et al., 2010; Tuittila et al., 2013; Treat et al., 2021; Zhao et al., 2022), and have shown that existing peatland models can reproduce observed patterns to some extent. However, these tests suffer from two problems. First, they cannot reliably identify the parameter values or model equations that cause discrepancies between model predictions and measurements because they test entire peatland models against observed data. Second, there often are large uncertainties on both sides of the test; peatland models have large uncertainties in parameter values and model structure and these may produce a range of predictions as illustrated by uncertainty analyses (e.g., Quillet et al., 2013a, Quillet et al. (2013b)) and model intercomparisons (e.g., Zhao et al., 2022). Observed data also has uncertainty from measurements, peat dating, or simply missing data, for example for past precipitation. Large uncertainties can make tests inconclusive, no matter how much data we use. As a consequence, there remains large and often not quantified uncertainty about parameter values that control decomposition rates.

An alternative that avoids some of these problems is to test only some part of a model while taking into account relevant uncertainty sources. To estimate uncertainties in and test values of parameters that directly control decomposition rates, such a test could address the decomposition module of a peatland model. For example, in the Holocene Peatland Model (HPM) (Frolking et al., 2010), we only need to know litter species, peat degree of saturation, the depth of the litter below the peat surface, water table depth, and only five parameters to predict decomposition rates. The predictions can be compared to decomposition rates estimated from litterbag data and therefore future litterbag studies can directly test whether discrepancies identified in such a test are replicable. Admittedly, such a test is restricted to short time ranges and not representative for long-term decomposition rates which may differ from that of fresh litter (e.g., Frolking et al., 2001), but future tests with different scope and applications of the model will benefit from the reduced parameter uncertainties and can consider where the model fails already on short time scales.



A test of decomposition modules is relevant because of the importance of decomposition for long-term C accumulation in peatlands. Previous sensitivity analyses of the HPM and applications to peat cores suggest that the anoxia scale length ( $c_2$ ), the parameter controlling how anaerobic decomposition rates are limited by electron acceptor depletion and accumulation of decomposition products, can result in a doubling of accumulated C, depending on climate conditions (Frolking et al., 2010; Quillet et al., 2013b; Kurnianto et al., 2015). These sensitivity analyses used assumed parameter ranges that are not informed by litterbag experiments. A test of only the HPM decomposition module can provide better estimates for  $c_2$  and may therefore help to reduce uncertainties in predicted C accumulation rates.

Currently, litterbag experiments are not as extensively used for testing peatland models as they could and only a fraction of the information available from litterbag experiments is used to develop models. The HPM derives initial decomposition rates of moss plant functional types from litterbag data, but parameters for environmental controls of decomposition are assumptions which appear to be informed at most qualitatively by litterbag experiments, and it is not tested whether the HPM decomposition module successfully fits available litterbag data (Frolking et al., 2010). This is also the case for other dynamic peatland models, e.g. Frolking et al. (2001), Bauer (2004), Heijmans et al. (2008), Heinemeyer et al. (2010), Morris et al. (2012), Chaudhary et al. (2018), Bona et al. (2020).

One reason why such tests have been difficult is that suitable litterbag raw data to test peatland models are scarce. Bona et al. (2018) developed a Peatland Productivity and Decomposition Parameter Database, but it contains only data from studies older than 2010 and no error estimates for remaining masses in litterbag data. Since decomposition rates have been estimated with different litterbag decomposition models in previous studies, their values are not directly comparable. Moreover, initial leaching losses (losses of soluble compounds, which do not originate from microbial depolymerization, due to leaching during the first days to weeks of incubation) can bias decomposition rate estimates if they are not explicitly considered and can vary between species and experiments (Yu et al., 2001; Teickner et al., 2024b). Therefore, raw data (remaining masses) are necessary for any meaningful test of decomposition modules with litterbag data. The recently published Peatland Decomposition Database (Teickner and Knorr, 2024b) contains raw data from available *Sphagnum* litterbag experiments and therefore allows to estimate parameters with any mass loss-based decomposition model and therefore also allows to consider initial leaching losses.

Even though tests of only a part of a model are less uncertain than tests of whole models, there still is a risk that they are dominated by uncertainties. Remaining masses in litterbag experiments are often very variable, even under controlled environmental conditions (e.g., Bengtsson et al., 2018), and for many litterbag experiments, a range of decomposition rates may produce similar predictions for remaining masses (e.g., Yu et al., 2001), also if a litterbag decomposition model compatible with the HPM is used (Teickner et al., 2024b). Finally, also only five model parameters, as in the case of the HPM decomposition module, can make predictions uncertain. These uncertainties have to be taken into account to check whether litterbag data are compatible with the peatland model. A possible way to do this is to combine the HPM decomposition module, a litterbag decomposition model compatible with this module, and available litterbag experiments into one model and use Bayesian data analysis (Gelman et al., 2014) to estimate uncertainties of data and parameters.

If such a test suggests that decomposition rates predicted by the HPM decomposition module do not fit estimates from litterbag experiments, or only if parameter estimates of the decomposition module differ from the parameter values originally

suggested, even if main uncertainty sources are considered, the test has identified a discrepancy worth considering in more detail. We can then analyze whether previous sensitivity analyses of the HPM suggest that these discrepancies may have larger effects on the predicted C accumulation, and if this is the case, the discrepancies are worth testing in future litterbag experiments.

Our aim is to test the HPM decomposition module against decomposition rates estimated from available *Sphagnum* litterbag experiments. Specifically, we want to:

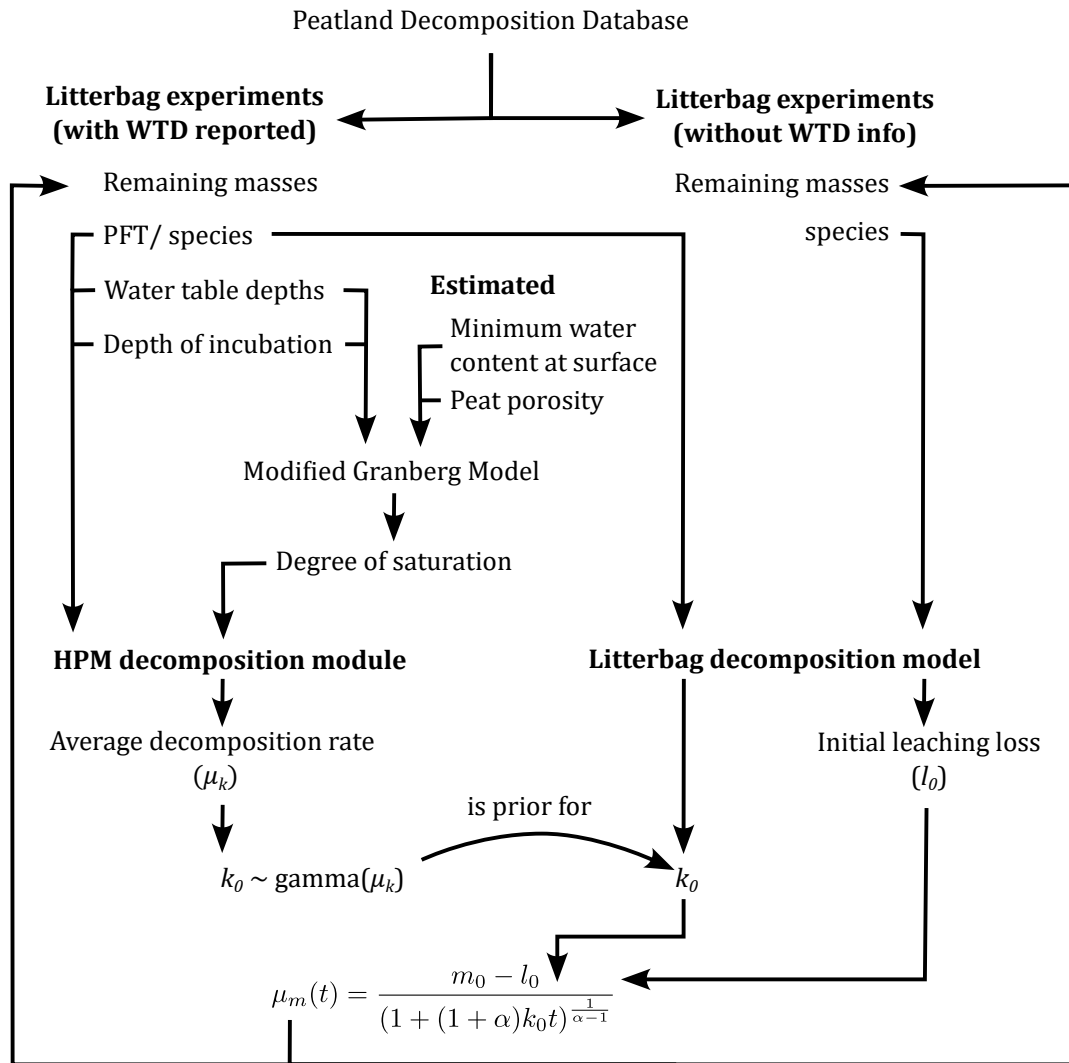
1. Test whether the HPM decomposition module can predict litterbag decomposition rates for different *Sphagnum* species along the gradient from oxic to anoxic conditions.
2. Estimate HPM decomposition module parameters from litterbag data and compare them to the originally suggested values (standard parameter values) (Frolking et al., 2010) that are often used when applying the HPM (Tab. 1).
3. If some of the parameter values differ, identify the possible causes why parameter estimates from litterbag data differ to provide guidance for future litterbag experiments.
4. Analyze whether estimated differences in HPM parameter values could imply significant differences in decomposition rates and long-term peat accumulation.

To address these aims, we used the HPM decomposition module to predict decomposition rates in available litterbag experiments and compared these to decomposition rates estimated for the same litterbag experiments with a litterbag decomposition model that considers initial leaching losses (Teickner et al., 2024b) (Fig. 1). These predictions require the peat degree of saturation, which we estimate with the modified Granberg model (Granberg et al., 1999; Kettridge and Baird, 2007) from water table depth data reported in these studies. Furthermore, some *Sphagnum* litterbag experiments do not report water table depths and therefore cannot be used to test the HPM, but they still provide information on initial leaching losses and decomposition rates and therefore help to constrain parameter estimates. We therefore include these data via Bayesian hierarchical modeling in the litterbag decomposition model. In summary, our approach combines the HPM decomposition module, the modified Granberg model, and a *Sphagnum* litterbag decomposition model that allows to consider initial leaching losses and to pool information across litterbag experiments (Teickner et al., 2024b). While this approach has its limitations, it exploits available data as far as possible, while considering known confounders and propagating relevant uncertainties.

We only test the decomposition module of the HPM, but the decomposition modules of many other peatland models are also parameterized based on litterbag experiments and our modeling approach is flexible enough to be combined with other decomposition modules. Therefore, our test could serve as a blueprint for similar tests of other peatland model decomposition modules. Similarly, the parameter discrepancies identified here suggest future litterbag experiments that would provide novel insights into oxic and anoxic controls of *Sphagnum* decomposition rates and our study therefore suggests a strategy to improve decomposition modules in general.

**Table 1.** Standard values of parameters of the decomposition module in the Holocene Peatland Model (Frolking et al., 2010).

HPM parameter	Standard value	Description
$W_{opt}$ ( $L_{water} L_{pores}^{-1}$ )	0.450	Optimum degree of saturation for aerobic decomposition.
$c_1$ (-)	2.310	Curvature of the relation of the aerobic decomposition rate to the degree of saturation (larger values imply a steeper decrease of decomposition rates for degrees of saturation diverging from $W_{opt}$ ).
$f_{min}$ ( $yr^{-1}$ )	0.001	Minimum anaerobic decomposition rate.
$c_2$ (m)	0.300	Anoxia scale length. Represents limitation of anaerobic decomposition rates with increasing distance below the annual average water table depth due to end product accumulation and limitation of available electron acceptors. Larger values mean that anaerobic decomposition rates decrease less strongly with depth below the average annual water table level.
$k_{0,hollow}$ ( $yr^{-1}$ )	0.130	Maximum possible decomposition rate for hollow <i>Sphagnum</i> species.
$k_{0,lawn}$ ( $yr^{-1}$ )	0.080	Maximum possible decomposition rate for lawn <i>Sphagnum</i> species.
$k_{0,hummock}$ ( $yr^{-1}$ )	0.060	Maximum possible decomposition rate for hummock <i>Sphagnum</i> species.



**Figure 1.** Conceptual representation of the modeling approach. Arrows represent flows of information. Litterbag data that have information on water table depths (WTD) and incubation depths are used to estimate average decomposition rates with the HPM decomposition module ( $\mu_k$ ). The HPM decomposition module needs plant functional type identity, peat degree of saturation, WTD, and incubation depth to predict decomposition rates. The modified Granberg model is used to estimate peat degree of saturation at incubation depths from WTD, minimum water content at the surface, and porosity, of which the latter two are estimated from the remaining masses. The litterbag decomposition model is used to estimate decomposition rates ( $k_0$ ) for all litterbag studies, including those that have information on WTD and those that have not. A gamma distribution with  $\mu_k$  as average is used as prior distribution for  $k_0$  for the litterbag experiments that have information on WTD (curved arrow). This helps to constrain initial leaching loss and decomposition rate estimates for studies that can be predicted with the HPM decomposition module. The Litterbag decomposition model also estimates initial leaching losses ( $l_0$ ) for all litterbag experiments. The equation at the bottom uses these to estimate remaining masses in the litterbag experiments. The litterbag decomposition model is described in more detail in section 2.2.1. See the text for further details.

## 2.1 *Sphagnum* litterbag data

To test the HPM decomposition module against litterbag data, we used the Peatland Decomposition Database (Teickner and Knorr, 2024b). In this study, we use data from Bartsch and Moore (1985), Vitt (1990), Johnson and Damman (1991), Szumigalski and Bayley (1996), Prevost et al. (1997), Scheffer et al. (2001), Thormann et al. (2001), Asada and Warner (2005), Trinder et al. (2008), Breeuwer et al. (2008), Straková et al. (2010), Hagemann and Moroni (2015), Golovatskaya and Nikonova (2017), and Mäkilä et al. (2018) to estimate  $k_0$  using the litterbag decomposition model. Data from Johnson and Damman (1991), Szumigalski and Bayley (1996), Prevost et al. (1997), Straková et al. (2010), Golovatskaya and Nikonova (2017), and Mäkilä et al. (2018) reported WTD and therefore only these data were used to predict  $k_0$  also with the HPM decomposition module. Samples originally classified as *Sphagnum magellanicum* are here classified as *Sphagnum magellanicum aggr.* (Hassel et al., 2018).

**Table 2.** Overview on litterbag experiments included for each *Sphagnum* taxon in this study. “HPM microhabitat” is the HPM microhabitat assigned to each taxon. Taxa without value are not considered in Johnson et al. (2015) (see section 2.2.2). “Number of experiments” is the number of litterbag experiments available from the Peatland Decomposition Database (these are either individual replicates or average values of replicates, depending on what data were reported in the studies). “Number of experiments with WTD data” is the number of litterbag experiments that also report water table depths and for which we therefore could make predictions with the HPM decomposition module. “Depth range” are the maximum and minimum depth below the peat surface at which litterbags were placed [cm]. Missing values mean that no study reported depths.

Taxon	HPM microhabitat	Number of studies	Number of experiments	Number of experiments with WTD data	Depth range
<i>Sphagnum spec.</i>		2	16	10	10, 30
<i>S. angustifolium</i>	Hummock	4	14	8	1, 30
<i>S. auriculatum</i>		1	3	0	0, 6
<i>S. balticum</i>	Lawn	3	12	3	1, 30
<i>S. cuspidatum</i>	Hollow	1	5	5	10, 50
<i>S. fallax</i>	Lawn	1	4	1	1, 1
<i>S. fuscum</i>	Hummock	9	32	13	1, 50
<i>S. lindbergii</i>	Lawn	1	2	0	
<i>S. magellanicum aggr.</i>	Hummock	3	7	5	1, 50
<i>S. majus</i>	Hollow	1	2	2	10, 30
<i>S. papillosum</i>	Lawn	2	6	1	0, 1
<i>S. rubellum</i>	Hummock	1	2	2	10, 30
<i>S. russowii</i>	Hummock	1	3	2	1, 1
<i>S. russowii</i> and <i>capillifolium</i>		1	18	0	5, 5
<i>S. squarrosum</i>	Lawn	1	2	0	0, 0
<i>S. teres</i>	Lawn	1	1	1	2, 2

## 2.2 Prediction of litterbag decomposition rates with the Holocene Peatland Model

To predict decomposition rates, the HPM decomposition module needs as inputs the litter type in terms of the HPM plant functional types (PFT), the fraction of mass already lost due to previous decomposition, the depth of the litter below the peat surface, the water table depth, and the peat degree of saturation (Frolking et al., 2010).

140 Predicting decomposition rates for the available litterbag data is not straightforward because the HPM decomposition module does not consider specific features of available litterbag experiments. The HPM does not specify how to assign species to plant functional types. Moreover, none of the available litterbag studies reported the degree of saturation which therefore needs to be estimated in order to make predictions with the HPM decomposition module. The only variables that can be directly linked are the depth of the litter below the peat surface, and water table depths (both reported in litterbag experiments). All other variables  
145 can be estimated from available litterbag experiments only with additional assumptions that are described in the following subsections.

In the following subsection, we give a more detailed description of our modeling approach, in particular of the model used to estimate decomposition rates from litterbag data, of the HPM decomposition module and how it predicts decomposition rates, and how we link the decomposition rates estimated from litterbag data to those predicted by the HPM decomposition module.  
150 The remaining subsections discuss how we derived or estimated PFT, WTD, and degree of saturation for the litterbag data and additional steps to make the litterbag data compatible with the HPM decomposition module.

### 2.2.1 Remaining masses and decomposition rates

To estimate decomposition rates for available *Sphagnum* litterbag experiments we use the equation from the HPM that computes remaining masses from decomposition rates and decomposition time (Frolking et al., 2001, 2010), with three modifications.

155 The original equation (equation (4) in Frolking et al. (2001)) is:

$$m(t) = \frac{m_0}{(1 + (1 + \alpha)k_0 t)^{\frac{1}{\alpha-1}}}, \quad (1)$$

where  $m(t)$  is the fraction of initial mass remaining at time  $t$ ,  $m_0$  is the fraction of initial mass remaining at time  $t = 0$ ,  $k_0$  is the decomposition rate, and  $\alpha$  is a parameter that describes how decomposition slows down as mass is lost, where the HPM assumes  $\alpha = 2$  for simplicity (Frolking et al., 2001, 2010).

160 The modified version we use here is:

$$\mu_m(t) = \begin{cases} m_0 & \text{if } t = 0 \\ \frac{m_0 - l_0}{(1 + (\alpha - 1)k_0 t)^{\frac{1}{\alpha-1}}} & \text{if } t > 0 \end{cases}, \quad (2)$$

where  $l_0$  is the fraction of mass lost due to initial leaching. The HPM decomposition process does not assume that there are initial leaching losses, but these are commonly observed in litterbag experiments and bias decomposition rate estimates when

they are ignored (Yu et al., 2001; Teickner et al., 2024b); therefore, the modification is necessary to allow a sensible test of the  
 165 HPM decomposition module with litterbag data.

The second modification is that we do not assume  $\alpha = 2$ , but consider it as unknown parameter that is estimated from litterbag data. Since  $\alpha = 2$  was chosen for simplicity and attempts to reliably estimate  $\alpha$  have failed (e.g., Clymo et al., 1998; Froelking et al., 2001; Teickner et al., 2024b), we estimate  $\alpha$  mainly to consider the possible error introduced by this parameter.

The third modification is that we change  $m(t)$  to  $\mu_m(t)$  because we assume that equation (2) describes only the average fraction  
 170 of the initial mass remaining. For each retrieved litterbag, we assume that the remaining mass can be described with a beta distribution with precision parameter  $\phi_m$ :

$$m(t) \sim \text{beta}(\mu_m(t)\phi_m, (1 - \mu_m(t))\phi_m), \quad (3)$$

Values for  $k_0$  are estimated from remaining masses reported in available litterbag experiments conditional on equation (2) and a hierarchical prior structure (Teickner et al., 2024b):

$$175 \quad k_0 = \exp(\beta_{k,1} + \beta_{k,2,\text{species}} + \beta_{k,3,\text{species} \times \text{study}} + \beta_{k,4,\text{sample}}), \quad (4)$$

where  $\beta_{k,1}$  is the estimated decomposition rate across all litterbag experiments,  $\beta_{k,2,\text{species}}$  describes the difference of the average decomposition rate for the *Sphagnum* species,  $\beta_{k,3,\text{species} \times \text{study}}$  for the study (nested within species), and  $\beta_{k,4,\text{sample}}$  for the sample (litterbag experiment). All these parameters have normal distributions as priors. Hierarchical models of the same structure are used to estimate  $l_0$  and  $\alpha$  from equation (2) and to estimate  $\phi_m$  from equation (3).

180 These decomposition rates estimated from litterbag experiments are constrained by decomposition rates the HPM decomposition module (Froelking et al., 2010) predicts for the same litterbag experiments. The HPM decomposition module describes how decomposition rates depend on the *Sphagnum* PFT, the degree of saturation and the depth of a litter sample below the water table. Similar to the remaining mass, we here assume that the HPM decomposition module predicts an average decomposition rate,  $\mu_k$ , instead of the decomposition rate of individual samples:

$$185 \quad \mu_k = \begin{cases} k_{0,i} f_1(W) & \text{if } \hat{z} \leq 0 \\ k_{0,i} f_2(\hat{z}) & \text{if } \hat{z} > 0 \end{cases} \quad (5)$$

where  $k_{0,i}$  is the PFT-specific maximum possible decomposition rate (Tab. 1),  $W$  is the degree of saturation ( $L_{\text{water}} L_{\text{sample}}^{-1}$ ),  $\hat{z}$  the depth of the sample below the average annual water table ( $\hat{z} = z - z_{\text{wt}}$ , where  $z_{\text{wt}}$  and  $z$  are the depth of the water table and litterbag below the peat surface), and  $f_1$  and  $f_2$  are modifiers due to  $W$  (under oxic conditions) and  $\hat{z}$  (under anoxic conditions), respectively. These modifiers are described in equations (8) and (9) in Froelking et al. (2010):

$$190 \quad f_1(W) = 1 - c_1(W - W_{\text{opt}})^2 \quad (6)$$

$$f_2(\hat{z}) = f_{min} + (f_1(1) - f_{min}) \exp\left(\frac{-\hat{z}}{c_2}\right), \quad (7)$$

where all not yet mentioned parameters are defined in Tab. 1.

In our model,  $k_0$  estimated from the litterbag data for each litterbag experiment with reported WTD (sample) (equation (2)) is assumed to follow a gamma distribution with shape parameter  $\alpha_{\mu_k}$  (estimated) and average  $\mu_k$  (predicted for each sample  
195 with equation (5)):

$$k_0 \sim \text{gamma}\left(\alpha_{\mu_k}, \frac{\alpha_{\mu_k}}{\mu_k}\right), \quad (8)$$

Thus, the decomposition rate predicted by the HPM decomposition module (equation (8)) is a prior for  $k_0$  as estimated from the litterbag decomposition model (equation (4)). This forms the link between the litterbag decomposition model and the HPM decomposition module (Fig. 1) and also allows us to estimate parameters of the HPM decomposition module from the  
200 litterbag data. The advantage of this modeling approach is that we can consider litterbag experiments without water table depth to estimate  $l_0$  and  $k_0$  for individual *Sphagnum* species, which is additional information to constrain estimates of the HPM decomposition module parameters. Moreover, combining the litterbag decomposition model and the HPM decomposition module into one Bayesian model does not only estimate HPM decomposition module parameters from the litterbag data, but it also adjusts the decomposition rates estimated from litterbag data to the HPM decomposition module because the HPM  
205 decomposition module serves as prior in the combined model which therefore estimates what parameter values are compatible with the data and the combined model. This is exactly what we want because there is uncertainty both in the remaining masses reported in litterbag experiments and in HPM decomposition module parameters. If HPM decomposition module parameter estimates from the combined model are different from the standard values used in the original model (Tab. 1), even if we consider these uncertainties and use the HPM decomposition module as prior for the litterbag data, this is a discrepancy worth  
210 testing in future experiments.

### 2.2.2 Assignment of *Sphagnum* species to plant functional types

The HPM defines maximum possible decomposition rates ( $k_{0,i}$ ) for three *Sphagnum* PFT (hollow, lawn, and hummock species), but not how to assign species to them. We assigned individual *Sphagnum* species to the three PFT by comparing their niche WTD with the optimal WTD for net primary production defined in the HPM. Specifically, we defined fixed average annual  
215 WTD intervals for the PFT: hollow (<5 cm), lawn ( $\geq 5$  cm and < 15 cm), hummock ( $\geq 15$  cm) based on the HPM (Frolking et al., 2010). Then, we used niche WTD and standard deviations from Johnson et al. (2015) to assign *Sphagnum* species to these three microhabitats. Using only average values and the microhabitat WTD thresholds resulted in unintuitive assignments, such as assigning *S. fallax* to hummocks. To avoid such obvious misclassifications, we defined rules to assign species to HPM microhabitats based on the probability a species would occur in the three niche WTD intervals. To compute the probabilities,  
220 we assumed a normal distribution (Johnson et al., 2015):



1. Species with a probability of occurrence  $\geq 15\%$  in the intervals of all three PFT were classified as lawn species.
2. In all other cases, species were assigned to the PFT for which their probability of occurrence was largest.

Litterbag data from Prevost et al. (1997) are incubations of peat samples where the species is unknown. Based on descriptions in this study, it is likely that the peat was formed by hummock species. Hummock species are assumed to have the smallest decomposition rate among the three *Sphagnum* PFT in the HPM (Frolking et al., 2010) and this is in line with small decomposition rate estimates for these samples (Teickner et al., 2024b). For these reasons, we assigned these samples to the hummock PFT of the HPM.

When estimating parameters of the HPM decomposition module from the litterbag data (see section 2.3.1), we also estimated the maximum possible decomposition rate ( $k_{0,i}$ ). *Sphagnum* species differ in their decomposition rate and the PFT of the HPM are a simplification that may cause misfits of the HPM decomposition module to litterbag data. We therefore estimated  $k_{0,i}$  for individual *Sphagnum* species in models HPM-all, HPM-leaching, and HPM-outlier (see section 2.3.1) and evaluated the variability of these species-specific estimates compared to the standard  $k_{0,i}$  values of the HPM *Sphagnum* PFT.

### 2.2.3 Degree of saturation

We estimated the degree of saturation with the modified Granberg model (ModGberg model) (Granberg et al., 1999; Kettridge and Baird, 2007) from minimum water content at the surface ( $\theta_{0,\min}$ ), total porosity ( $P$ ), the water table depth below the peat surface ( $z_{\text{wt}}$ ), and the depth of the litterbags below the peat surface during the incubation ( $z$ ):

$$\theta(z) = \min \left( P, \theta_0 + (P - \theta_0) \left( \frac{z}{z_{\text{wt}}} \right)^2 \right) \quad (9)$$

$$\theta_0 = \max \left( \theta_{0,\min}, 0.15z_{\text{wt}}^{-0.28} \right),$$

where  $\theta_0$  is the water content at the surface and  $0.15z_{\text{wt}}^{-0.28}$  is an empirical relation of  $\theta_0$  with the WTD (Kettridge and Baird, 2007).

The minimum water content at the surface was not reported in any study and we therefore assumed a minimum water content at the surface of  $0.05 L_{\text{water}} L_{\text{sample}}^{-1}$  with a standard deviation of  $0.05 L_{\text{water}} L_{\text{sample}}^{-1}$ , based on measurements from Hayward and Clymo (1982). The total porosity was not reported in any study and therefore we assumed an average value of 80% with a standard deviation of 10%, roughly based on values reported for low-density *Sphagnum* peat (Liu and Lennartz, 2019). An improved test of the HPM decomposition module would require litterbag experiments with direct measurements of the degree of saturation at sufficient temporal resolution.

### 2.2.4 Fraction of mass lost during previous decomposition

The HPM decomposition module assumes that decomposition rates decrease the more of the initial mass has already been decomposed (Frolking et al., 2001, 2010). All litterbag data we use here, except samples from Prevost et al. (1997), are from

*Sphagnum* samples collected from the surface of peatlands and therefore can be expected to have not experienced mass loss due to decomposition at the start of the experiments ( $m(t = 0) = 1$  in equation (2)). Prevost et al. (1997) incubated *Sphagnum* peat collected from two different depth levels from the same location and these samples probably had already experienced some decomposition, however it is difficult to estimate how much. To avoid this problem, we estimated  $k_{0,i}$  separately for samples from different depths in Prevost et al. (1997), implicitly assuming that these are two different PFT with different maximum possible decomposition rate.

## 2.3 Testing the HPM decomposition module against litterbag data

### 2.3.1 Model versions

To test different aspects of the HPM decomposition module and the additional assumptions we make, we computed several models which differ in whether HPM decomposition module parameters were fixed to their standard values or estimated from data, whether peat properties (porosity, water table depth, water content, minimum water content at the surface) are estimated from data or not, and whether the HPM decomposition module was extended to also predict  $l_0$  or not (Tab. 3).

The first model (HPM-standard) does not estimate any parameters of the HPM decomposition module (equations (5) to (7)) and does not estimate peat properties from the litterbag data and therefore corresponds to the HPM decomposition module with standard parameter values, while propagating prior uncertainties for peat properties. For this model, predictions of  $k_0$  equal  $\mu_k$  (equation (5)). This version of the HPM decomposition module is completely independent of the litterbag decomposition model, meaning that the HPM decomposition module is not used as prior for the litterbag decomposition model (Fig. 1). This also means that to compare  $k_0$  predicted by HPM-standard to  $k_0$  estimated from the litterbag decomposition model, we need to estimate the litterbag decomposition model independently, without using the HPM decomposition module as prior. This independent litterbag decomposition model is called LDM-standard (Tab. 3). We use LDM-standard not only to compare  $k_0$  estimates to  $k_0$  predictions of HPM-standard, but also to analyze how  $k_0$  estimates of the litterbag decomposition model changes when we use different versions of the HPM decomposition module as prior in the subsequent models.

Each subsequent model combines the HPM decomposition module and the litterbag decomposition model into one Bayesian model via equation (8). Each of these models estimates an additional set of parameters from the litterbag data relative to the previous model (Tab. 3). First, only the peat properties (HPM-peat) are estimated, and second all HPM parameters ( $k_{0,i}$ ,  $c_1$ ,  $W_{opt}$ ,  $f_{min}$ ,  $c_2$ ) (HPM-all). Finally, HPM-leaching extends HPM-all by adding formulas to model how  $l_0$  depends on the degree of saturation, similar to how the HPM decomposition module predicts  $k_0$  with equation (6).

HPM-peat tested whether the HPM decomposition module can fit available litterbag data when the HPM decomposition module and the litterbag decomposition model are combined and when peat properties are estimated from data.

HPM-all estimates what HPM decomposition module parameter values are compatible with available litterbag data and therefore allows to test whether the standard parameter values are extreme relative to these estimates. Values of  $k_{0,i}$  were estimated for each species separately, as described in section 2.2.2.

HPM-leaching was computed because decomposition rates estimated from available litterbag experiments are sensitive to initial leaching losses (Yu et al., 2001; Lind et al., 2022; Teickner et al., 2024b). It is therefore interesting to see whether litterbag decomposition rates are estimated differently in HPM-leaching — when initial leaching losses are constrained by adding formulas to model how  $l_0$  depends on the degree of saturation — compared to HPM-all — when initial leaching loss estimates are constrained only by the litterbag decomposition model. Based on previous experiments with tea bags it is reasonable to assume that there is some relation between initial leaching losses and the degree of saturation (Lind et al., 2022). Specifically, we use the following logistic regression model to describe an average initial leaching loss per sample, in dependency of the degree of saturation:

$$\begin{aligned}\mu_l &= \text{logit}^{-1}(\beta_{l,1} + \beta_{l,2}W) \\ l_0 &\sim \text{beta}(\mu_l\phi_l, (1 - \mu_l)\phi_l),\end{aligned}\tag{10}$$

where  $\mu_l$  is the average initial leaching loss for a sample,  $\beta_{l,1}$  is the (hypothetical) average initial leaching loss at a degree of saturation 0 for each taxon,  $\beta_{l,2}$  is the coefficient that describes the relation to the degree of saturation ( $W$ ), and  $\phi_l$  transforms  $\mu_l$  and  $(1 - \mu_l)$  into the shape and rate parameters of a beta distribution. This beta distribution has the same function as the gamma distribution (equation (8)) for  $k_0$  (compare also with Fig. 1): it is a prior for  $l_0$  estimated with the litterbag decomposition model, where the average of this prior is  $\mu_l$ .

To check whether outliers in the litterbag data could influence our results, we computed one additional model, HPM-outlier, with the same structure as HPM-leaching, but estimated without litterbag experiments identified as outliers. Litterbag experiments were defined as outliers if the reported average remaining mass of any litterbag (batch) during the experiment had a posterior probability  $> 99\%$  to be different from the remaining mass predicted by the litterbag decomposition model alone. This procedure identified experiments as outliers where remaining masses increased over time, where litterbags collected at intermediate time points had unexpectedly low remaining masses, or where initial leaching losses were retarded to later time points, presumably because of freezing after the start of the experiment (Teickner et al., 2024b). In total, 5 litterbag experiments were identified as outliers. Results for HPM-outlier are shown in supporting information S8 and HPM decomposition module parameter estimates agree with estimates of HPM-leaching and HPM-all.

Strictly, we do not test the decomposition module in the HPM, but the combination of the HPM decomposition module and the modified Granberg model, assuming that uncertainties in water table depths are negligible and that we accounted sufficiently for uncertainties in total porosity. This ambiguity has to be accepted when combining heterogeneous litterbag data where some variables have to be estimated. Litterbag experiments where water table depths and the degree of saturation are measured at sufficient temporal resolution are needed to avoid this ambiguity in future studies and to improve any test of the HPM decomposition module.

**Table 3.** Overview of HPM decomposition module modifications computed in this study.

Model	Description
LDM-standard	The litterbag decomposition model without the HPM decomposition module as prior. This is model 1-4 from Teickner et al. (2024b).
HPM-standard	The Holocene Peatland Model decomposition module with standard parameter values (Frolking et al., 2010). The model is run with peat water contents estimated with the modified Granberg model, using water table depths and litterbag depths reported from the litterbag studies, and assuming a fixed peat porosity, and minimum peat water content at the surface.
HPM-peat	The same as HPM-standard, but combined with LDM-standard into one Bayesian model, where the HPM decomposition module is a prior for the litterbag decomposition model (Fig. 1). Water table depths, peat porosity, and minimum peat water content at the surface are estimated from data.
HPM-all	The same as HPM-peat, but now also parameters from the HPM decomposition module ( $k_{0,i}$ , $W_{opt}$ , $f_{min}$ , $c_1$ , $c_2$ ) are estimated from the litterbag data.
HPM-leaching	The same as HPM-all, but now also an average initial leaching loss for each species and, across all species, a factor, by which this average leaching loss increases or decreases as the peat degree of saturation increases, are estimated (equation (10)).
HPM-outlier	The same as HPM-leaching, but computed without litterbag experiments that were identified as outliers (see the text for details).

### 310 2.3.2 Bayesian data analysis

All models listed in Tab. 3 were computed with Bayesian statistics to account for relevant uncertainty sources and include relevant prior knowledge (for example that *Sphagnum* decomposition rates are unlikely to be larger than  $0.5 \text{ yr}^{-1}$ ). Bayesian computations were performed using Markov Chain Monte Carlo (MCMC) sampling with Stan (2.32.2) (Stan Development Team, 2021a) in R (4.2.0) (R Core Team, 2022) via the rstan package (2.32.5) (Stan Development Team, 2021b) using the  
315 NUTS sampler (Hoffman and Gelman, 2014), with four chains, 4000 total iterations per chain, and 2000 warmup iterations per chain. None of the models had divergent transitions, the minimum bulk effective sample size was larger than 400, and the largest rank-normalized  $\hat{R}$  was 1.01, indicating that all chains converged (Vehtari et al., 2021). All models used the same priors for the same parameters and prior choices are listed and justified in supporting Tab. S1. Results of prior and posterior predictive checks are shown in supporting section S3.

320 We used power-scaling of the prior and likelihood distributions as implemented in the priorsense package (0.0.0.9000)  
(Kallioinen et al., 2024) to analyze the relative sensitivity of the posterior distribution to small perturbations of the prior  
and likelihood in HPM-leaching for HPM decomposition module parameters and peat properties. This is a computationally  
nonexpensive way to check whether the data provide information about a parameter and where prior and data may provide  
conflicting information (Kallioinen et al., 2024). Results of this analysis and further information on the data analysis are shown  
325 in supporting information S2.

### 2.3.3 Fit of model predictions to estimated decomposition rates and observed remaining masses

To analyze how well the models fit remaining masses observed in the litterbag experiments, we plotted reported remaining  
masses versus remaining masses estimated by the litterbag decomposition model in HPM-peat, HPM-all, and HPM-leaching.  
HPM-standard is not linked to the litterbag decomposition model and therefore does not predict remaining masses.

330 To analyze how well all HPM decomposition module versions fit  $k_0$  estimated by the respective litterbag decomposition  
model, we created a similar plot for  $k_0$ . Here, we compared predictions of HPM-standard (equation (8)) against estimates of  
LDM-standard (equation (4)). We also computed the average difference of  $k_0$  predicted by the HPM decomposition module  
and estimated from the litterbag data. We then computed the posterior probability that this average difference is different from  
zero. A large probability indicates a misfit of the model to available litterbag data. We also tested the same difference for  
335 specific species because graphical checks indicated that the decomposition rate prediction skill of the HPM decomposition  
module depends on species.

To test whether HPM-leaching has not only a better fit to available litterbag data, but also a better predictive accuracy for  
novel data than the model with standard parameter values (HPM-standard), we compared how well both can predict  $k_0$  from  
litterbag experiments. HPM decomposition module parameters of HPM-standard are not estimated from data and therefore we  
340 could compute the root mean square error of prediction ( $\text{RMSE}_{\text{test}}$ ) directly with  $k_0$  predicted by HPM-standard and estimated  
with LDM-standard. HPM decomposition module parameters of HPM-leaching are estimated from the litterbag data and we  
therefore used cross-validation (CV) to estimate  $\text{RMSE}_{\text{test}}$ . Since decomposition rates from the same species and study usually  
are not independent, we defined blocks which were used as CV-folds. Each fold represents the data from one study, but only if  
there were still data for the same *Sphagnum* species left in the remaining data (we want to estimate the predictive accuracy not  
345 for new species). Species with data from one study only were always used for model training and not part of the testing folds.  
This procedure resulted in 5 folds. HPM-standard and HPM-leaching were tested against the same data. In the text,  $\text{RMSE}_{\text{train}}$   
is the RMSE computed with the data a model was estimated with (for HPM-standard, the data the litterbag decomposition  
model was estimated with), and  $\text{RMSE}_{\text{test}}$  is the RMSE computed with independent test data.

### 2.3.4 Changes in $k_0$ and $l_0$ estimates of the litterbag decomposition models compared to LDM-standard

350 To analyze how parameter values of the litterbag decomposition model change when it is combined with different versions of  
the HPM decomposition module as prior, we estimated the average difference of  $k_0$  and  $l_0$  estimates of each model version  
to  $k_0$  and  $l_0$  estimates of LDM-standard. In particular, this allowed us to analyze whether there is any change in the relative

magnitude of  $l_0$  and  $k_0$  because the litterbag decomposition module would adjust these parameter values to fit the respective HPM decomposition module prior and still fit the observed remaining masses.

### 355 2.3.5 Magnitudes of $k_0$ along the gradient from oxic to anoxic conditions

To analyze how  $k_0$  changes along the gradient from oxic to anoxic conditions, we plotted  $k_0$  estimated by LDM-standard versus the water table depth below the litterbags. To this plot, we added  $k_0$  predicted by HPM-standard. To analyze how the relation of  $k_0$  changes for the HPM decomposition module modifications compared to HPM-standard, we computed differences between  $k_0$  estimated by HPM-peat, HPM-all, and HPM-leaching, respectively, and HPM-standard, and plotted these differences versus  
360 the water table depth below the litterbags.

### 2.3.6 Difference between values of $k_{0,i}$ , $c_1$ , $W_{opt}$ , $c_2$ , $f_{min}$ estimated from litterbag data to the standard parameter values

For HPM-all and HPM-leaching, we computed the posterior probability that the HPM decomposition module parameter values estimated from litterbag data ( $k_{0,i}$ ,  $c_1$ ,  $W_{opt}$ ,  $c_2$ ,  $f_{min}$ ) differ from the standard parameter values (Tab. 1). This way, we could  
365 identify discrepancies between standard parameter values and parameter values estimated from available litterbag data.

For HPM-leaching, we conducted in addition a sensitivity analysis, where we simulated decomposition of *S. fuscum* incubated at different depths in a peatland with water table depth of 40 cm below the surface, a porosity of  $0.7 L_{pores} L_{sample}^{-1}$ , and a minimum water content at the surface of  $0.05 g_{water} g_{sample}^{-1}$ . With these settings, we predicted five sets of average  $k_0$ : (1) with HPM-leaching ( $k_{0,modified}(HPM-leaching)$ ). The remaining four sets were also predicted with HPM-leaching, but each time  
370 setting one of the HPM decomposition module parameters to their standard value ( $k_{0,standard}(HPM-leaching)$ ): (2)  $c_1$ , (3)  $W_{opt}$ , (4)  $f_{min}$ , (5)  $c_2$ . We then computed the difference of  $k_0$  from set (1) and (2) to analyze the effect of the new  $c_1$  estimate, from set (1) and (3) to analyze the effect of the new  $W_{opt}$  estimate, and so on for sets (4) and (5). This gives the difference in decomposition rates of HPM-leaching if we would set individual HPM decomposition module parameters to their standard values. This way, we could analyze what HPM decomposition module parameters contribute to a change in  $k_0$  predictions  
375 along the gradient from oxic to anoxic conditions.

## 3 Results

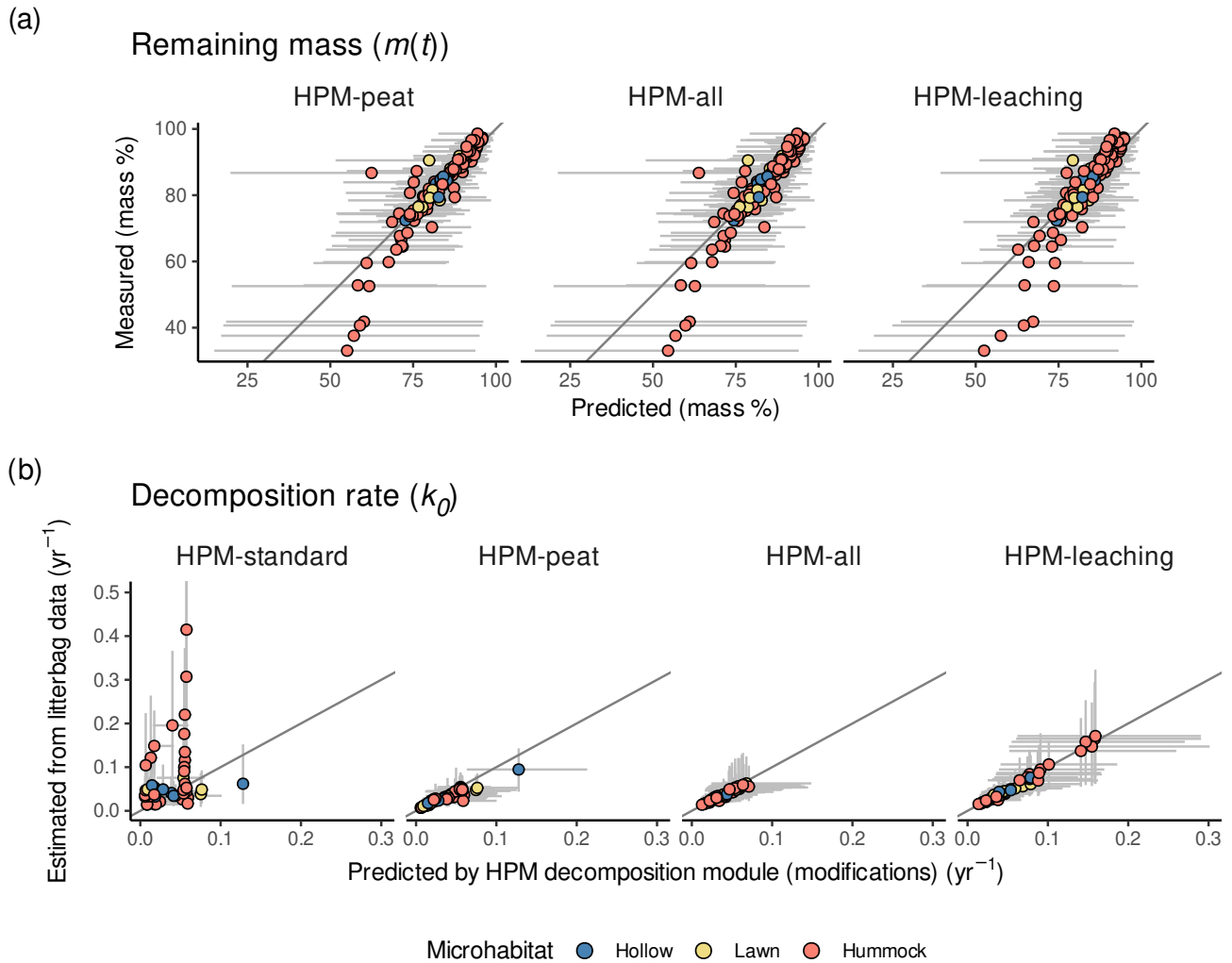
### 3.1 Fit and predictive accuracy of the different versions of the HPM decomposition module to available litterbag data

In each model, the litterbag decomposition model fitted the observed remaining masses similarly well (Fig. 2 (a) and supporting Fig. S2), no matter whether the HPM decomposition module was used as prior or not, and whether its parameters were  
380 estimated from data (HPM-all, HPM-leaching) or not (HPM-peat). Thus, remaining masses do not indicate large differences between the model versions.

For  $k_0$ , the picture is more nuanced: When the HPM decomposition module is not used as prior (HPM-standard), it fitted  $k_0$  estimated by the litterbag decomposition model on average less well than when it was used as prior (all other model versions) (Fig. 2, Tab. 4). For example, HPM-standard had an average  $\text{RMSE}_{\text{train}}$  of  $0.11 \text{ yr}^{-1}$ , whereas HPM-leaching had an average  $\text{RMSE}_{\text{train}}$  of  $0.02 \text{ yr}^{-1}$ . However, the cross-validation indicates that when applied to novel samples, both HPM-standard and HPM-leaching would perform similarly well if one considers the large uncertainty of the  $\text{RMSE}_{\text{test}}$  estimates (Tab. 4). Interestingly, all model versions where the HPM decomposition module was used as prior had comparable fits ( $\text{RMSE}_{\text{train}}$ ) (Tab. 4), even the version that still has standard parameter values for the HPM decomposition module (HPM-peat). This indicates that a change in HPM decomposition module standard parameter values is not required to make the HPM decomposition module fit  $k_0$  values estimated from available litterbag data via the litterbag decomposition model, under the assumptions we made. Instead, the results indicate that parameter values of the litterbag decomposition model can be adjusted to fit predictions of this HPM decomposition module prior.

**Table 4.** Training and testing RMSE for decomposition rates as predicted by different versions of the decomposition module of the Holocene Peatland Model (see Tab. 3 for a description of the models) and number of misfits.  $\text{RMSE}_{\text{train}}(k_0)$  is the root mean square error of model predictions for litterbag replicates used during model computation.  $\text{RMSE}_{\text{test}}(k_0)$  is the RMSE for litterbag replicates used in blocked cross-validation. Where no  $\text{RMSE}_{\text{test}}(k_0)$  is given, it was not computed for these models. Values are averages and lower and upper bounds of central 95% posterior intervals ( $\text{yr}^{-1}$ ). Misfits counts the number of litterbag experiments for which  $k_0$  predicted by the HPM decomposition module modification differed from  $k_0$  as estimated from the litterbag decomposition model with a posterior probability of at least 99%. In total,  $k_0$  was predicted with the HPM decomposition module modifications for 53 litterbag experiments ( $\text{RMSE}_{\text{train}}(k_0)$ ) or 29 ( $\text{RMSE}_{\text{test}}(k_0)$ ).

Model	$\text{RMSE}_{\text{train}}(k_0)$	$\text{RMSE}_{\text{test}}(k_0)$	Misfits
HPM-standard	0.105 (0.051, 0.191)	0.136 (0.06, 0.252)	13
HPM-peat	0.02 (0.013, 0.029)		0
HPM-all	0.014 (0.008, 0.021)		0
HPM-leaching	0.022 (0.012, 0.039)	0.088 (0.038, 0.179)	0
HPM-outlier	0.021 (0.013, 0.032)		0



**Figure 2.** (a) Measured remaining masses versus remaining masses predicted by the litterbag decomposition model combined with each HPM decomposition module version. Values are shown for litterbag experiments with reported water table data. For HPM-standard no values are shown because it was not combined with a litterbag decomposition model. (b)  $k_0$  estimated by the litterbag decomposition model versus  $k_0$  predicted by different modifications of the HPM decomposition module (Tab. 3). For HPM-standard, y-axis values are  $k_0$  estimates of LDM-standard. For all other model versions, y-axis values are  $k_0$  estimates of the litterbag decomposition module with the respective HPM decomposition module version as prior. Points represent average estimates and error bars 95% posterior intervals. Points are colored according to the microhabitat classification of *Sphagnum species* (see the Methods section for details). In (b), error bars exceeding  $0.5 \text{ yr}^{-1}$  are clipped.



### 3.2 How are parameter values of the litterbag decomposition model adjusted when different versions of the HPM decomposition module are used as prior?

395 To understand how using the HPM decomposition module as prior changes  $k_0$  and  $l_0$  estimates of the litterbag decomposition model, we compared  $k_0$  and  $l_0$  estimates of the litterbag decomposition model of each model version with the  $k_0$  and  $l_0$  estimates of LDM-standard. We computed the average difference of  $k_0$  estimates by the litterbag decomposition model for all models compared to the  $k_0$  estimates of LDM-standard (using only litterbag experiments with reported WTD). Average differences compared to LDM-standard are in the order HPM-peat < HPM-all < HPM-leaching (average and 95% confidence interval: -0.04 (-0.06, -0.02) < -0.03 (-0.06, -0.01) < -0.01 (-0.04, 0.01) yr<sup>-1</sup>). The magnitude (mean absolute difference) of adjustments of  $k_0$  estimates is different for different species (species with at least 3 samples): The largest average absolute differences across all models were made for *S. angustifolium* (0.15 (0.06, 0.27) yr<sup>-1</sup>) and the smallest for *Sphagnum* spec. (0.01 (0.01, 0.02) yr<sup>-1</sup>). This indicates that for some species  $k_0$  estimates of the litterbag decomposition model are forced to smaller values for HPM-peat and HPM-all, whereas differences are smaller for HPM-leaching.

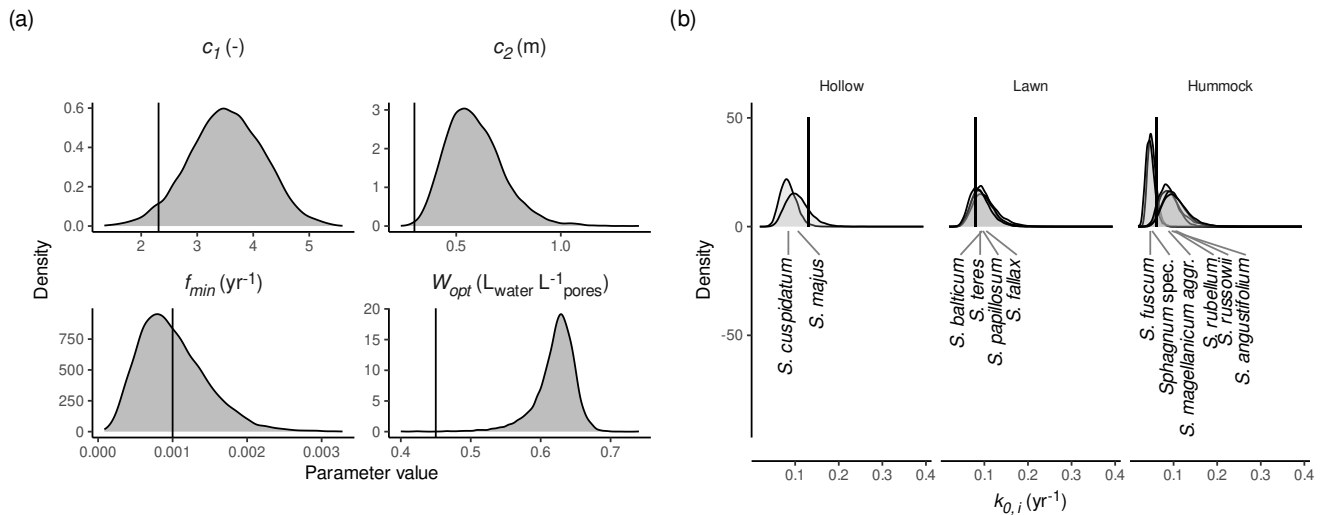
405 With these changes in  $k_0$  estimates, a similar fit to remaining masses as observed for all models (see the previous subsection) is only possible when  $l_0$  estimates are changed in the opposite direction. To check this, we computed the average difference of  $l_0$  estimates by the litterbag decomposition model for all model versions compared to the  $l_0$  estimates of LDM-standard. Differences compared to LDM-standard are in the order HPM-leaching < HPM-all < HPM-peat (average and 95% confidence interval: 0.1 (-1.9, 2.2) < 2.8 (0.7, 4.8) < 3.3 (1.6, 5) mass %). Again, the magnitude (mean absolute difference) of adjustments of  $l_0$  estimates is different for different species (species with at least 3 samples): The largest average absolute differences across all models were made for *S. angustifolium* (11.4 (7, 16.6) mass %) and the smallest for *Sphagnum* spec. (1.43 (0.86, 2.39) mass %). Thus, the smaller  $k_0$  estimates are indeed compensated by larger  $l_0$  estimates for HPM-peat and HPM-all, whereas the difference to LDM-standard is smaller for HPM-leaching.

Overall, this analysis indicates that errors in remaining masses observed in available litterbag experiments are large enough to support a range of  $k_0$  and  $l_0$  estimates. The equivalent fit of the different model versions is therefore caused by adjusting  $k_0$  to the HPM prior, and adjusting  $l_0$  as needed to fit observed masses.

### 3.3 How do HPM decomposition module parameter estimates differ to the standard values?

Two model versions estimated HPM decomposition module parameters ( $c_1, W_{opt}, f_{min}, c_2, k_{0,i}$ ): HPM-all and HPM-leaching. These models indicate larger values for  $c_2$  and  $W_{opt}$  than the standard values. Figure 3 shows marginal posterior densities of the HPM decomposition module parameters for HPM-all, with standard parameter values as defined in Frolking et al. (2010) indicated by vertical lines. For both HPM-all and HPM-leaching, there are large posterior probabilities that  $c_2$  ( $P_{\text{HPM-all}}(c_2 > 0.3 \text{ m}) = 1$  and  $P_{\text{HPM-leaching}}(c_2 > 0.3 \text{ m}) = 1$ ) and  $W_{opt}$  ( $P_{\text{HPM-all}}(W_{opt} > 0.45 L_{\text{water}} L_{\text{pores}}^{-1}) = 1$  and  $P_{\text{HPM-leaching}}(W_{opt} > 0.45 L_{\text{water}} L_{\text{pores}}^{-1}) = 0.98$ ) have larger values than the standard parameter values, indicating a discrepancy between the HPM decomposition module and available litterbag data (Fig. 3 and supporting Fig. S11). In contrast, estimates for  $f_{min}$  do not differ much to the prior value and the power-scaling sensitivity analysis indicates a weak influence of the data (supporting information

S2) and therefore that currently available litterbag data provide only little information about minimum decomposition rates under anoxic conditions. HPM-all and HPM-leaching suggest a large variability of  $k_{0,i}$  for individual species: Both models estimate a large posterior probability ( $> 95\%$ ) that *S. russowii* and *S. rubellum* have a larger, and that *S. cuspidatum* has a smaller maximum possible decomposition rate ( $k_{0,i}$ ) than the standard values for the respective PFT (Fig. 3 (b) and supporting 430 Fig. S11). However, estimates for  $k_{0,i}$  were very variable for the same species when different subsets of the litterbag data were used to estimate the model in the cross-validation. This indicates that samples of the same species from different studies have a large variability in  $k_{0,i}$  values. In summary, when HPM decomposition module parameters are estimated from available litterbag data, estimates for  $W_{opt}$  and  $c_2$  are larger than the standard values, differences to the  $c_1$  and  $f_{min}$  standard value cannot be detected, and estimates for  $k_{0,i}$  are variable and have large errors for different species.

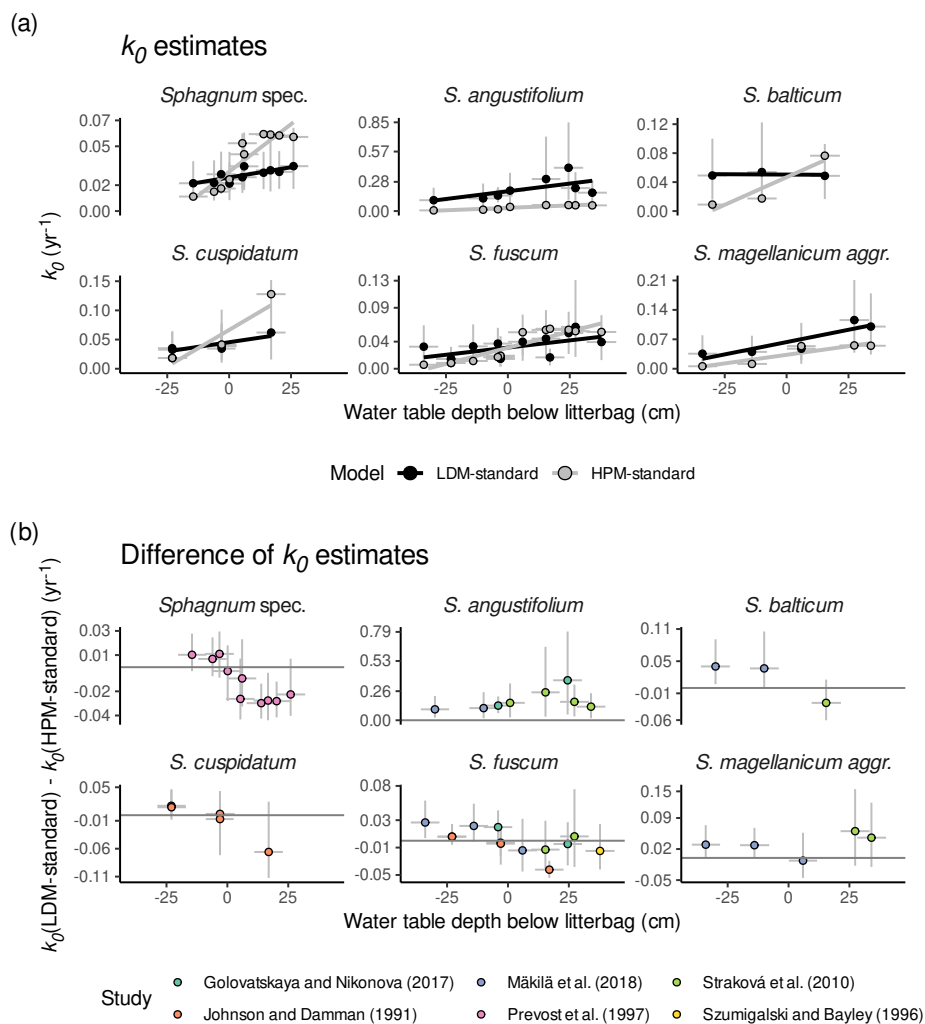


**Figure 3.** Marginal posterior distributions of HPM decomposition module parameters (see Tab. 1) as estimated by HPM-all. (a) Marginal posterior distributions for  $c_1$ ,  $W_{opt}$ ,  $f_{min}$ , and  $c_2$ . (b) Marginal posterior distributions for  $k_{0,i}$  (maximum possible decomposition rate for species  $i$ ). Species were assigned to HPM microhabitats as described in section 2.2.2. Vertical black lines are the standard parameter values from Froelking et al. (2010). *Sphagnum spec.* are samples that have been identified only to the genus level.

### 435 3.4 Magnitude and change of decomposition rates along the gradient from oxic to anoxic conditions

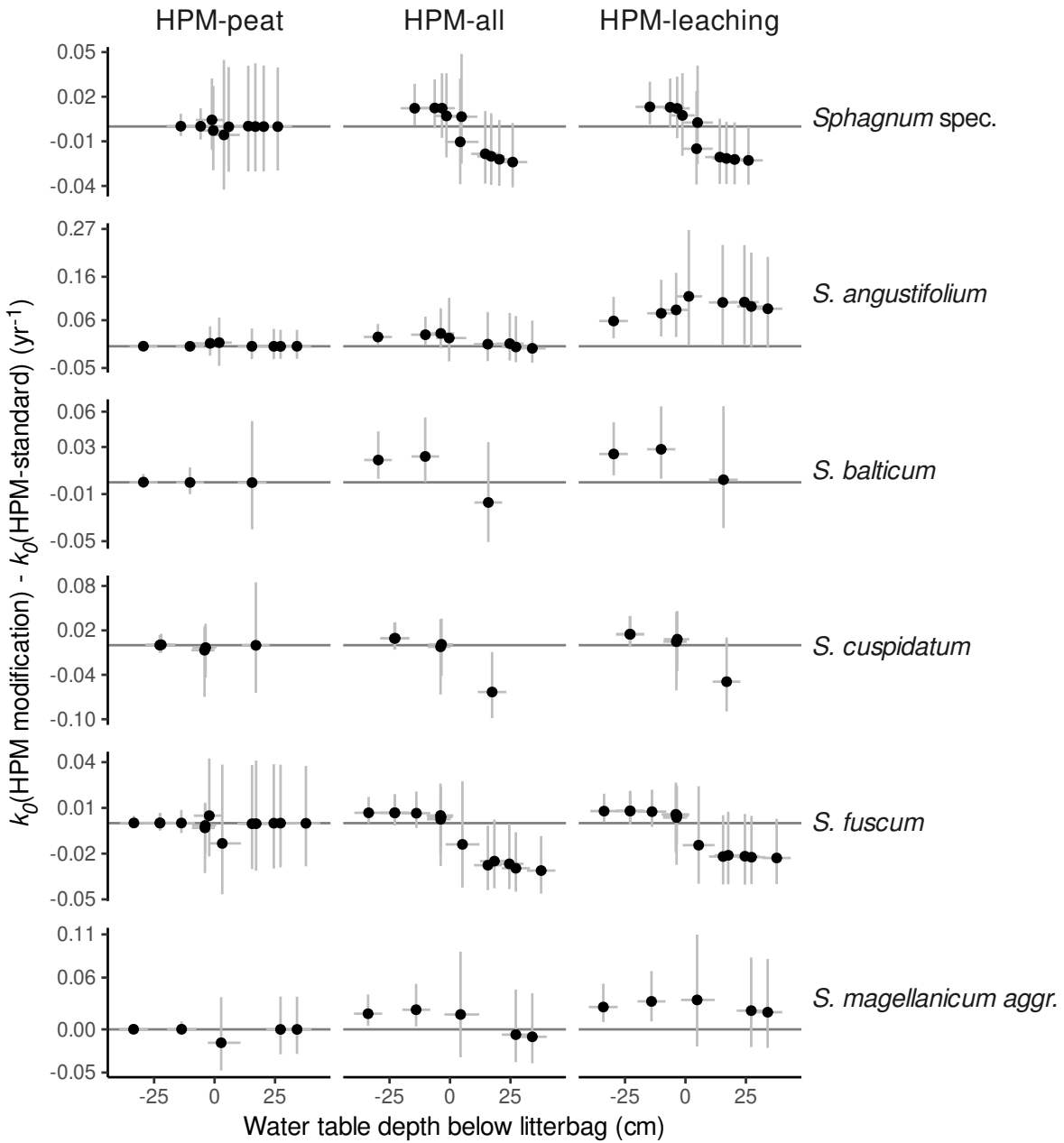
A comparison of  $k_0$  estimates of LDM-standard and  $k_0$  estimates of HPM-standard shows that the HPM decomposition module with standard parameter values implies a steeper decrease of decomposition rates from oxic to anoxic conditions than LDM-standard and, for some species, smaller anaerobic decomposition rates. Figure 4 (a) shows  $k_0$  estimated by LDM-standard and  $k_0$  predicted by HPM-standard versus water table depths below the litterbags reported in the studies for species with at 440 least three litterbag experiments. Regression lines were fitted to both sets of  $k_0$  values and they indicate an on average steeper slope for HPM-standard than for LDM-standard for many species (with large uncertainties). Moreover, under anoxic conditions

(negative water table depth),  $k_0$  estimates by LDM-standard are larger on average for many of the litterbag experiments than what HPM-standard predicts (Fig. 4 (b)).



**Figure 4.** Comparison of  $k_0$  estimates of HPM-standard and LDM-standard (Tab. 3) for species with at least three litterbag experiments. (a)  $k_0$  estimates of HPM-standard (grey) and  $k_0$  estimates of LDM-standard (black) versus reported average water table depths below the litterbags (negative values represent litterbags placed below the water table, positive values represent litterbags placed above the water table in the unsaturated zone). (b)  $k_0$  estimates of LDM-standard minus  $k_0$  estimates of HPM-standard versus reported average water table depths below the litterbags (i.e., the difference of the values shown in (a)). Grey horizontal lines indicate a difference in  $k_0$  of  $0 \text{ yr}^{-1}$ . Points represent average estimates and error bars 95% posterior intervals. Lines are predictions of linear models fitted to the average estimates. *Sphagnum spec.* are samples that have been identified only to the genus level.

A comparison of  $k_0$  estimates of HPM-standard and the other modifications of the HPM decomposition module suggests that  
445 when HPM decomposition module parameters are estimated, larger anaerobic decomposition rates and a less steep decrease  
of decomposition rates from oxic to anoxic conditions are predicted, similar to LDM-standard. We computed the difference of  
 $k_0$  predicted by HPM-standard and the other HPM decomposition module versions (Fig. 5). When the HPM decomposition  
module with standard parameter values is used as prior for the litterbag decomposition module (HPM-peat), it predicts  $k_0$  nearly  
identical to HPM-standard. In contrast, both model versions where HPM decomposition module parameters were estimated  
450 predict larger anaerobic decomposition rates and less of an increase under oxic conditions relative to anoxic conditions  
than HPM-standard. Thus, the HPM decomposition module with standard parameter values predicts a steeper decrease of  
decomposition rates from oxic to anoxic conditions and overall smaller anaerobic decomposition rates than LDM-standard and  
the models that estimate HPM decomposition module parameters from available litterbag data.



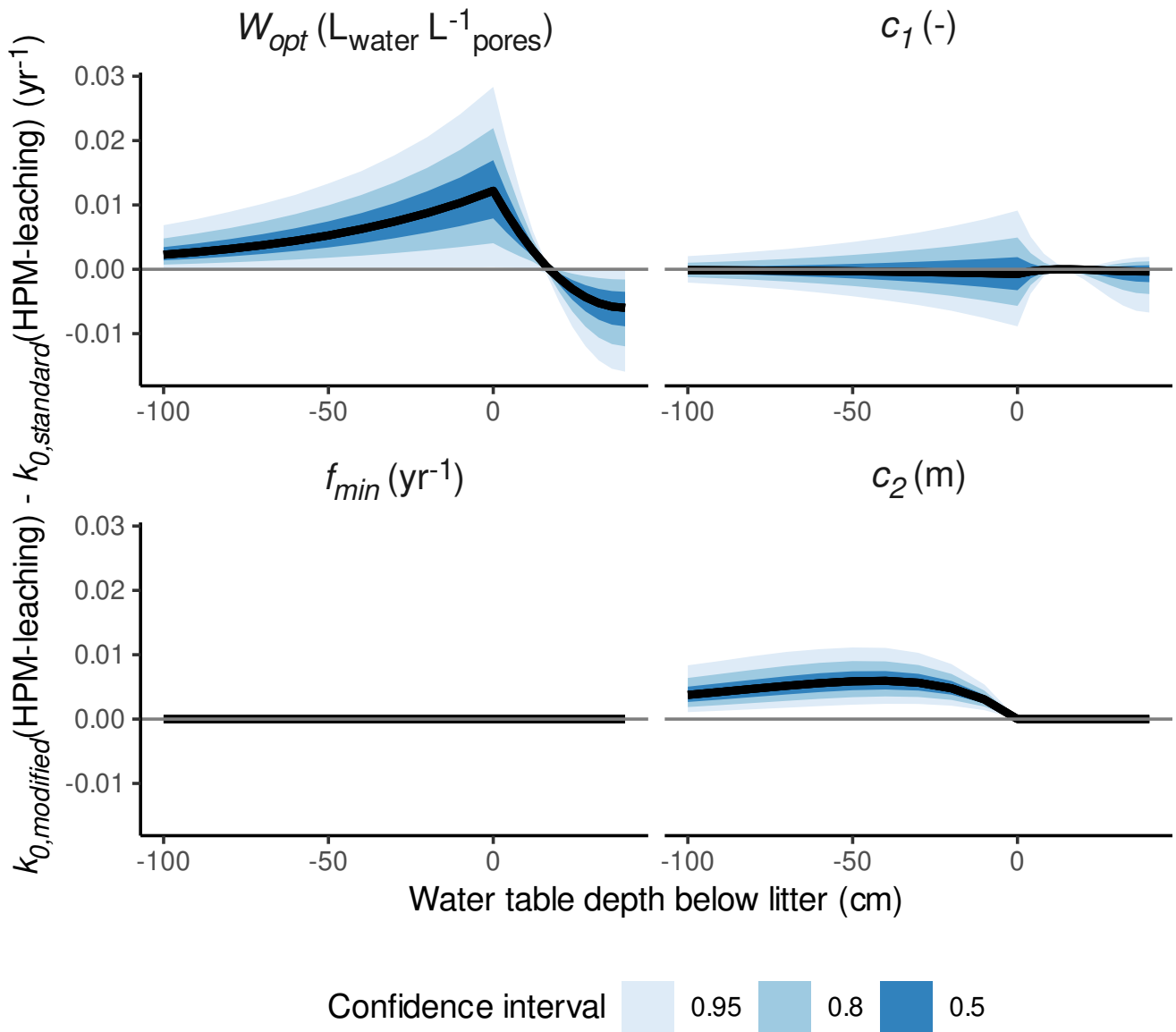
**Figure 5.**  $k_0$  predicted by HPM decomposition module modifications (either HPM-peat, HPM-all, or HPM-leaching) minus  $k_0$  predicted by the HPM decomposition module with standard parameter values (HPM-standard) versus estimated average water table depths below the litterbags (negative values represent litterbags placed below the water table, positive values represent litterbags placed above the water table in the unsaturated zone). Points represent average estimates and error bars 95% posterior intervals. *Sphagnum spec.* are samples which that been identified only to the genus level. Only data for species with at least three replicates are shown.

### 3.5 HPM decomposition module parameters that are responsible for the less steep gradient in decomposition rates from oxic to anoxic conditions

455

To analyze which of the HPM decomposition module parameters ( $c_1$ ,  $W_{opt}$ ,  $f_{min}$ ,  $c_2$ ) cause the less steep gradient in decomposition rates from oxic to anoxic conditions, we conducted a sensitivity analysis, where we made predictions with HPM-leaching for the same species and the same gradient from oxic to anoxic conditions, each time setting one of the four parameters to their standard values (four sets of predictions in total). We then computed the difference of the predicted  $k_0$  values to predictions of HPM-leaching (with no parameter value set to its standard value). This difference is plotted versus the depth of the water table below the litter, as shown in Fig. 6. This analysis suggests that  $W_{opt}$  and  $c_2$  cause the less steep gradient in decomposition rates from oxic to anoxic conditions, whereas the other two parameters have no qualitative influence.

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**Figure 6.** Difference between decomposition rates for *S. fuscum* predicted with parameter values estimated by HPM-leaching ( $k_{0,modified}(HPM-leaching)$ ), and when setting the HPM decomposition module parameter in the panel title to its standard value ( $k_{0,standard}(HPM-leaching)$ ), versus the water table depth below the litter (negative values represent litter placed below the water table, positive values represent litter placed above the water table in the unsaturated zone). Panels show results when different parameters are set to their standard values. Positive  $k_{0,modified}(HPM-leaching) - k_{0,standard}(HPM-leaching)$  means that decomposition rates are larger when using the estimated parameter value compared to using the standard parameter value. Shaded areas are central confidence intervals with probabilities given in the figure legend.

### 3.6 Relation of $l_0$ to the degree of saturation

In model HPM-leaching, we included a logistic regression model that estimates the relation between  $l_0$  and the degree of saturation. The parameter estimates suggest that both positive and negative relations of  $l_0$  to the degree of saturation are compatible with available litterbag data (95% confidence intervals for the slope (logit scale): (-0.28, 0.15)). Thus, available litterbag data do not allow to conclude whether  $l_0$  are positively related to the degree of saturation or not.

## 4 Discussion

Our aims were to test whether the HPM decomposition module fits decomposition rates estimated from available litterbag experiments, to estimate HPM decomposition module parameters from available litterbag experiments, to understand what factors could cause differences in parameter estimates to the standard values, and to check whether the estimates from litterbag data could imply significant differences in peat accumulation predicted by the HPM compared to the standard parameter values.

The parameter estimates derived from available litterbag data suggest differences in the control of decomposition rates compared to the standard parameter values: the HPM decomposition module with standard parameter values predicts a steeper decrease of decomposition rates from oxic to anoxic conditions and smaller anaerobic decomposition rates for several species than estimated from LDM-standard and the models that estimate HPM decomposition module parameters from available litterbag data. These differences imply larger estimates for  $W_{opt}$ , the degree of saturation where decomposition rates are maximal, and  $c_2$ , the anoxia scale length (the parameter that controls how strong decomposition rates decrease below the water table depth). We will show here, by comparing parameter estimates to results from sensitivity analyses of the HPM, that the new parameter estimates can cause large differences in long-term peat accumulation predicted by the HPM.

Our analysis suggests that the HPM decomposition module with standard parameter values fits available litterbag data, but our modifications, where  $W_{opt}$ ,  $c_2$ , and (for some species)  $k_{0,i}$  estimates significantly differ from the standard values, have equivalent fit. This can be explained by two mechanisms: first, the litterbag decomposition model explains mass loss by initial leaching and decomposition. Thus, remaining masses reported in a litterbag experiment can be fitted either by assuming a larger  $l_0$  and smaller  $k_0$ , or by assuming a smaller  $l_0$  and larger  $k_0$ . By this first mechanism, the litterbag decomposition model can first estimate  $k_0$  to agree with the HPM decomposition module and then adjust  $l_0$  to fit the remaining masses of the litterbag experiments. The second mechanism is the impact of the design of available *Sphagnum* litterbag experiments on the accuracy of  $l_0$  and  $k_0$  estimates: initial leaching losses can explain mass losses only at the start of the experiment (equation (2)), but decomposition explains a continuous mass loss. It is therefore possible to estimate  $l_0$  and  $k_0$  accurately when remaining masses shortly after the start of the experiment are recorded, but the majority of litterbag experiments collects the first litterbags only after half a year or later (Teickner et al., 2024b). This causes large errors in  $l_0$  and  $k_0$  estimates and therefore allows the model to adjust  $l_0$  and  $k_0$  by the first mechanism, such that all model versions have equivalent fit to remaining masses while also fitting decomposition rates suggested by different HPM decomposition module priors. Improved litterbag experiments are needed for more accurate tests of any peatland decomposition module and for obtaining parameter estimates accurate enough to allow



495 even only approximate predictions of long-term peat accumulation. Applications of the HPM should consider this variability in parameter estimates compatible with available litterbag experiments.

In the next subsections, we first evaluate the reliability of our test. We discuss whether the identified parameter value differences could be an artifact of using heterogeneous litterbag data, and we discuss how compatible the new HPM decomposition module parameter estimates are with other studies that analyzed how decomposition rates differ in dependency of water availability or that estimated  $c_2$  from peat core data. Second, we address the remaining aims: we discuss what factors could cause the larger anaerobic decomposition rates and, in some cases, smaller aerobic decomposition rates estimated by the litterbag decomposition model, and we discuss what implications the differences between estimated and standard parameter values have for peat accumulation predicted by the HPM. Finally, we give recommendations for improving tests of peat decomposition modules.

#### 505 4.1 Reliability of the identified discrepancies

Before analyzing potential causes of the discrepancies found for  $c_2$  and  $W_{opt}$  we first ask if combining different litterbag experiments is reliable evidence for the less steep gradient in decomposition rates from oxic to anoxic conditions.

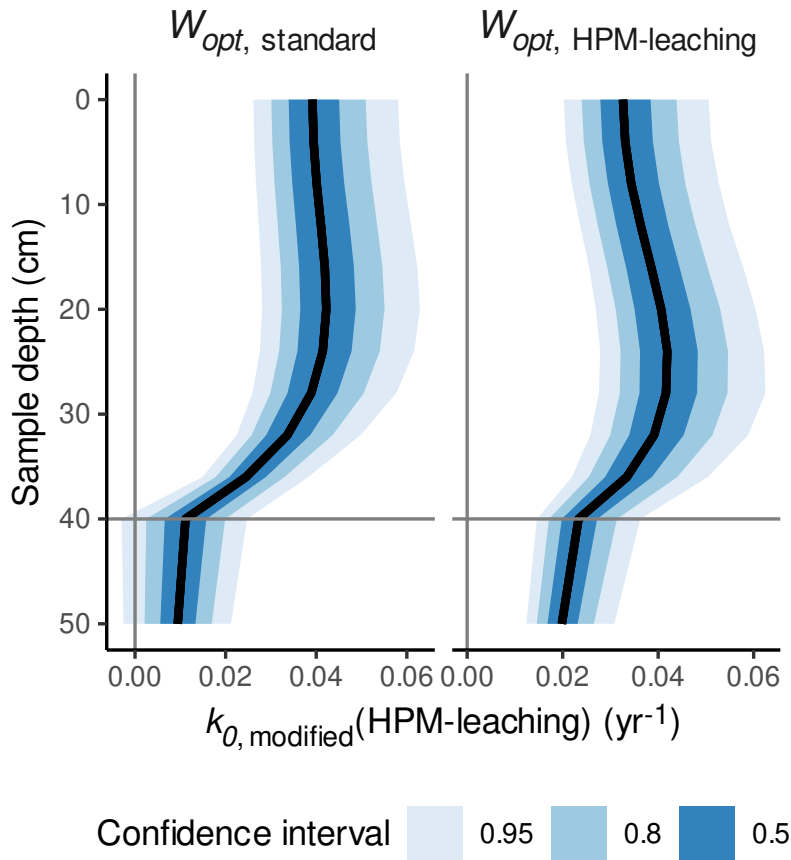
If we take a look at the misfits of the standard HPM decomposition module (HPM-standard) shown in Fig. 4, many, but not all underestimations of aerobic decomposition rates could have been caused by other factors: for example for *S. balticum* the difference may have been caused by differences in the two litterbag experiments from which we collected the data because the replicate with positive water table depth is from Straková et al. (2010), whereas the two others are from Mäkilä et al. (2018) (Fig. 4). The less pronounced gradient in measured decomposition rates above the water table depth is, however, also visible for *S. fuscum* replicates within the same study and in addition similar across these (independent) studies (Fig. 4, supporting information S6) (Johnson and Damman, 1991; Golovatskaya and Nikonova, 2017; Mäkilä et al., 2018), indicating that this pattern cannot be explained in all cases by differences between studies. In addition, during the cross-validation, we removed data from individual studies from the model and the remaining subsets still resulted in similar estimates for  $c_2$  and  $W_{opt}$  (supporting Fig. S12). Finally, numerous previous studies suggest that water table depth is an important control of decomposition rates (e.g., Blodau et al., 2004) and one may therefore expect that also between different studies decomposition rate differences should be controlled to a large degree by differences in water table depths. Thus, even with the heterogeneous litterbag data currently available, a less steep gradient of decomposition rates from oxic to anoxic conditions appears to be replicable between studies and species. To fully rule out that this pattern may be biased by heterogeneous litterbag data and biases of the litterbag decomposition model, controlled litterbag experiments that systematically estimate decomposition rates along the gradient from oxic to anoxic conditions are needed.

The  $W_{opt}$  estimate suggested by HPM-leaching is near the average optimum of heterotrophic respiration estimated across a range of mineral soils (Moyano et al., 2013). The estimate is also in line with a study where the largest decomposition rates of the same litter type were observed at or just above the average water table level in hummocks (Belyea, 1996), and with maximum CO<sub>2</sub> production rates around 13 cm above the water table level in a mesocosm study (Blodau et al., 2004). According to the ModGberg model the degree of saturation at this depth is near the  $W_{opt}$  estimate suggested by HPM-all

and HPM-leaching. For example, for our simulation analysis used to produce Fig. 6, the average  $W_{opt}$  estimated by model  
530 HPM-leaching ( $0.57 L_{water} L_{pores}^{-1}$ ) is reached around 16 cm above the water table level, as shown in Fig. 7. At shallower depths,  
the degree of saturation decreases below the  $W_{opt}$  estimate and this would decrease decomposition rates as observed in Belyea  
(1996). In contrast, according to the the ModGberg model, a degree of saturation corresponding to the standard  $W_{opt}$  value  
( $0.45 L_{water} L_{pores}^{-1}$ ) is reached at shallower depths and in the same simulation with this standard  $W_{opt}$  value, no pronounced sub-  
535 surface peak in decomposition rates is observed (supporting Fig. S15). In hollows, the optimum degree of saturation suggested  
by HPM-leaching is reached near the surface for either  $W_{opt}$  value (supporting Fig. S15). Thus, a larger value for  $W_{opt}$  would  
be compatible with results from several previous studies.

Larger and smaller  $c_2$  than the standard value have been estimated for several peatland cores with the HPM and a modified  
version with monthly time step (Quillet et al., 2015; Treat et al., 2021, 2022). Smaller values have been estimated for tropical  
peatlands (Kurnianto et al., 2015). To our knowledge, no litterbag experiment directly estimated  $c_2$ . A difficulty is that available  
540 litterbag experiments cover only a comparatively small depth range below the water table level (at most around 30 cm, Fig.  
4) and therefore gradients in anaerobic decomposition rates across larger depths below the water table currently cannot be  
estimated with available litterbag data.

The estimates for the maximum possible decomposition rate ( $k_{0,i}$ ) have large errors and removal of data during the cross-  
validation caused larger relative differences in  $k_{0,i}$  estimates compared to  $W_{opt}$  and  $c_2$  (supporting Fig. S12). On the one hand,  
545 this variability indicates that available litterbag data are not sufficient to estimate  $k_{0,i}$  accurately and that our assignment of  
*Sphagnum* species to HPM PFT may not be optimal, but on the other hand, this variability may also indicate that categorizing  
*Sphagnum* species into three PFT may not accurately describe the variability of maximum possible decomposition rates. Several  
studies suggest that diverse aspects of litter chemistry may increase  $k_{0,i}$  (Turetsky et al., 2008; Bengtsson et al., 2018). However,  
we are not aware of studies that systematically analyze what factors control  $k_{0,i}$  within the same species.



**Figure 7.** Decomposition rates predicted with HPM-leaching ( $k_{0,\text{modified}}(\text{HPM-leaching})$ ) for *S. fuscum* (hummocks), using either the standard value for  $W_{opt}$  or the  $W_{opt}$  value estimated by HPM-leaching versus depth of the litter below the peat surface. The horizontal line is the average water table depth. Shaded areas are central confidence intervals with probabilities given in the figure legend.

550 **4.2 Water table fluctuations may explain the discrepancies in  $c_2$  and  $W_{opt}$  and larger anaerobic and smaller aerobic decomposition rates.**

The HPM decomposition module predicts decomposition rates based on average annual water table depths (Frolking et al., 2010) and ignores water table fluctuations. Our evaluation of the HPM decomposition module also assumed an average water table depth during the litterbag experiments and the HPM decomposition module translated this into a clear pronounced  
 555 transition between anaerobic and aerobic decomposition rates (Fig. 4). In reality, water table levels fluctuate and this causes transient and nonlinear changes in decomposition rates due to variations in the availability of oxygen and other electron acceptors, flushing of end products of anaerobic decomposition, and possibly other factors (Siegel et al., 1995; Blodau and Moore, 2003; Blodau et al., 2004; Beer and Blodau, 2007; Knorr and Blodau, 2009; Walpen et al., 2018; Campeau et al.,

2021; Kim et al., 2021; Treat et al., 2022; Obradović et al., 2023). A possible explanation why the gradient in decomposition rates from oxic to anoxic decomposition is less steep across litterbag experiments, on average, than suggested by the standard HPM decomposition module could therefore be that an averaging effect of fluctuating water table levels on both aerobic and anaerobic decomposition rates is neglected by the HPM decomposition module. An additional factor may be that litterbags cover a depth range and therefore the decomposition rate estimate is an average over the depth covered by the litterbag. If moisture conditions vary over this depth, the decomposition rate estimate also averages over moisture conditions, with similar effects as the temporal average caused by water table fluctuations.

If this is the case,  $c_2$  would have to be re-interpreted as transition parameter that accounts for both limitation of anaerobic decomposition under anoxic conditions and the effects of periodically oxic conditions. Similarly,  $W_{opt}$  would have to be re-interpreted as the optimum average degree of saturation for decomposition under water table level variations and its value would be necessarily different from the optimum degree of saturation for depolymerization under static degree of saturation.

Adjusting the HPM decomposition module parameters as implied by our modified models may be an easy way to account for the effect of sub-annual variation in water table levels on decomposition rates, if the discrepancies are caused by fluctuating water tables and if the model is representative for different effects variations in water table level may have on decomposition rates (e.g., short-term fluctuations compared to seasonal water table variations compared to prolonged droughts). What we have not considered due to limited data is that  $c_2$  can be expected to depend on long-term changes in groundwater flow (e.g., Siegel et al., 1995) or site-specific differences in hydrology and other factors (e.g., Frolking et al., 2010; Treat et al., 2021, 2022). Therefore,  $c_2$  can be expected to differ between litterbag studies and our data only indicate that  $c_2$  is larger on average, whereas more research is necessary to estimate and understand site-specific controls of  $c_2$  and how a change in hydrology controls  $c_2$ . Similarly,  $W_{opt}$  may differ between sites and over time. It would be interesting to know whether litterbag experiments can quantify these controls and whether  $c_2$  estimated from litterbag experiments is generally larger in peatlands with larger water table fluctuations.

It is also worth mentioning that a modification of the HPM, HPM-Arctic (Treat et al., 2021), has a seasonally dynamic WTD and this modification may account for at least a part of the discrepancies we observed here. Unfortunately, most available litterbag data do not report WTD at sufficient temporal resolution to test whether standard HPM parameter values are more compatible with litterbag data when such seasonal variations in WTD are considered.

#### 4.3 Implications of the discrepancies in $W_{opt}$ , $c_2$ , and $k_{0,i}$ for long-term C accumulation

A larger  $c_2$  implies larger anaerobic decomposition and may thus indicate that the HPM decomposition module underestimates anaerobic decomposition rates. Previous global and local sensitivity analyses, where HPM parameter values were varied in broad ranges and environmental conditions were varied, identified  $c_2$  as influential for C accumulation in the HPM (Quillet et al., 2013a, b).

If  $c_2$  is varied within the range from the standard value (0.3 m) to the average posterior estimate from HPM-leaching (0.64 m), this would cause differences in predicted C accumulation of a maximum of ca. 20% in the sensitivity experiment of Quillet et al. (2013a) (depending on precipitation, Fig. 1 c in Quillet et al. (2013a)). If values are changed across the complete posterior

range compatible with litterbag data and if other HPM parameters would also be varied, the effect would be even larger (Fig. 2 c in Quillet et al. (2013a)).

595 Due to parameter interactions and feedbacks, an increase in anaerobic decomposition rates can result in smaller or larger C accumulation of the HPM, depending on environmental conditions (Quillet et al., 2013a). Small anaerobic decomposition may cause too rapid C accumulation resulting in a low water table level, a thick aerobic zone, and thus smaller overall C accumulation after a longer time. Larger anaerobic decomposition may result in higher water table levels and this can increase C accumulation in the long-term. Too large anaerobic decomposition decreases C accumulation (Quillet et al., 2013a).

600 A larger  $W_{opt}$  implies that the largest aerobic decomposition rates are reached under more saturated conditions.  $W_{opt}$  has not been identified as influential in a sensitivity analysis of the HPM (Quillet et al., 2013a), but as shown above, it contributes to the less steep decrease of decomposition rates from oxic to anoxic conditions. Importantly, since the HPM does not have a seasonally resolved water table depth, the two sensitivity analyses did not consider how seasonal variations of the water table depth may control long-term C accumulation, and consequently the re-interpreted  $W_{opt}$  may be more important to long-term C accumulation than previously assumed. In addition, HPM-leaching suggests an average  $W_{opt}$  value of  $0.57 L_{water} L_{pores}^{-1}$ , which is outside the range of values tested in Quillet et al. (2013a) (0.3 to  $0.5 L_{water} L_{pores}^{-1}$ ). This implies that the sensitivity of long-term C accumulation to  $W_{opt}$  has been evaluated over a too small range.

A larger  $k_{0,i}$  increases decomposition rates for a species and *Sphagnum*  $k_{0,i}$  are particularly relevant for many peatlands because the bulk of the peat is *Sphagnum* peat. In the sensitivity analysis in Quillet et al. (2013b),  $k_{0,hummock}$  had large interaction effects with other parameters of the HPM and therefore could either cause larger or smaller peat accumulation, depending on environmental conditions, other parameters, and what vegetation shifts occur in a specific case. Similar to  $W_{opt}$ , our  $k_{0,i}$  estimates have errors that are larger than the range of values tested in Quillet et al. (2013b). For example, for hummock *Sphagna*,  $k_{0,i}$  was varied from 0.04 to 0.06 yr<sup>-1</sup>, whereas average estimates for  $k_{0,i}$  of HPM-leaching for species assigned to the hummock PFT range from 0.04 to 0.19 yr<sup>-1</sup>. As mentioned above, this range of  $k_{0,i}$  estimates may be biased because of the difficulty to assign *Sphagnum* species to HPM PFT, but from a different perspective, this is an additional error source for  $k_{0,i}$  estimates that should be considered in sensitivity analyses unless more evidence becomes available to define PFT and their maximum possible decomposition rates.

A further aspect that needs to be considered is that HPM-all and HPM-leaching estimate parameter distributions based on available data, whereas existing studies defined fixed parameter values or ranges of parameter values based on expert knowledge. Based on Quillet et al. (2013a), the uncertainties would cause non-negligible differences in predicted long-term C accumulation. For example, values within the uncertainty range of  $c_2$  estimated by HPM-leaching ((0.4, 0.97), 95% confidence interval), would imply differences up to 100 kg m<sup>-2</sup> of accumulated C over 5000 years in some simulations (Fig. 1 (c) in Quillet et al. (2013a), with a maximum total accumulation of ca. 430 kg<sub>C</sub> m<sup>-2</sup>). Simulations of remaining masses for different *Sphagnum* species under different conditions also indicate large uncertainties in predicted remaining masses (supporting info S9). This implies that more work is required to estimate parameters accurately enough to detect even relative large differences among peatland models and between model predictions and peat cores.

Summarized, based on existing sensitivity analyses of the HPM the parameter discrepancies suggested by HPM-all and HPM-leaching can translate into non-negligible differences in long-term C accumulation rates. They also imply gaps in previous sensitivity analyses of the HPM, namely that  $W_{opt}$  and possibly  $k_{0,i}$  (for some species) have been analyzed over a too restricted value range and may play a more important role if water table fluctuations are taken into account.

#### 4.4 How can we improve tests of peatland decomposition modules?

We suggest the following steps to estimate peatland decomposition module parameters more accurately and therefore also to improve the accuracy of tests of peatland decomposition modules:

1. High temporal resolution measurements of WTD: For many available litterbag studies, it is not clear whether reported WTD estimates are unbiased estimates of average WTD (i.e., are derived from high-resolution measurements during the incubation) or biased (due to a too small temporal resolution or coverage). This limitation could be reduced by reporting high temporal resolution WTD measurements along litterbag experiments. Such data are also necessary to investigate whether HPM decomposition module parameters are controlled by WTD fluctuations.
2. Eliminate the need of auxiliary models to estimate the degree of saturation: There is a lack of data on the degree of saturation (or porosity and volumetric water content, from which the degree of saturation could be computed) for available litterbag experiments. For this reason, we used the modified Granberg model to estimate the degree of saturation based on reported WTD and an assumed peat porosity. The modified Granberg model, reported WTD, and our assumed peat porosity are error sources for our test. This limitation could be reduced by measurements of peat porosity and high temporal resolution measurements of volumetric water content during litterbag experiments.
3. Implementing a standard for how to assign *Sphagnum* species to model PFT: The HPM does not specify how to assign *Sphagnum* species to PFT (Frolking et al., 2010), which makes it difficult to compare litterbag experiments to parameters for HPM PFT. Ideally, peatland models should provide lists of species they assign to certain PFT to facilitate tests. Moreover, available niche data used here to assign species to PFT may be biased by short term measurements during summer that are not in line with average niches defined in peatland models, similar to how transfer model for testate amoebae are suggested to be biased (Swindles et al., 2015).
4. Decreasing errors in  $k_0$  and  $l_0$  estimates from litterbag experiments: Our analysis suggests that a comparatively large range of  $c_2$ ,  $W_{opt}$ , and  $k_{0,i}$  estimates in the HPM decomposition module are compatible with available litterbag data because errors in remaining masses are large enough to support a range of  $k_0$  and  $l_0$  estimates and because of deficiencies in the design of the litterbag experiments. As a consequence,  $k_0$  estimates of the litterbag decomposition model can be adjusted to fit predictions of the HPM decomposition module for a range of HPM decomposition module parameter values. We also assume that because of these large errors and a large variability of initial leaching losses due to differences in litter handling (Teickner et al., 2024b), we could not detect an expected positive relation of  $l_0$  to the degree of saturation

(Lind et al., 2022). Future litterbag experiments that aim to improve peatland models should reduce errors of  $k_0$  and  $l_0$  estimates (e.g., Teickner et al., 2024b).

- 660 5. Systematic litterbag experiments along the gradient from oxic to anoxic conditions: There are few litterbag experiments available that systematically analyze how decomposition rates differ along the gradient from oxic to anoxic conditions. Problems are that many studies test only few conditions and do not cover depth ranges large enough to estimate the minimum decomposition rate ( $f_{min}$ ) and  $c_2$ . An ideal study would use litter material of the same species and origin (thus making sure  $k_{0,i}$  would be the same for all replicates) and systematically record remaining masses under different degrees
- 665 of saturation in the same peat material to accurately estimate  $W_{opt}$  and  $c_1$ . Another ideal study would systematically record remaining masses at many depth levels, and deeper than 30 cm below the average annual WTD to allow accurate estimation of  $c_2$ . Similar experiments could be used to estimate how WTD fluctuations affect decomposition rates along the gradient from oxic to anoxic conditions and how this would change estimates for  $W_{opt}$  and  $c_2$ .
- 670 6. Understanding the controls of  $k_{0,i}$ : Values of  $k_{0,i}$  can be assumed to be controlled, among other factors, by litter chemistry. Even though there are studies that analyze how litter chemistry controls decomposition rates (e.g., Turetsky et al., 2008), there are few that do this systematically (e.g., Bengtsson et al., 2018) and these do not consider initial leaching losses and thus may confound initial leaching and decomposition, both of which may depend on initial litter chemistry. Studies that systematically change litter chemistry within species would be required to estimate  $k_{0,i}$ . These estimates would also be useful to define PFT for decomposition modules.
- 675 7. Understanding how  $c_2$  and  $W_{opt}$  vary between sites and in dependency of peat characteristics: Too few litterbag experiments with too few replicates are available to estimate  $c_2$  and  $W_{opt}$  separately for individual sites (or how they may vary over time). Systematic litterbag experiments are needed to estimate how environmental conditions control the magnitude of these parameters, for example due to temporal variations in water and oxygen availability or differences in availability of alternative electron acceptors under anoxic conditions.
- 680 Systematic and high-quality litterbag experiments that are designed specifically to test peatland decomposition modules are required to achieve these improvements. To support the design of such experiments, we created an R package (hmpdpredict, supporting information S10) that allows to make predictions with HPM-leaching for hypothetical litterbag experiments and that also allows to change parameter values (Teickner and Knorr, 2024a). This could for example be useful to estimate the sample sizes that are required to detect specific differences in remaining masses, to test to what extent litterbag experiments
- 685 are compatible with HPM-leaching, or to analyze the effect of changing HPM decomposition module parameter values from the standard values or our estimates.

## 5 Conclusions

Based on the litterbag data, the degree of saturation where decomposition is largest ( $W_{opt}$ ) and the anoxia scale length ( $c_2$ , controls how fast decomposition rates decrease below the average annual WTD) are significantly larger than the standard

690 parameter values. Moreover, maximum possible decomposition rates ( $k_{0,i}$ ) for individual species are overall more variable than implied by the standard HPM decomposition module parameter values. According to previous sensitivity analyses, these parameter estimates imply differences in predicted C accumulation rates of up to  $100 \text{ kg}_C \text{ m}^{-2}$  over 5000 years (with a maximum total C accumulation of ca.  $430 \text{ kg}_C \text{ m}^{-2}$ ) when compared to the standard parameter values. The differences in HPM parameter estimates imply larger anaerobic decomposition rates for several species and a less steep gradient of decomposition  
695 rates from oxic to anoxic conditions. This pattern may be caused by water table fluctuations, differences in groundwater flow, or spatial averaging in litterbag experiments; factors that are currently not explicitly considered both in the HPM decomposition module and available litterbag experiments.

Our analysis suggests that the HPM decomposition module with standard parameter values fits available *Sphagnum* litterbag data, but model versions where HPM decomposition module parameters were estimated from available litterbag data have  
700 an equivalent fit. This is caused by two mechanisms: First, remaining masses in litterbag experiments can be explained by initial leaching losses and decomposition. If remaining masses are reported only some time after the initial leaching loss has happened, they can be explained either by small initial leaching losses and a large decomposition rate or by large initial leaching losses and a smaller decomposition rate. Second, the majority of available *Sphagnum* litterbag experiments reports remaining masses only a long time after the initial leaching loss happened. Taken together, this means that available litterbag  
705 data are compatible with a broad range of decomposition rates suggested by HPM decomposition module versions with large differences in parameter values. Improved litterbag experiments are needed for more accurate tests of any peatland decomposition module and for obtaining parameter estimates accurate enough to allow even only approximate predictions of long-term peat accumulation. Applications of the HPM and any other peatland model that relies on litterbag data to parameterize its decomposition process should consider that a broad range of decomposition module parameter values is  
710 compatible with available litterbag experiments.

The modeling approach used here can be combined with different data sources and peatland decomposition modules and therefore may serve as blueprint for future tests and to obtain more accurate parameter estimates once improved litterbag experiments are available. In light of the large differences in long-term peat accumulation suggested by the parameter estimates, we conclude that it is worth to conduct such litterbag experiments, not only to improve the decomposition module of the HPM,  
715 but to improve peatland models in general.

. Data and code to reproduce this manuscript are available from Teickner et al. (2024a). The data used in this study are derived from Teickner and Knorr (2024b). An R package to make predictions for litterbag experiments with model HPM-leaching is available from Teickner and Knorr (2024a).



720 . HT: Conceptualization, methodology, software, validation, formal analysis, investigation, data curation, writing - original draft, visualization, project administration. EP: supervision, funding acquisition, writing - review & editing. KHK: supervision, funding acquisition, writing - review & editing.

. The authors declare no competing interests.

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