ECOSPHERE
AN ESA OPEN ACCESS JOURNAL

# Edge effects on decomposition in *Sphagnum* bogs: Implications for carbon storage

**Emil Nordström**　|　**Rolf Lutz Eckstein**　|　**Lovisa Lind** 🔵

Department of Environmental and Life Sciences, Karlstad University, Karlstad, Sweden

**Correspondence**
Lovisa Lind
Email: lovalind@gmail.com

**Funding information**
Karlstad University

**Handling Editor:** Jean-François Lapierre

## Abstract

Peatlands provide multiple ecosystem services, including extensive carbon sequestration and storage, yet many peatlands have been degraded or destroyed. Peatlands' carbon storage capacity is connected to inherently low decomposition rates, causing the buildup of organic matter. This pattern could be explained by waterlogged conditions that reduce the amount of available oxygen for the decomposer community, a low pH that inhibits bacterial decomposition, or colder temperatures lowering metabolic rates. This study focused on edge effects on decomposition in the transition zone (lagg) between *Sphagnum* bogs and the surrounding forest, with the expectation that decomposition is lowest in the bog and highest in the forest but with a mix of factors causing intermediate decomposition rates near the bog edge. Transitional decomposition rates were measured across six bogs in central Sweden during the summer of 2021, following the Tea Bag Index. Three 20-m transects, each containing seven pairs of tea bags, were buried across the margins of each bog, centered at the edge of the *Sphagnum* moss. Soil moisture content, pH, and plant composition were also recorded at each burial site, and temperature loggers placed evenly among four of the bogs. Our results confirmed our hypothesis regarding edge effects, with soil moisture levels showing a strong negative interaction with decomposition rate. The interaction between pH and decomposition rate was significant, but with an unexpected negative relation, most likely due to low pH in the surrounding forest. Temperature displayed no significance, and plants indicative of low decomposition rates included *Vaccinium oxycoccos*, *Drosera rotundifolia*, and *Sphagnum* species. In contrast to other studies, we did not find an increase in decomposition with increased species richness among the studied bog ecosystems. In conclusion, there is an edge effect on decomposition, and maintaining, or restoring, the hydrology of a peatland is the most important factor for continued carbon storage, with a rough estimation of an area decomposition rate possible to be estimated based on its vegetation.

**KEYWORDS**
carbon sequestration, carbon storage, edge effects, peatlands, Tea Bag Index, waterlogging

# INTRODUCTION

One of the main ecosystems responsible for carbon sequestration, and storage, is peatlands. These are water-logged ecosystems with a base layer of accumulated organic matter, often covered by living *Sphagnum* mosses, which host many unique species (Rydin & Jeglum, 2013). Most of the world's peatlands reside in northern and high altitudes, and despite only covering approximately 3% of Earth's land area, peatlands are estimated to store $415 \pm 150$ Pg C (Hugelius et al., 2020), which is about twice the amount of what is stored in all the world's forests (Parish et al., 2008). The large carbon storage capacity of peatlands is connected to decomposition rates. In peatlands, waterlogged conditions cause the soils to become anoxic, strongly impeding aerobic decomposition. Decomposition rates are also reduced by the low pH in peat (Amesbury et al., 2019), causing many of the common decomposers to struggle. The latter is especially true in *Sphagnum* bogs (a type of ombrotrophic peatland; Rydin & Jeglum, 2013), where peat mosses exchange cations for hydrogen ions, which causes further acidification (Mandal et al., 2018). A low pH inhibits bacterial decomposition (Rousk et al., 2010), which decreases the decomposition rates, and the decomposer community is shifted toward fungi instead of bacteria (Blagodatskaya & Anderson, 1998).

Despite the importance of peatlands for the atmospheric carbon flux, and other ecosystem services such as water flow mediation (Ballard et al., 2012; Prévost et al., 1999), many peatlands are either threatened or already destroyed. Leifeld et al. (2019) estimate that approximately 51.4 million hectares of peatlands were lost globally between the years 1850 and 2015, resulting in around 80 Pg of carbon dioxide equivalents being released into the atmosphere. This has been recognized as a problem, and efforts are being made to start understanding the underlying mechanisms of carbon storage in peatlands and, if possible, restore them (e.g., Renou-Wilson et al., 2019; Zerbe et al., 2013). The previous large-scale destruction of peatlands implies that more knowledge is needed in order to best prioritize efforts regarding peatland protection and restoration. Because of limited resources, it is unlikely that conservation measurements will be taken at every individual peat bog (see Hansson & Dargusch, 2018, for cost estimates).

One factor that might affect the carbon storage capacity of peatlands is the edge effect. Edge effects cause the environment at the edge of a habitat to differ from that in the interior, usually including interactions with the adjacent habitat (Sher & Primack, 2020). This transitional zone between the open peatland and the peat bog catchment is defined as lagg. The lagg transitional zone has often been overlooked in studies, but some have shown that there are differences in the microbial community between the adjacent forest, lagg, and peat bog (Miezcan et al., 2012). An increased nutrient input to the peatland may lead to increased decomposition (Juutinen et al., 2018). This has been tested artificially by adding nutrients in the study by Juutinen et al. (2018), but a similar effect could occur along the bog edges where more nutrient-rich water flows in from the surrounding landscape. The lagg can also buffer the peatland from the influence of nutrient-rich inflow (Howie & Meerveld, 2011). The water level is also of relevance, since the lowest rate of decomposition occurs under constantly waterlogged conditions or well above the water level, that is, hollows or hummocks, respectively (common features of a bog interior) (Belyea, 1996). Those parts of the bog that are influenced by fluctuating moisture levels may have higher decomposition rates (Belyea, 1996). Hence, the latter can be expected to occur more often along the bog margins (Howie & Meerveld, 2011). The edge effect could also apply to the surrounding landscape if a *Sphagnum* bog was to overflow. Plants without adaptations for anoxic soils will struggle under the waterlogged conditions created, the soil decomposer community will be disrupted, and many chemical processes will be affected, such as nitrification and sulfide production by anaerobic bacteria (Blom & Voesenek, 1996). Low nutrient levels in bog water also mean that very little of the horizontal nutrient transfer normally associated with flooding wetlands takes place (Bayley, 1995), which could otherwise have benefited the surrounding vegetation. Over time, extensive flooding can cause the encroachment of bog vegetation on the surrounding terrestrial ecosystem, with *Sphagnum* moss replacing plants succumbing to the waterlogged conditions (Asada et al., 2005), leading to the expansion of the bog. Knowledge of whether there is a significant edge effect across the forest–bog transition in terms of decomposition and how steep this effect is could help to prioritize efforts for bog conservation for carbon retention. Several methods exist for evaluating decomposition rates, including the Tea Bag Index (TBI) by Keuskamp et al. (2013), which has been used in this study. Hence, the decomposition of two different substrates (green and rooibos tea) was used to estimate overall decomposition rates (including both the biological and physical loss of organic matter). For larger scale conservation efforts, easy vegetation-based proxies for decomposition rates would also be very useful. For example, vegetation height, species richness, and aboveground biomass have been shown to be good proxies for peatland C stocks and could be estimated with remote sensing (Lopatin et al., 2019).

We hypothesized *Sphagnum* bogs to experience edge effects, (1) with lowest decomposition rates in the bog interior, due to its high soil moisture and low pH, (2) with

increased decomposition along the transition (lagg) between bog and surrounding forest, due to a lower degree of waterlogging and an influx of water not influenced by the peat, but still (3) with the highest decomposition rate in the forest furthest away from the bog. Additionally, we also studied whether plant community composition correlated with changes in decomposition rates.

## MATERIALS AND METHODS

### Study area

In this study, decomposition rates of six Swedish *Sphagnum* bogs were investigated during the summer of 2021 (June–September), in bogs located approximately 10 km north of Falun in central Sweden (Figure 1). All of
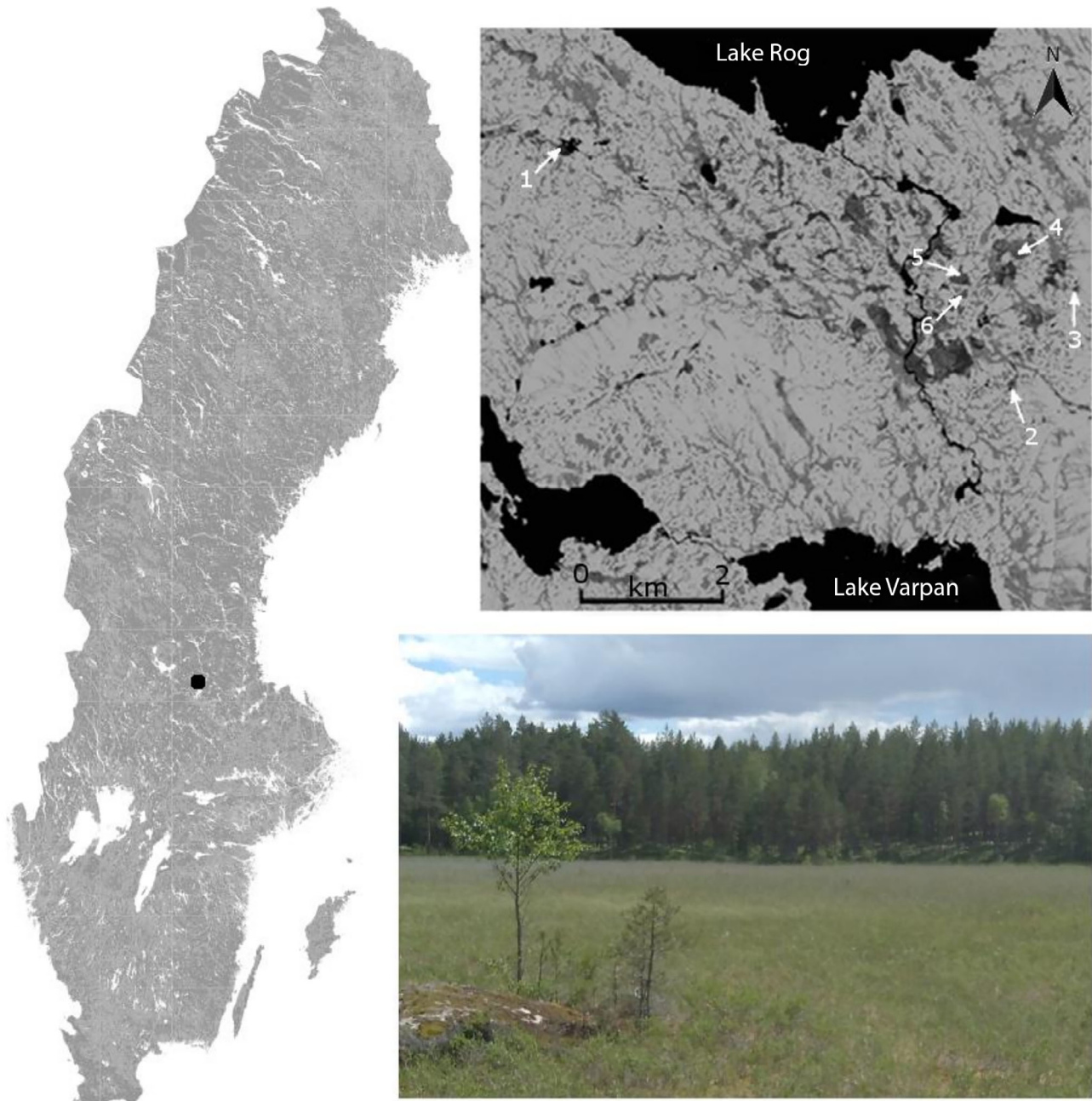


**FIGURE 1** Study site's location in Sweden (left), and the individual bog (1–6) distributions between Lake Rog and Lake Varpan (top right), with an example photograph showing bog 1 at the time of the study (lower right). Maps were based on ©Lantmäteriet's General Map and Geological Survey of Sweden Wetness Map, and photograph by Emil Nordström.

the studied bogs were dominated by *Sphagnum* and *Carex* species and surrounded by Scots pine (*Pinus sylvestris*) forest. The latter without recent clear-cuts or plantation patches, and with an understory was dominated by *Vaccinium spp.* or *Calluna vulgaris*. Our sites thus represent relatively intact peatland edges (laggs). The Swedish forestry agency has set the minimum buffer width along wetlands to 5 m (Andersson et al., 2016). Therefore, twice that distance from the bog edge was included in the study.

## Experimental setup

To quantify the decomposition rate, the TBI developed by Keuskamp et al. (2013) was used, with adaptations made by MacDonald et al. (2018) allowing it to be applied in *Sphagnum* bogs. At each site, three transects were established, with each individual transect having one pair of tea bags (green tea: Sencha exclusive collection EAN 8714100770542; rooibos tea: Rooibos and hibiscus infusion EAN 8722700188438) placed at the border of the *Sphagnum* moss (lagg) and three pairs extending perpendicular to the transition zone in either direction at 2, 5, and 10 m (Figure 2). Tea bags were placed approximately 8 cm below the soil surface, or below the transition to living *Sphagnum* moss when within the bog, following the method of MacDonald et al. (2018). The tea bags were placed at the transition zone between the bog and

surroundings (Table 1), avoiding a direct southerly or northerly aspect to limit the effects of varying sun exposure. The synthetic mesh of the bags, with a gap size of 0.25 mm, excludes macrofauna and allows the tea remaining after a set amount of time to be recovered. The mass loss of tea bags and the difference between the tea types can then be used to calculate the decomposition rate ($k$) and stabilization factor ($S$) (for more information, see http://www.teatime4science.org). The stabilization factor represents the rate at which the environment causes some easily decomposed substances in the tea to be converted into more slowly decomposing ones, making decomposition rates level off early at high $S$ values (Keuskamp et al., 2013). Before placement, tea bags were marked and weighed using an OHAUS Traveler scale (OHAUS Europe GmbH, resolution: 0.01 g), after which they remained buried for 89–90 days. When excavated, tea bags were cleaned of attached soil and roots, followed by drying at below 70°C for at least 48 h, and then reweighed without the label (but with the string still remaining). The weights were adjusted by subtracting the average weight of 10 empty bags of the respective type, with the label intact for the before-incubation weights or without the label for the after-treatment weights. After this, the corrected weights could be used to calculate $S$ and $k$ values using equations presented in Keuskamp et al. (2013).

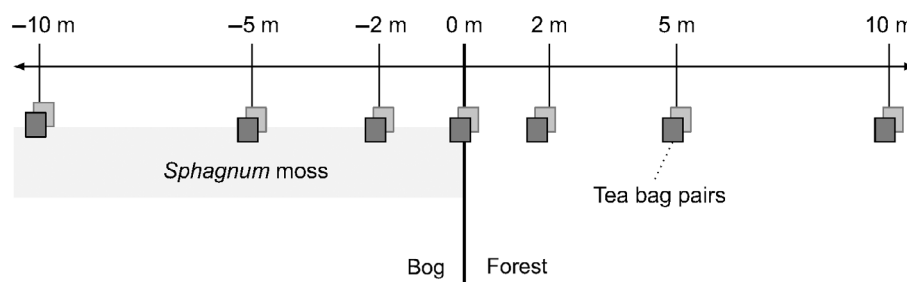To be able to account for temperature differences, HOBO pendant data loggers (model MX2201; Onset



**FIGURE 2**   Placement of tea bag pairs relative to the bog edge where 0 m indicates the edge between bog and forest.

**TABLE 1**   Bogs, their location, aspect of transects, and between which dates tea bags were buried.

| Bog no. | Coordinates[a] | Aspect | Placement date | Recovery date |
|---|---|---|---|---|
| 1 | 60.712563° 15.519263° | Northwest | 15 June | 13 September |
| 2 | 60.681934° 15.636574° | East | 16 June | 13 September |
| 3 | 60.693432° 15.652276° | Southwest | 17 June | 15 September |
| 4 | 60.697589° 15.637415° | Southeast | 18 June | 15 September |
| 5 | 60.695968° 15.623207° | Northeast | 19 June | 17 September |
| 6 | 60.693844° 15.624265° | Northeast | 20 June | 17 September |

[a]World Geodetic System 1984, north and east.

Computer Corporation, Bourne, MA) were buried next to tea bags at positions −10, 0, and 10 m along one of the transects for bogs 1–4; these loggers then recorded the temperature every 30 min during the circa 90-day incubation period. Soil moisture content, pH, and vegetation coverage were also measured at the site of each tea bag pair. The moisture measurements were taken with an HH2 Moisture Meter (Delta-T Devices, Cambridge, UK) at the placement of tea bags, at all positions every second week, and when recovering tea bags. The pH was measured using a Hach multimeter (model HQ40D; Hach, Loveland, CO) on 5 g of field wet soil, or peat, collected next to each tea bag pair, to which 10 ml of deionized water was added and mixed in thoroughly, then allowed to settle for 1 h, following the method of MacDonald et al. (2018). Surveys of the vegetation cover were conducted between 30 June and 2 July (2 weeks after burying tea bags), in 0.25-m$^2$ quadrats centered around each pair of placed tea bags. The cover of vascular plants and *Sphagnum* moss, but excluding tree canopy cover, was then evaluated to the nearest 10% of area coverage.

## Statistical methods

For the analysis, the individual values of the three transects at each bog were averaged. We tested the effect of position along the transect on $S$ and $k$ and accounted for variation among the individual bogs using linear mixed-effect (LME) models with bog as the random factor. Soil moisture and pH were excluded from the model as they were highly correlated with position (Table 2). We separately checked for correlations between $S$ and $k$, and soil moisture, pH values, and position, using linear regression analyses. We calculated accumulated growing degree-days (GDDs) for the whole sampling period and tested whether $S$ and $k$ were influenced by GDD using an ANOVA. GDDs was calculated by taking the daily maximum and minimum temperatures compared with a temperature base of 5°C. An ANOVA was also used for the analysis of species richness and decomposition at different positions. We did a

**TABLE 2** Correlation matrix of different variables.

| Variable | Position | $S$ | $k$ | pH | Moisture |
|---|---|---|---|---|---|
| Position | 1.00 | | | | |
| $S$ | 0.652 | 1.00 | | | |
| $k$ | 0.531 | 0.609 | 1.00 | | |
| pH | −0.682 | −0.746 | −0.407 | 1.000 | |
| Moisture | −0.865 | −0.804 | −0.596 | 0.865 | 1.000 |

Abbreviations: $k$, decomposition rate; $S$, stabilization factor.

nonmetric multidimensional scaling ordination for two dimensions with the vegetation data (transect means). To this end, species with <3 occurrences were removed, and absolute abundance transformed to relative abundance. After the ordination, we calculated correlations of environmental variables ($k$, $S$, position, pH, and soil moisture) with ordination axes, using a bootstrap approach with $n = 999$ randomizations. In a second step, we tested for effects of position on species composition through a perMANOVA, using the "adonis" function in the R package "vegan" (Oksanen et al., 2020); the assumptions of multivariate variance homogeneity were tested using the "betadisper" function ($F_{6,35} = 1.31$, $p = 0.28$). All analyses were made in RStudio (version 2021.9.0.351; RStudio Team, Boston, MA).

## RESULTS

Of 252 placed tea bags, 244 were recovered intact, with the calculations for the stabilization factor ($S$) and decompositions rate ($k$) based on 122 and 121 values, respectively. There were some fluctuations in temperature between positions and locations, with the −10 position in bog 1 having an average temperature over one degree warmer (at 16.04°C) than the second warmest location (bog 2 at position −10 with an average of 14.92°C), and almost three degrees warmer than the coolest location (13.31°C at bog 2, position 0). However, the temperature differences, measured as accumulated GDDs, did not affect $S$ ($F_{1,10} = 0.127$, $p = 0.729$) or $k$ ($F_{1,10} = 0.02$, $p = 0.89$). *Sphagnum* spp. and *Carex* spp. were the dominant species of all studied bogs, with the *Sphagnum* cover coming to an abrupt end at the edge of the bog. For a complete plant species list, see Appendix S1.

Both $S$ and $k$ were affected by their position relative to the bog edge (LME: $t_{35} = 5.44$, $p < 0.001$, $t_{35} = 4.27$, $p < 0.001$). The overall trend was for $S$ and $k$ to increase, starting from the interior of the bog onto drier land ($S$: $R^2 = 0.411$, $F_{1,40} = 29.55$, $p < 0.001$; $k$: $R^2 = 0.263$, $F_{1,40} = 15.66$, $p < 0.001$; Figure 3a,b) but with some fluctuation in $k$. Conversely, for soil moisture, $S$ and $k$ values decreased significantly as the soil became increasingly waterlogged ($S$: $R^2 = 0.638$, $F_{1,40} = 73.17$, $p < 0.001$; $k$: $R^2 = 0.340$, $F_{1,40} = 22.08$, $p < 0.001$), with $S$ showing a closer relationship than $k$ (Figure 4a,b). Regarding pH, $S$ displayed a steady decrease as the pH value increased from 3.51 to 5.88 (Figure 4c: $R^2 = 0.546$, $F_{1,40} = 50.24$, $p < 0.001$). The $k$ value did also show a decrease with increasing pH ($R^2 = 0.144$, $F_{1,40} = 7.917$, $p < 0.008$) but with some considerable fluctuation (Figure 4d). We also found that species richness decreased toward the forest ($F_{3,38} = 13.22$, $p = 0.012$), as well as $k$ ($F_{3,38} = 13.22$, $p = 0.011$), but there was no difference in $S$ depending on species richness ($p > 0.1$) (Figure 5).
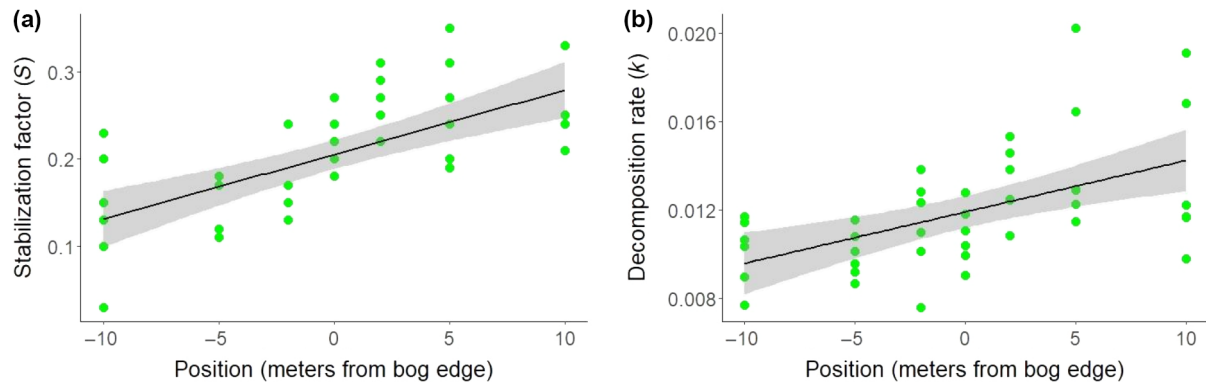
**FIGURE 3** Interaction between where tea bags were placed relative to the edge of the bog, with the −10 position furthest out into the bog, and their resulting (a) $S$ (stabilization factor) and (b) $k$ (decomposition rate) values. The shaded area represents 95% CI of the line fit.
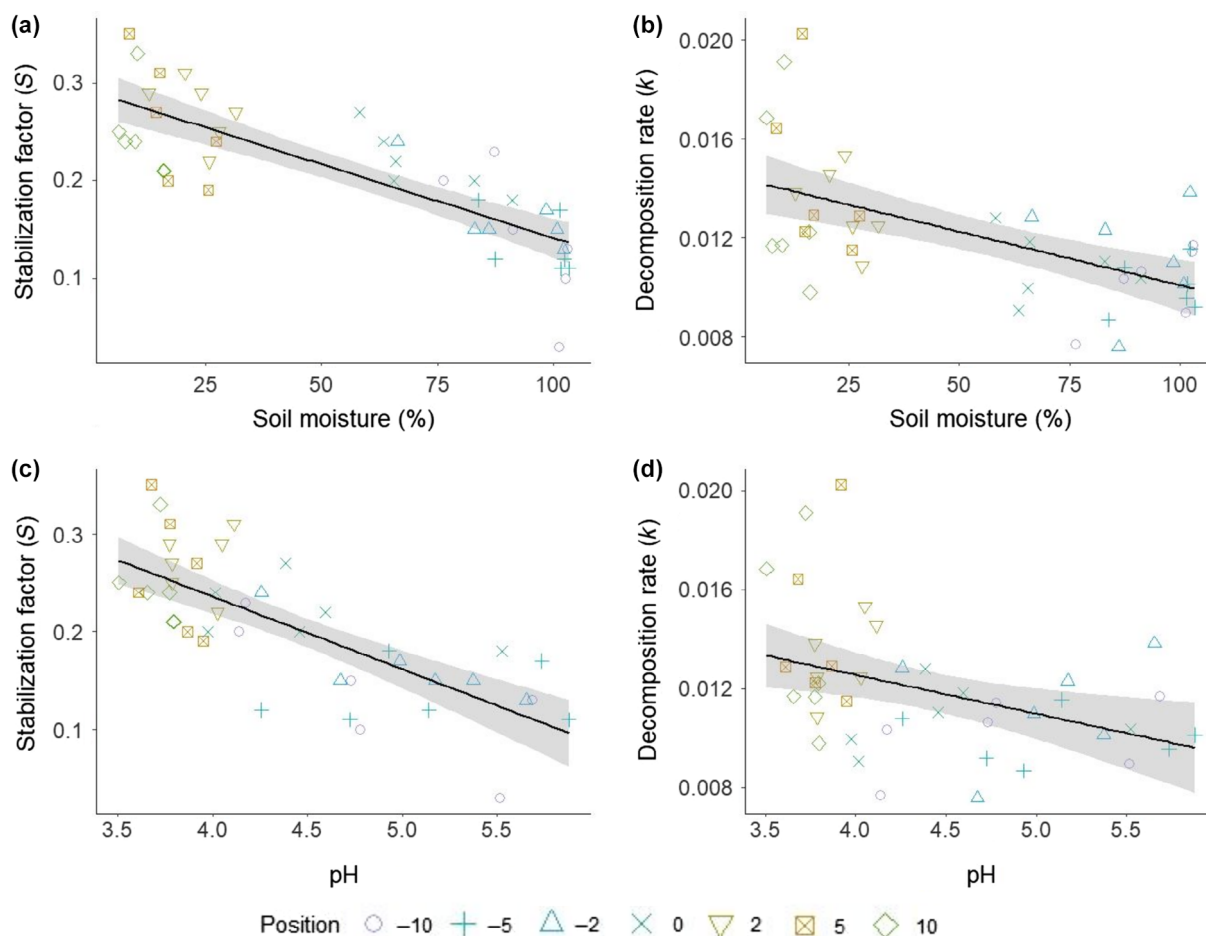


**FIGURE 4** (a) Decline in $S$ (stabilization factor) with increasingly waterlogged conditions, (b) the decline in $k$ (decomposition rate) with increasingly waterlogged conditions, (c) the decline in $S$ with rising pH values, and (d) the decline in $k$ with rising pH values. The shaded area represents 95% CI of the line fit.

Plots were primarily arranged along the first ordination axis according to their position in relation to the bog margin, with some overlap among sites toward the bog interior and among sites outside the bog (Figure 6a). All environmental variables were significantly (bootstrapping approach with $n = 999$ randomizations, $p = 0.001$) correlated with the first ordination axis. Typical bog species such as *Sphagnum* spp., *Andromeda polifolia*, *Drosera*
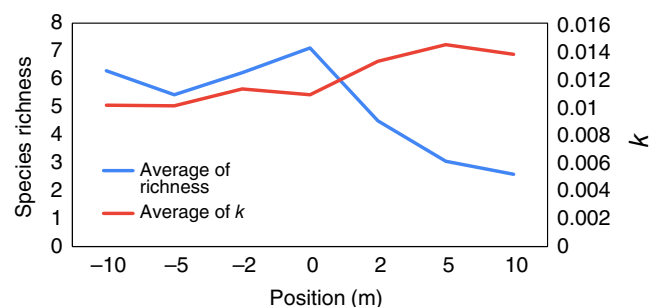
**FIGURE 5** Species richness (blue line) and $k$ (decomposition rate) (red line) in relation to the distance (position in meters) from the bog edge (lagg).

*rotundifolia*, *Vaccinium oxycoccus*, and *Carex* species were associated with positions −10, −5, and −2, whereas ericaceous dwarf shrubs such as *Empetrum nigrum*, *Vaccinium vitis-idaea*, and *Vaccinium myrtillus* were associated with positions +2, +5, and +10 (Figure 6b). Accordingly, species composition differed significantly among positions (perMANOVA: $F_{1,40} = 71.7$, $p = 0.001$).

## DISCUSSION

The results show a linear increase in both $S$ and $k$ along the transition from bog to the surrounding forest. Both
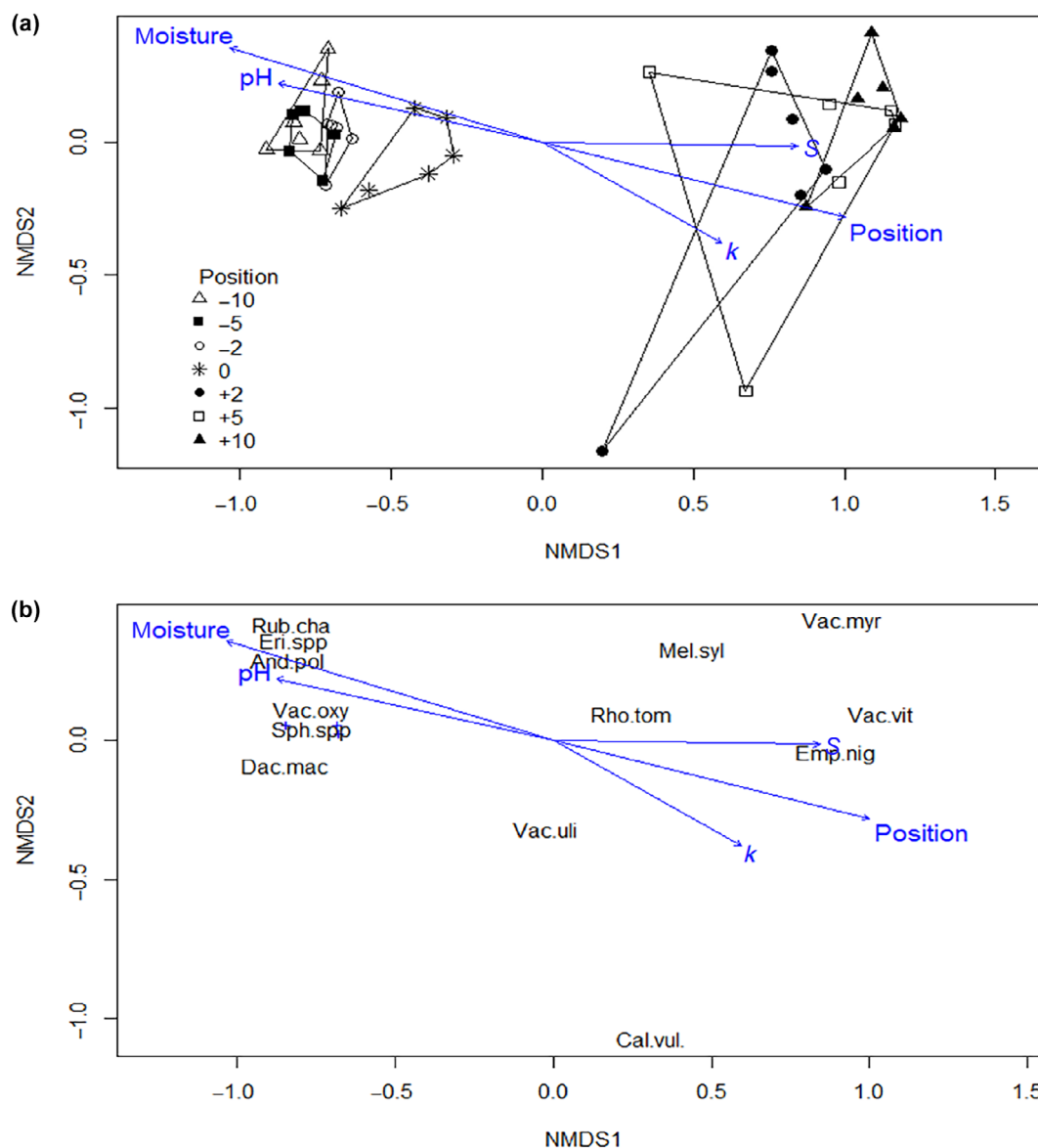


**FIGURE 6** Nonmetric multidimensional scaling (NMDS) plots (a) of each site in relation to soil moisture, pH, $S$ (stabilization factor), $k$ (decomposition rate), and distance from the bog edge (position), and (b) showing the different species. Due to overlap, blue + indicates the position of *Carex* spp., *Drosera rotundifolia*, and *Equisetum* spp. Abbreviations are: And.pol, *Andromeda polifolia*; Cal.vul, *Calluna vulgaris*; Dac.mac, *Dactylorhiza maculata*; Emp.nig, *Empetrum nigrum*; Eri.spp, *Ericaceae*; Rho.tom, *Rhododendron tomentosum*; Rub.cha, *Rubus chamaemorus*; Sph.spp, *Sphagnum* spp.; Vac.myr, *Vaccinium myrtillus*; Vac.oxy, *Vaccinium oxycoccos*; Vac.uli, *Vaccinium uliginosum*; Vac.vit, *Vaccinium vitis-idaea*.

$S$ and $k$ values within the bog and in the surrounding forest corresponded to values for temperate peatlands and forests presented by Keuskamp et al. (2013) but with intermediate values closest to the bog edge. The pattern of decomposition across the gradient was roughly followed by the vegetation, with a few plant species associated with both maximum and minimum decomposition rates.

Regarding the different abiotic factors, soil moisture had the largest impact on both $S$ and $k$. For the stabilization factor, soil moisture has previously been demonstrated as the most important factor, with one study showing a decrease in stabilization rates from 70% to 3% as the soil moisture rose from 15% to 150% (Larionova et al., 2017). This, combined with some leaching of recalcitrant but water-soluble compounds, could explain the pattern for $S$. The pattern for decomposition rate ($k$) is also realistic, since waterlogging causes the peat to become anoxic (Amesbury et al., 2019) and reduces decomposition. This pattern has been previously demonstrated, showing that rewetted peatlands become carbon sinks even during relatively dry years, contrary to drained sites, which were acting as carbon sources during droughts (Beyer et al., 2021; Reiche et al., 2009; Schwieger et al., 2021). That intermediate moisture values produced intermediate decomposition rates could be connected to the porous and water-absorbent structure of the *Sphagnum* moss (Turunen et al., 2019), which becomes partially water-filled long before the peat becomes truly waterlogged. This reduces the gas exchange to the lower soil layers, and in a study by Molchanov (2015), carbon dioxide output from a bog increased when the water level dropped from 7 to 21 cm below the soil surface, which suggests improved oxygen availability for decomposers. There could also be some degree of measurement errors; since the soil moisture could not be measured within tea bags without damaging them, the ground-up tea in their bags might turn anoxic slightly earlier than the more porous *Sphagnum* moss (Turunen et al., 2019).

A lower pH is generally believed to reduce decomposition rates (Amesbury et al., 2019; Rousk et al., 2010), not increase them as we found in this study. The reason for the perceived effect of pH on decomposition is, however, probably due to the overshadowing effect of the soil moisture, with the higher pH found in wetter portions due to the strongly acidic nature of the surrounding pine forest (Bååth et al., 1980). The unexpected trend between decomposition and pH could also be further mediated by mechanisms behind low pH values. Hence, in *Sphagnum* bogs, the pH is reduced due to the uptake of nutrients, while in a coniferous forest, acidification is caused by the leaching of acids from decomposing vegetation (Lundström et al., 2000).

Some of these acids can then be further metabolized by soil microbes (Lundström et al., 2000), providing nutrients to the forest decomposer community. A study by Bååth et al. (1980) also found that liming of a Scots pine forest, despite raising the pH considerably, had little effect on decomposition rates, indicating that the decomposer community is well suited to functioning in acidic soils. Any future studies might want to take this latest consideration into account by measuring soil nitrogen and phosphorus levels to estimate how much nutrients are available to sustain the decomposer community.

That temperature did not appear to affect decomposition rates also contradicts earlier studies. Lafleur et al. (2005) considered temperature more important than water level, and suggested that the generally cooler temperatures found in bogs, compared with the surrounding landscape, was one reason for low decomposition rates. On the contrary, in this study, the highest temperatures were found in bogs, while the decomposition was higher in the surrounding forest. The cause behind warm bogs is likely due to decreased canopy cover from trees, while the greater soil moisture might have buffered against heat loss toward the end of summer (McLaughlin & Cohen, 2013). Overall, the temperature effect, similar to pH, was likely overshadowed by the soil moisture effect on decomposition in this study.

As for using vegetation as decomposition indicators, two groups of plants correlated relatively well with decomposition rates. Those with a positive relationship to decomposition, *V. vitis-idaea*, *E. nigrum*, and *V. myrtillus*, are all dwarf shrubs with a preference for drier soils (Mossberg et al., 2003), especially *V. vitis-idaea*. These species most likely mirrored the gradient in soil moisture, although the strong correlation between decomposition and *E. nigrum* was unexpected considering the plant's allelopathic properties might have affected the decomposer community negatively (Plathe, 2021). Plants with a negative correlation to decomposition, the *Sphagnum* mosses, *Vaccinium oxycoccos*, *Carex* species, *D. rotundifolia*, *Rubus chamaemorus*, and *A. polifolia*, were all plants associated with the bog itself, with the *Sphagnum* mosses responsible for some of the factors causing the bog to have a low decomposition rate in the first place (Mandal et al., 2018), and the other plants connected to low decomposition rates either associated with *Sphagnum* bogs or at least growing on waterlogged soils (Mossberg et al., 2003). Previous studies in terrestrial habitats have shown that a higher plant diversity leads to an increased decomposition (Ebeling et al., 2014; Tresch et al., 2019). We did, however, find contrasting results when testing the relationships between plant richness and decomposition in our bog systems, suggesting that the hydrological factor is the dominant one in peatlands.

The ability to use vegetation as a proxy for decomposition has implications for future conservation work, as species composition can highlight areas especially important from a carbon storage perspective. The strong correlation between *Sphagnum* moss and low decomposition rates means that the distribution of peat-forming *Sphagnum* species provides a clear and relatively easy-to-identify delineation for some peatlands, something that is lacking in the current guidelines from the study area (Swedish forestry agency guidelines; Andersson et al., 2016), thereby highlighting areas that are unsuitable for forestry and traffic by heavy machinery. If damage to a *Sphagnum* bog is unavoidable, preservation of areas with, for example, *V. oxycoccos* and *A. polifolia* should be prioritized over those with *Rhododendron tomentosum* or *V. uliginosum*. The effects of the *Sphagnum* moss itself on decomposition could also merit further studies to see at which size a patch of *Sphagnum* is starting to affect decomposition rates. This study since all the bogs studied here, despite differing in size, produced a rather coherent pattern, and earlier studies showed that *Sphagnum* litter inhibits decomposition even in small quantities (Hájek et al., 2011; Verhoeven & Toth, 1995).

For restoration purposes, rewetting and reestablishment of *Sphagnum* appear to be most important. Couwenberg et al. (2011) suggest raising the water level close to the soil surface and that the flora should consist of low-growing species, in order to optimize carbon sequestration. Combining rewetting with the introduction of *Sphagnum* moss, both for its decomposition reduction properties (Verhoeven & Toth, 1995) and its water retention ability (Turunen et al., 2019), could improve the results of the restoration. However, we have been working in relatively undisturbed laggs, whereas bog degradation through drainage may affect both hydrology and peat chemistry (Krüger et al., 2015; Szajdak et al., 2020). Therefore, more process-based studies in intact and degraded systems are needed to evaluate how generalizable these findings are.

To conclude, soil moisture appears to be the most important factor determining decomposition rates at the edge of *Sphagnum* bogs and overshadows the expected effects of pH and temperature. This means that despite the relatively low number of studied bogs, the strength of the effect posed by soil moisture on the decomposition pattern will likely remain when looking at similar sites. The presence of *Sphagnum* moss itself also indicates low decomposition rates, especially when accompanied by *V. oxycoccos*, *Carex* species, and *D. rotundifolia*. All of this suggests that even small bogs can have low decomposition rates as long as one maintains, or restores, a high ground water level. This is then preferably combined with having a natural *Sphagnum* bog flora, to both improve carbon sequestration further and provide other ecosystem services associated with *Sphagnum* bogs.

## CONFLICT OF INTEREST
The authors declare no conflict of interest.

## DATA AVAILABILITY STATEMENT
Data (Nordström et al., 2022) are available from Zenodo: https://doi.org/10.5281/zenodo.66198784.

## ORCID
*Lovisa Lind* https://orcid.org/0000-0002-7212-8121

## REFERENCES
Amesbury, M. J., A. Gallego-Sala, and J. Loisel. 2019. "Peatlands as Prolific Carbon Sinks." *Nature Geoscience* 12(11): 880–1. https://doi.org/10.1038/s41561-019-0455-y.

Andersson, E., Andersson, M., Blomquist, S., Forsberg, O., and Lundh, G. (2016). "Nya och reviderade målbilder för god miljöhänsyn (No. 12)." Skogsstyrelsen. Retrieved from https://www.skogsstyrelsen.se/malbilder.

Asada, T., B. G. Warner, and S. L. Schiff. 2005. "Effects of Shallow Flooding on Vegetation and Carbon Pools in Boreal Peatlands." *Applied Vegetation Science* 8(2): 199–208. https://doi.org/10.1111/j.1654-109X.2005.tb00646.x.

Bååth, E., B. Berg, U. Lohm, B. Lundgren, H. Lundkvist, T. Rosswall, B. Söderström, and A. Wiren. 1980. "Effects of Experimental Acidification and Liming on Soil Organisms and Decomposition in a Scots Pine Forest." *Pedobiologia* 20(2): 85–100.

Ballard, C. E., N. McIntyre, and H. S. Wheater. 2012. "Effects of Peatland Drainage Management on Peak Flows." *Hydrology and Earth System Sciences* 16(7): 2299–310. https://doi.org/10.5194/hess-16-2299-2012.

Bayley, P. B. 1995. "Understanding Large River: Floodplain Ecosystems." *Bioscience* 45(3): 153–8. https://doi.org/10.2307/1312554.

Belyea, L. R. 1996. "Separating the Effects of Litter Quality and Microenvironment on Decomposition Rates in a Patterned Peatland." *Oikos* 77(3): 529–39. https://doi.org/10.2307/3545942.

Beyer, F., F. Jansen, G. Jurasinski, M. Koch, B. Schröder, and F. Koebsch. 2021. "Drought Years in Peatland Rewetting: Rapid Vegetation Succession Can Maintain the Net $CO_2$ Sink Function." *Biogeosciences* 18(3): 917–35. https://doi.org/10.5194/bg-18-917-2021.

Blagodatskaya, E. V., and T.-H. Anderson. 1998. "Interactive Effects of pH and Substrate Quality on the Fungal-to-Bacterial Ratio and $qCO_2$ of Microbial Communities in Forest Soils." *Soil Biology and Biochemistry* 30(10–11): 1269–74. https://doi.org/10.1016/S0038-0717(98)00050-9.

Blom, C. W. P. M., and L. A. C. J. Voesenek. 1996. "Flooding: The Survival Strategies of Plants." *Trends in Ecology & Evolution* 11(7): 290–5. https://doi.org/10.1016/0169-5347(96)10034-3.

Couwenberg, J., A. Thiele, F. Tanneberger, J. Augustin, S. Bärisch, D. Dubovik, N. Liashchynskaya, et al. 2011. "Assessing Greenhouse Gas Emissions from Peatlands Using Vegetation as a Proxy." *Hydrobiologia* 674(1): 67–89. https://doi.org/10.1007/s10750-011-0729-x.

Ebeling, A., S. T. Meyer, M. Abbas, N. Eisenhauer, H. Hillebrand, M. Lange, C. Scherber, A. Vogel, A. Weigelt, and W. W. Weisser. 2014. "Plant Diversity Impacts Decomposition and Herbivory Via Changes in Aboveground Arthropods." *PLoS One* 9(9): e106529. https://doi.org/10.1371/journal.pone.0106529.

Hájek, T., S. Ballance, J. Limpens, M. Zijlstra, and J. T. A. Verhoeven. 2011. "Cell-Wall Polysaccharides Play an Important Role in Decay Resistance of Sphagnum and Actively Depressed Decomposition In Vitro." *Biogeochemistry* 103(1–3): 45–57. https://doi.org/10.1007/s10533-010-9444-3.

Hansson, A., and P. Dargusch. 2018. "An Estimate of the Financial Cost of Peatland Restoration in Indonesia." *Case Studies in the Environment* 2(1): 1–8. https://doi.org/10.1525/cse.2017.000695.

Howie, S. A., and I. T. Meerveld. 2011. "The Essential Role of the Lagg in Raised Bog Function and Restoration: A Review." *Wetlands* 31(3): 613–22. https://doi.org/10.1007/s13157-011-0168-5.

Hugelius, J. L., J. Loisel, S. Chadburn, R. B. Jackson, M. Jones, G. MacDonald, M. Marushchak, et al. 2020. "Large Stocks of Peatland Carbon and Nitrogen Are Vulnerable to Permafrost Thaw." *PNAS* 117(34): 20438–46.

Juutinen, S., T. R. Moore, J. L. Bubier, S. Arnkil, E. Humphreys, B. Marincak, C. Roy, and T. Larmola. 2018. "Long-Term Nutrient Addition Increased CH4 Emission from a Bog through Direct and Indirect Effects." *Scientific Reports* 8(1): 3838. https://doi.org/10.1038/s41598-018-22210-2.

Keuskamp, J. A., B. J. J. Dingemans, T. Lehtinen, J. M. Sarneel, and M. M. Hefting. 2013. "Tea Bag Index: A Novel Approach to Collect Uniform Decomposition Data across Ecosystems." *Methods in Ecology and Evolution* 4(11): 1070–5. https://doi.org/10.1111/2041-210X.12097.

Krüger, J. P., J. Leifeld, S. Glatzel, S. Szidat, and C. Alewell. 2015. "Biogeochemical Indicators of Peatland Degradation – A Case Study of a Temperate Bog in Northern Germany." *Biogeosciences* 12: 2861–71.

Lafleur, P. M., T. R. Moore, N. T. Roulet, and S. Frolking. 2005. "Ecosystem Respiration in a Cool Temperate Bog Depends on Peat Temperature but Not Water Table." *Ecosystems* 8(6): 619–29. https://doi.org/10.1007/s10021-003-0131-2.

Larionova, A. A., A. N. Maltseva, V. O. Lopes de Gerenyu, A. K. Kvitkina, S. S. Bykhovets, B. N. Zolotareva, and V. N. Kudeyarov. 2017. "Effect of Temperature and Moisture on the Mineralization and Humification of Leaf Litter in a Model Incubation Experiment." *Eurasian Soil Science* 50(4): 422–31. https://doi.org/10.1134/S1064229317020089.

Leifeld, J., C. Wüst-Galley, and S. Page. 2019. "Intact and Managed Peatland Soils as a Source and Sink of GHGs from 1850 to 2100." *Nature Climate Change* 9(12): 945–7. https://doi.org/10.1038/s41558-019-0615-5.

Lopatin, J., T. Kattenborn, M. Galleguillos, J. F. Perez-Quezada, and S. Schmidtlein. 2019. "Using Aboveground Vegetation Attributes as Proxies for Mapping Peatland Belowground Carbon Stocks." *Remote Sensing of Environment* 231: 111217. https://doi.org/10.1016/j.rse.2019.111217.

Lundström, U. S., N. van Breemen, and D. Bain. 2000. "The Podzolization Process. A Review." *Geoderma* 94(2–4): 91–107. https://doi.org/10.1016/S0016-7061(99)00036-1.

MacDonald, E., M. Brummell, A. Bieniada, J. Elliott, A. Engering, T.-L. Gauthier, S. Belwase, S. Touchette, L. Turmel-Courchesne, and M. Strack. 2018. "Using the Tea Bag Index to Characterize Decomposition Rates in Restored Peatlands." *Boreal Environment Research* 23: 221–35.

Mandal, S., D. Raghunandan, and V. Suneetha. 2018. "Effectiveness of *Sphagnum* Peat Moss in Purification of Water." *Research Journal of Pharmacy and Technology* 11(9): 3909–12. https://doi.org/10.5958/0974-360X.2018.00717.5.

McLaughlin, D. L., and M. J. Cohen. 2013. "Realizing Ecosystem Services: Wetland Hydrologic Function along a Gradient of Ecosystem Condition." *Ecological Applications* 23(7): 1619–31. https://doi.org/10.1890/12-1489.1.

Miezcan, T., M. Tarkowska-Kukuryk, and I. Bielańska-Grajner. 2012. "Hydrochemical and Microbiological Distinction and Function of Ombrotrophic Peatland Lagg as Ecotone between *Sphagnum* Peatland and Forest Catchment (Poleski National Park, Eastern Poland)." *Annales de Limnologie—International Journal of Limnology* 48: 323–36.

Molchanov, A. G. 2015. "Gas Exchange in Sphagnum Mosses at Different near-Surface Groundwater Levels." *Russian Journal of Ecology* 46(3): 230–5. https://doi.org/10.1134/S1067413615030066.

Mossberg, B., L. Stenberg, and T. Karlsson. 2003. *Den Nya Nordiska Floran (2. Totally Rev. Ed.)*. Stockholm, Sweden: Wahlström & Widstrand.

Nordström, E., L. Lind, and R. L. Eckstein. 2022. "Edge Effects on Decomposition in Sphagnum Bogs." Data set. Zenodo. https://doi.org/10.5281/zenodo.6619878.

Oksanen, J., Blanchet, F. G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P., et al. 2020. "Vegan Community Ecology Package Version 2.5-7." https://github.com/vegandevs/vegan.

Parish, F., Sirin, A., Charman, D., Joosten, H., Minayeva, T., Silvius, M. and Stringer, L. (Eds.) (2008). "Assessment on Peatlands, Biodiversity and Climate Change: Main Report." Global Environment Centre, Kuala Lumpur and Wetlands International, Wageningen.

Plathe, E. K. (2021). "Vegetation-Environment Analysis of Areas with Peat Accumulation and Hummock Formation in the Context of NiN (Natur i Norge)." A study from Laggu, Gamvik municipality, Troms and Finnmark county (Master's thesis). UiT Norges arktiske universitet.

Prévost, M., A. P. Plamondon, and P. Belleau. 1999. "Effects of Drainage of a Forested Peatland on Water Quality and Quantity." *Journal of Hydrology* 214(1–4): 130–43. https://doi.org/10.1016/S0022-1694(98)00281-9.

Reiche, M., A. Hädrich, G. Lischeid, and K. Küsel. 2009. "Impact of Manipulated Drought and Heavy Rainfall Events on Peat

Mineralization Processes and Source-Sink Functions of an Acidic Fen." *Journal of Geophysical Research Biogeosciences* 114: G02021. https://doi.org/10.1029/2008JG000853.

Renou-Wilson, F., G. Moser, D. Fallon, C. A. Farrell, C. Müller, and D. Wilson. 2019. "Rewetting Degraded Peatlands for Climate and Biodiversity Benefits: Results from Two Raised Bogs." *Ecological Engineering* 127: 547–60. https://doi.org/10.1016/j.ecoleng.2018.02.014.

Rousk, J., P. C. Brookes, and E. Bååth. 2010. "Investigating the Mechanisms for the Opposing pH Relationships of Fungal and Bacterial Growth in Soil." *Soil Biology and Biochemistry* 42(6): 926–34. https://doi.org/10.1016/j.soilbio.2010.02.009.

Rydin, H., and J. K. Jeglum. 2013. *The Biology of Peatlands*, 2nd ed, pp. 397. Oxford, UK: Oxford University Press.

Schwieger, S., J. Kreyling, J. Couwenberg, M. Smiljanić, R. Weigel, M. Wilmking, and G. Blume-Werry. 2021. "Wetter is Better: Rewetting of Minerotrophic Peatlands Increases Plant Production and Moves Them Towards Carbon Sinks in a Dry Year." *Ecosystems* 24(5): 1093–109. https://doi.org/10.1007/s10021-020-00570-z.

Sher, A., and R. B. Primack. 2020. *An Introduction to Conservation Biology*, 2nd ed. Oxford, UK: Oxford University Press.

Szajdak, L. W., A. Jezierski, K. Wegner, T. Meysner, and M. Szczepański. 2020. "Influence of Drainage on Peat Organic Matter: Implications for Development, Stability, and Transformation." *Molecules* 25: 2587.

Tresch, S., D. Frey, R.-C. Le Bayon, A. Zanetta, F. Rasche, A. Fliessbach, and M. Moretti. 2019. "Litter Decomposition Driven by Soil Fauna, Plant Diversity and Soil Management in Urban Gardens." *Science of the Total Environment* 658: 1614–29. https://doi.org/10.1016/j.scitotenv.2018.12.235.

Turunen, M., J. Hyväluoma, J. Heikkinen, R. Keskinen, J. Kaseva, J. Koestel, and K. Rasa. 2019. "Quantifying Physical Properties of Three *Sphagnum*-Based Growing Media as Affected by Drying–Wetting Cycles." *Vadose Zone Journal* 18(1): 190033. https://doi.org/10.2136/vzj2019.04.0033.

Verhoeven, J. T. A., and E. Toth. 1995. "Decomposition of Carex and Sphagnum Litter in Fens: Effect of Litter Quality and Inhibition by Living Tissue Homogenates." *Soil Biology and Biochemistry* 27(3): 271–5. https://doi.org/10.1016/0038-0717(94)00183-2.

Zerbe, S., P. Steffenhagen, K. Parakenings, T. Timmermann, A. Frick, J. Gelbrecht, and D. Zak. 2013. "Ecosystem Service Restoration after 10 Years of Rewetting Peatlands in NE Germany." *Environmental Management* 51(6): 1194–209. https://doi.org/10.1007/s00267-013-0048-2.

## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.