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LETTER

Satellite data archives reveal positive effects of peatland restoration: albedo and temperature begin to resemble those of intact peatlands

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Supplementary data for this article is available online

Abstract

Peatlands store significant amounts of carbon, which is released as greenhouse gases when peatlands are degraded. Restoration and rewetting can help prevent these emissions, while continuous monitoring is critical for evaluating their success. Using satellite-derived observations of essential climate variables, we conducted the first large-scale assessment of how peatland restoration influences land surface temperature (LST), albedo, and vegetation across 72 sites in North America and Europe. Our findings indicated that before restoration, degraded peatlands had a commonly lower daytime LST and albedo but higher nighttime LST, leaf area index (LAI), and fraction of absorbed photosynthetically active radiation (FPAR) compared to intact sites. The largest restoration-induced absolute values of monthly changes reached +3.18 °C (daytime LST), −1.22 °C (nighttime LST), −2.54 (LAI), −0.29 (FPAR), and −0.16 (albedo). While restored peatlands tended to align more closely with intact sites a decade after restoration began, the probability of this alignment varied depending on the climate variables. Restored peatlands became more similar than different to intact sites in nighttime LST and albedo after a post-restoration decade, with high similarity projected within five decades. Peatland restoration modifies local and regional climate and should be included in future climate projections.

1. Introduction

Restoration of ecosystems is increasingly seen as a vital requirement for humanity's well-being today and in future generations (Montanarella *et al* 2018, Pörtner *et al* 2023). Thus, the United Nations Decade on Ecosystem Restoration 2021–2030 aims to achieve the highest level of recovery possible for degraded ecosystems globally (FAO 2023). The EU has adopted the first countrywide Nature Restoration Law targeted at restoring degraded ecosystems (The European Parliament and The Council

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of the European Union 2024). Restoration implies 'preventing, halting, and reversing the degradation of ecosystems worldwide to regain their ecological functionality and to improve the productivity and capacity of ecosystems to meet the needs of society' (IUCN 2021). The restoration of carbon-rich ecosystems, such as peatlands, inter alia, leads to regaining their functions of carbon (C) storage (Humpenöder *et al* 2020, Taillardat *et al* 2020, Loisel and Gallego-Sala 2022, Mander *et al* 2023), which makes their restoration a cost-efficient method for climate change mitigation (Humpenöder *et al* 2020).

Peatlands store significant amounts of C globally (Pan *et al* 2011, Nichols and Peteet 2019) by accumulating more organic matter than they decompose (Page and Baird 2016). However, they have some of the highest irrecoverable C densities, meaning that once lost, C cannot be recovered in time to avoid significant climate impacts (Goldstein *et al* 2020, Noon *et al* 2021). Degraded peatlands lose irrecoverable C as, e.g. CO_2 greenhouse gas (Evans *et al* 2021), i.e. when peatlands are drained for forestry, peat extraction, and grazing (Loisel *et al* 2021). Peatland drainage and degradation have occurred worldwide (Hu *et al* 2017, Leifeld and Menichetti 2018, Humpenöder *et al* 2020, Fluet-Chouinard *et al* 2023) and led to the release of 645 Mt C yr^{-1}, equivalent to up to 5% of global annual anthropogenic C emissions (Ma *et al* 2022a). The largest area of degraded peatlands is in the northern region, mainly in Europe and Russia (Humpenöder *et al* 2020), where they annually emit 0.26 Gt CO_2 equivalent (Leifeld and Menichetti 2018).

Restoring peatlands can contribute up to 2.7 $GtCO_2$ equivalent annually toward climate mitigation efforts (Smith *et al* 2019). The significance of peatlands in reducing atmospheric C is reflected in an increasing number of national restoration strategies, especially among northern countries (Nordbeck and Hogl 2024). Given the importance of restoring northern peatlands for the C sink, monitoring and reporting systems under these national strategies are crucial for assessing the success of restoration efforts (IUCN 2021).

Peatland restoration actions include rewetting drained sites by blocking or filling drainage ditches, removal of topsoil and non-peatland vegetation, and revegetation (Similä *et al* 2014, Klimkowska *et al* 2019, Allan *et al* 2024). Monitoring ecosystem health aims to assess the change in measurable ecosystem attributes relative to reference sites (Nelson *et al* 2024). Accordingly, the progress of restoration is widely being monitored by assessing changes in the peatlands' hydrological regime (McCarter and Price 2013, Ahmad *et al* 2020, Armstrong *et al* 2022, Gatis *et al* 2023), vegetation cover (Howie *et al* 2009, Nugent *et al* 2018, González and Rochefort 2019), microclimate and surface energy balance (Wilson *et al* 2016, Worrall *et al* 2019).

As peatland restoration efforts expand globally, effective large-scale monitoring becomes essential. Remote sensing can facilitate in assessing restoration-induced changes by estimating, for example, proxies of groundwater depth (Burdun *et al* 2023, Toca *et al* 2023), vegetation greenness (Chasmer *et al* 2018, Lees *et al* 2019, Ball *et al* 2023), and daily variation in land surface temperature (LST) (Worrall *et al* 2019, 2020). These proxies reflect terrestrial biophysical properties, including evapotranspiration, energy fluxes, and vegetation productivity, that influence Earth's climate and are closely linked to essential climate variables (Global Climate Observing System 2024). However, to our knowledge, no studies have conducted a large-scale assessment of how restoration-induced changes in peatlands alter the essential climate variables. While existing studies focus on small-scale peatland restoration (Chasmer *et al* 2018, Nugent *et al* 2018, Lees *et al* 2019, Worrall *et al* 2019, Toca *et al* 2023), the absence of large-scale assessments creates uncertainty about how restoration outcomes may influence local and regional climate, surface energy balance, surface reflectivity, and vegetation cover.

In this study, we aim to reveal restoration-induced monthly changes in several essential climate variables of 72 degraded northern peatlands in Finland, Estonia, Latvia, Lithuania, the UK, Canada, and the USA. We hypothesize that the degraded peatlands' essential climate variables differ from the corresponding variables of intact reference peatlands before restoration, but show increasing similarity after restoration. To test the hypothesis, we utilized MODIS data which provide global coverage, high temporal resolution, and a long historical record since 2000. Specifically, we used data on LST, shortwave albedo, and MODIS and VIIRS based climate data records of sensor-independent leaf area index (LAI) and fraction of absorbed photosynthetically active radiation (FPAR), analyzing them using Bayesian regression models.

2. Materials and methods

2.1. Study sites

We selected 72 peatlands that were restored during the last three decades in Finland, Estonia, Latvia, Lithuania, the UK, Canada, and the USA (figure 1). We chose only the peatlands with restoration finished before 2022 to ensure at least two post-restoration years for data analysis (table S1). The restored peatlands were classified into four main groups based on their pre-restoration land cover properties: (i) tree-covered land indicates sites with dominant tree vegetation; (ii) cropland and grassland includes peatlands

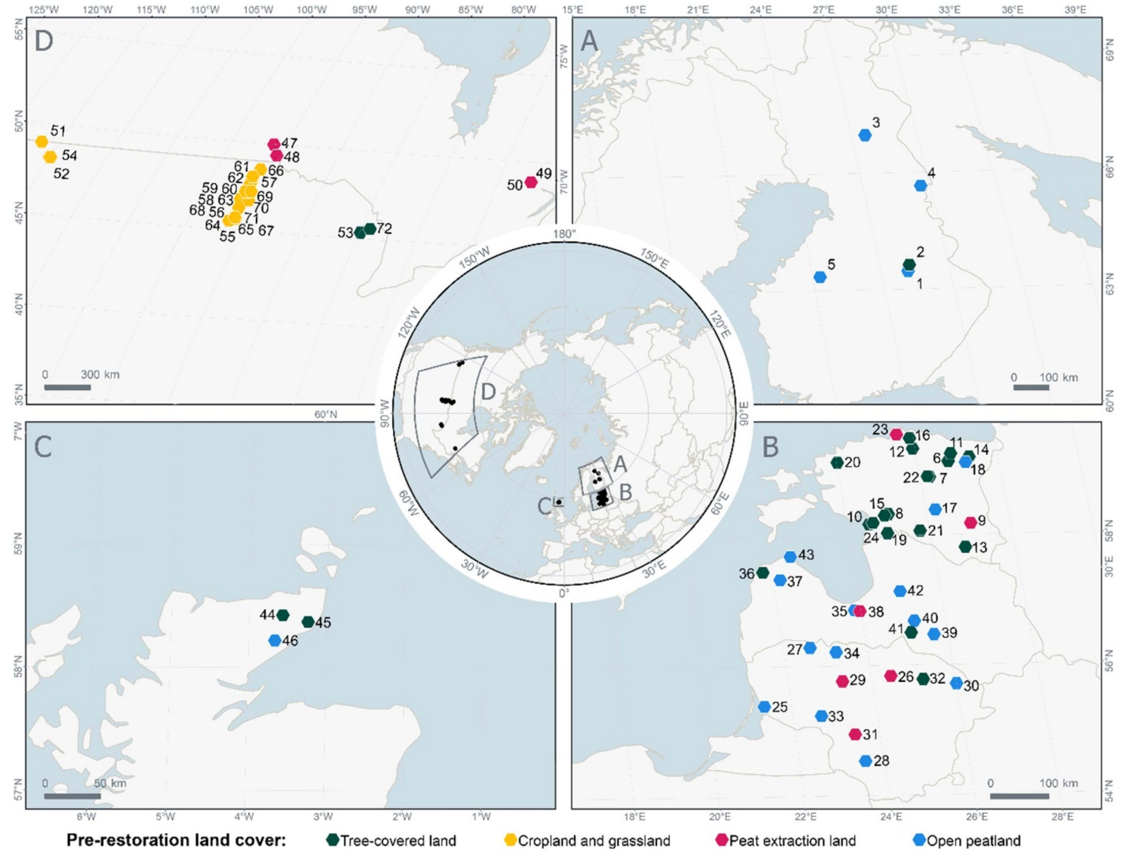

Figure 1. Location of restored peatlands. The color indicates the pre-restoration land cover type of the peatlands. The number refers to study sites listed in table S1. The location of each, locally matched intact reference site, relative to each of the degraded peatlands is given in tables S3 and S5.

primarily drained for agriculture; (iii) peat extraction land includes peatlands whose major area was used for peat extraction; (iv) open peatland represent drainage-modified sites that in general preserved peatland-specific vegetation cover (table S1). We chose intact peatlands that fell within 100 km of restored peatland as their reference sites (French *et al* 2016). For more information on study selection please refer to the supplementary data.

2.2. Essential climate variables

We selected the following essential climate variables, which are important for understanding Earth's climate: LST, albedo, LAI, and FPAR. Accordingly, we utilized data on (i) LST at 1 km spatial resolution (Wan 2013) from MODIS MOD11A1 (LST at 10:30 and 22:30) and MYD11A1 (LST at 13:30 and 01:30) version 6.1 products; (ii) broadband shortwave (0.3–5.0 μm) black-sky albedo at 500 m spatial resolution from MCD43A3 product version 6.1; (iii) MODIS and VIIRS based sensor-independent LAI and FPAR climate data record at 500 m spatial resolution (see supplementary data).

2.3. Statistical analysis

We modeled monthly satellite-derived essential climate variables of each restored peatland and associated intact peatlands both before and after restoration periods using R package brms (Bürkner 2017), which is specialized in fitting Bayesian regression models using 'Stan' (Stan Development Team 2022, 2024). For more detailed information on modeling, please see supplementary data.

Because MOD11A1 and MYD11A1 daytime and nighttime LSTs and LAI/FPAR showed similar patterns, the main text shows only LST at 13:30 and 22:30, LAI, and albedo; remaining variables are in the supplementary data.

3. Results

3.1. Differences between restored and intact peatlands before and after restoration

We observed distinct monthly patterns of modeled differences in LST, LAI, FPAR, and albedo between degraded peatlands categorized by four pre-restoration land covers, namely (i) tree-covered land (23 sites), (ii) cropland and grassland (20 sites), (iii) peat extraction land (10 sites), and (iv) open peatland (19 sites), and their intact reference sites before restoration (figures 2 and S1). Nevertheless, there was high heterogeneity in LST, LAI, FPAR, and albedo differences within each land cover category. Overall, degraded peatlands generally had lower daytime LST

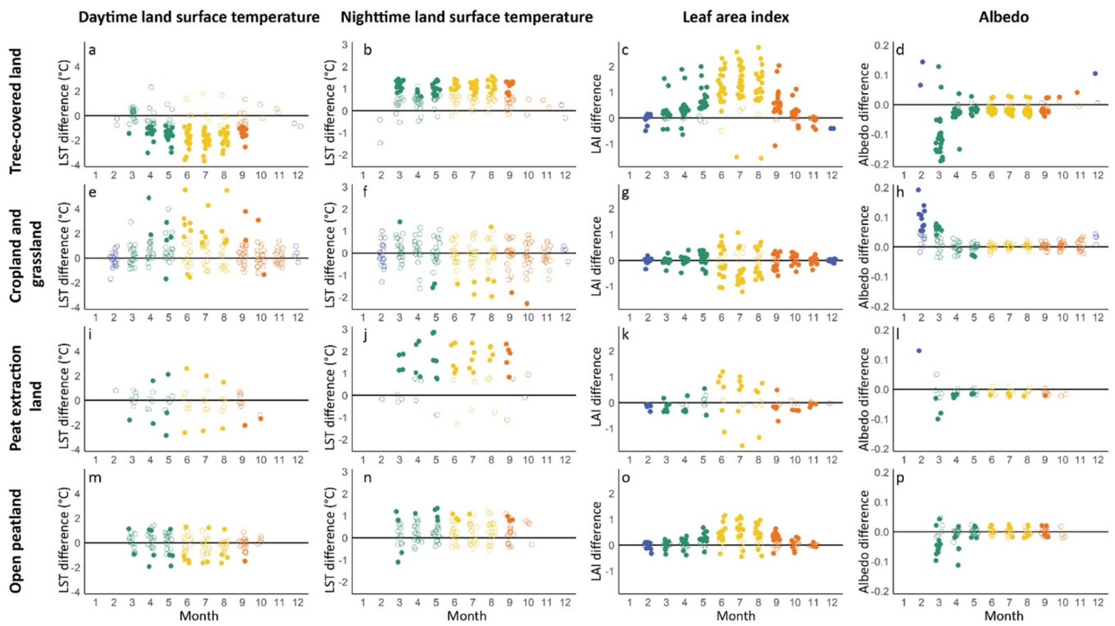

Figure 2. Monthly mean differences in daytime land surface temperature (LST at 13:30, panels: (a), (e), (i) and (m)), nighttime land surface temperature (LST at 22:30, panels: (b), (f), (j) and (n)), leaf area index (LAI, panels: (c), (g), (k) and (o)), and albedo (panels: (d), (h), (l) and (p)) between restored peatlands before restoration was started, and their respective intact reference peatlands. The furthest left *y*-axis labels are for four pre-restoration land cover types. The point colors represent the four seasons: blue corresponds to winter (December–February), green to spring (March–May), yellow to summer (June–August), and orange to autumn (September–November). Filled symbols denote months where the 95% credible interval does not include zero, indicating a statistically significant difference; open symbols denote intervals that overlap zero. Positive values of monthly differences indicate that the essential climate variable for restored peatland was larger than for the intact ones. Before-restoration data is not shown for peatlands restored before the availability of satellite-based products (year 2000), namely sites 47, 49, and 50 (see table S1).

and albedo, which were linked to higher nighttime LST, along with increased LAI and FPAR, compared to their respective intact peatlands both before (figures 2 and S1) and after restoration (figures 3 and S2). In the following paragraphs, we provide a description of the differences in LST, LAI, FPAR, and albedo for each land cover type, with results before restoration summarized in figure 2 and those after restoration in figure 3.

Degraded peatlands of the tree-covered land type had the most similar LST, LAI, FPAR, and albedo differences both before and after restoration compared to sites with other land cover types. Only two southernmost peatlands in the USA were largely distinct from others, namely sites 53 and 72 (figure S1). Tree-covered peatlands were generally cooler during the day (figure 2(a)) and warmer at night (figure 2(b)) compared to intact sites, with the daytime cooling being greater than the nighttime warming. Most of these peatlands usually had higher LAI and FPAR than intact peatlands, especially in summer (figure 2(c)).

Compared with tree-covered peatlands, those converted to cropland and grassland type were more variable, both among sites and across months, in the sign and magnitude of their divergence from reference intact peatlands. Although they typically had higher daytime LST (figure 2(e)) and lower nighttime LST (figure 2(f)) during the spring and summer compared to intact peatlands before restoration, the between-site difference in daytime LST was the largest compared with other land cover types and ranged from −2.95 °C (95% credible interval—CI: −4.05 to −1.87, site 71, May) to 5.53 °C (95% CI: 2.56–8.58, site 54, June). We observed seasonal patterns in both LAI and FPAR differences, with degraded peatlands usually having lower values of these climate variables in summer before and after restoration. The degraded peatlands also had higher albedo than intact sites in winter and early spring, a difference that was particularly noticeable prior to restoration (figure 2(h)).

Peatlands used for peat extraction demonstrated a strong inverse pattern in differences in LST, LAI, FPAR, and albedo both before and following restoration. Overall, degraded peatlands that were cooler during the day (i.e. had lower daytime LST) tended to be warmer at night (i.e. had higher nighttime LST) and had more green vegetation (i.e. higher LAI and FPAR) than intact sites during summer. Conversely, peatlands used for peat extraction that were warmer during the day were also typically cooler at night and had less green vegetation compared to intact peatlands. Interestingly, peatlands restored nearly 20 years ago (sites 49 and 50) exhibited noticeably lower LAI and FPAR values than the intact peatlands (figures 3(k) and S2).

Most of the degraded open peatlands tended to be warmer at night than intact sites, while some degraded open peatlands were cooler during the day,

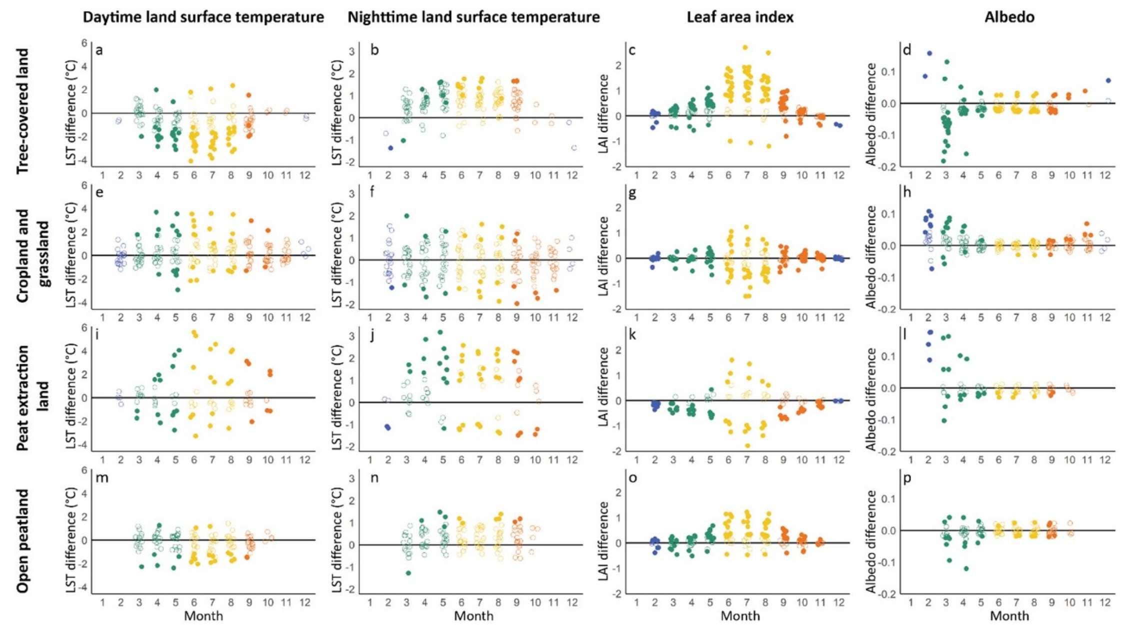

Figure 3. Monthly mean differences in daytime land surface temperature (LST at 13:30, panels: (a), (e), (i) and (m)), nighttime land surface temperature (LST at 22:30, panels: (b), (f), (j) and (n)), leaf area index (LAI, panels: (c), (g), (k) and (o)), and albedo (panels (d), (h), (l) and (p)) between restored peatlands after restoration was started, and their respective intact reference peatlands. The furthest left *y*-axis labels are for four pre-restoration land cover types. The point colors represent the four seasons: blue corresponds to winter (December–February), green to spring (March–May), yellow to summer (June–August), and orange to autumn (September–November). Filled symbols denote months where the 95% credible interval does not include zero, indicating a statistically significant difference; open symbols denote intervals that overlap zero. Positive values of monthly differences indicate that the essential climate variable for restored peatland was larger than for the intact ones.

both before (figures 2(m) and (n)) and after restoration (figures 3(m) and (n)). We also identified varying patterns in daytime and nighttime LST differences across these sites, ranging from daytime cooling and nighttime warming to consistent warming in both daytime and nighttime. Compared to other degraded peatlands, open peatlands had the smallest LST difference with their reference sites, which varied between −1.93 °C (95% CI: −2.66 to −1.15, site 43, April) and 1.41 °C (95% CI: −0.42–3.33, site 1, April) prior to restoration (figures 2(m) and (n)). Higher LAI and FPAR in summer (figures 2(o) and S1) and lower albedo in spring (figure 2(p)) were common features of most degraded open peatlands. The largest differences in LAI and FPAR were recorded in sites with relatively high tree cover before restoration (table S1). These sites typically exhibited lower daytime LST and warmer nighttime LST, similar to the behavior observed in tree-covered peatlands (figures 2 and S1). However, unlike most tree-covered peatlands, their albedo was not consistently lower than the reference sites.

3.2. How restoration affected the similarity between restored and intact peatlands

Overall, the restoration led to various changes in LST, LAI, FPAR, and albedo differences between restored and intact peatlands. These changes varied across sites and depended on pre-restoration land cover types (figures 4 and S3). Predominantly, we observed the following changes in differences between restored and intact peatlands: (i) decreased differences in daytime LST, (ii) increased differences in nighttime LST, (iii) changes in LAI and FPAR varied across sites, but both exhibited similar patterns of change, (iv) differences in albedo were the most noticeable in winter and early spring.

Tree-covered peatlands showed restoration-induced changes in daytime LST that varied from −1 °C (95% CI: −3.00–0.96, site 11, April) to 3.18 °C (95% CI: 0.86–5.50, site 44, June) (figures 4(a) and S3). One of the largest increase in LST differences was observed in restored sites 44 and 45—up to 3.18 °C (95% CI: 0.87–5.50, June) at 13:30. These sites also exhibited the strongest decrease in LAI, up to −2.54 (95% CI: −3.05 to −2.03, August), and FPAR, up to −0.29 (95% CI: −0.42 to −0.17, July) differences, as well as an increase in albedo difference up to 0.04 (95% CI: 0.02–0.06, March). In contrast, we observed the opposite direction of changes in LAI and FPAR in restored peatland 53, which had lower LAI and FPAR values than the intact site before restoration. Interestingly, decreased LAI and FPAR differences at sites 44 and 45, as well as increased LAI and FPAR differences at site 53, both contributed to an overall increase in similarity between these degraded peatlands and the intact sites (figures 4(c) and S3). In February and March, we observed an

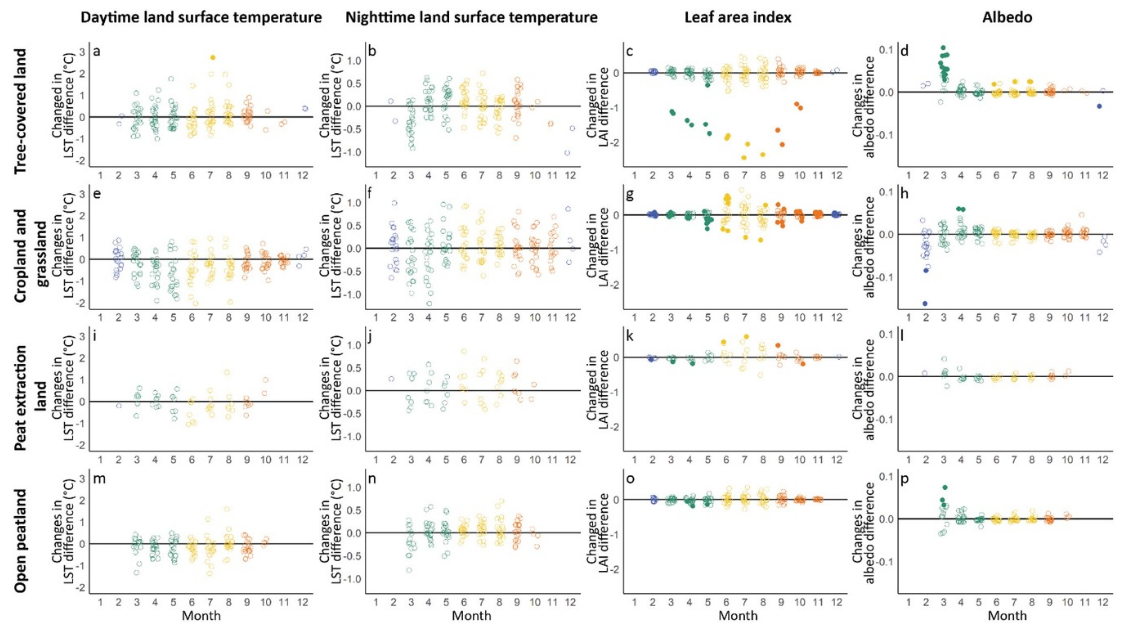

Figure 4. Change from after to before restoration in the monthly differences in daytime land surface temperature (LST at 13:30, panels: (a), (e), (i) and (m)), nighttime land surface temperature (LST at 22:30, panels: (b), (f), (j) and (n)), leaf area index (LAI, panels: (c), (g), (k) and (o)), and albedo (panels: (d), (h), (l), (p)) between restored peatlands and their intact reference peatlands. Positive values of these changes indicate that the difference between the restored and intact peatlands increased (became more positive or less negative) after restoration. Negative values indicate that the difference between the restored peatland and its reference peatland was higher before restoration and decreased (became more negative or less positive) after. These values do not indicate whether the restored and intact peatlands became similar. They show how the numerical difference changed after restoration. The point colors represent the four seasons: blue corresponds to winter (December–February), green to spring (March–May), yellow to summer (June–August), and orange to autumn (September–November). Filled symbols denote months where the 95% credible interval does not include zero, indicating a statistically significant change; open symbols denote intervals that overlap zero. Changes are not shown for peatlands restored before the availability of satellite-based products (year 2000), namely sites 47, 49, and 50 (see table S1).

increased difference in albedo between most restored and intact peatlands. This brought the albedo of restored peatlands, particularly those that had lower albedo than intact sites before restoration, closer to the levels of intact peatlands.

The restored peatlands that used to be croplands and grasslands showed the largest decrease in daytime LST difference—up to −2.04 °C (95% CI: −3.82 to −0.12, site 61, June) compared to peatlands of other land cover types (figures 4(e) and S3). This includes sites 54 and 55, which, before restoration, were warmer than intact peatlands up to 5.53 °C (95% CI: 2.56–8.58, June) (figures 2(e) and S1). As a result, these sites became more similar in daytime LST to intact peatlands after restoration. In contrast, peatlands cooler than intact sites before restoration—such as sites 51, 66, and 71 (figures 2(e) and S1)—also showed a decrease in daytime LST differences and, thus, were less likely to resemble intact peatlands. Additionally, we observed a rise in nighttime LST differences at many sites, with the magnitude of that rise in nighttime LST differences, up to 1.14 °C (95% CI: −0.79–3.05, site 71, May) being lower than the reduction in daytime LST differences (figures 4(e), (f) and S3). Remarkably, we observed a decrease in albedo differences between restored and intact sites in February, up to −0.16 (95% CI: −0.24 to −0.09, site 51), making many northernmost degraded sites more similar to intact peatlands (figures 4(h) and S3).

Peatlands previously used for peat extraction had the largest decrease in LST difference at 13:30 up to −1.05 °C (95% CI: −2.54–0.34, site 23, June) during summer months (figures 4(i) and S3). For these months, we also observed an increase in LAI and FPAR differences reaching 0.59 (95%CI: 0.21–1.01, site 23, July) and 0.08 (95% CI: 0.02–0.15, site 23, July), respectively (figure 4(k)). These degraded peatlands generally showed drops in albedo difference and, as a result, were less likely to resemble intact peatlands, except for site 48, which showed an increase in albedo difference and greater similarity to intact sites (figure S3).

In degraded open peatlands, the changes in LST difference were smaller on average—ranging from −1.37 °C (95% CI: −4.24–1.39, site 46, July) to 1.58 °C (95% CI: −0.22–3.42, site 34, August) during the day and from −1.02 °C (95% CI: −2.84–0.85, site 30, March) to 0.79 °C (95% CI: −0.79–2.38, site 46, May) at night—compared to peatlands of other land cover types (figures 4(m), (n) and S3). Although most of these peatlands had higher LAI and FPAR than intact sites before restoration (figures 2(o) and S1), restoration increased the LAI and FPAR difference in some of them (e.g. 18, 46, 43, and 27), resulting in

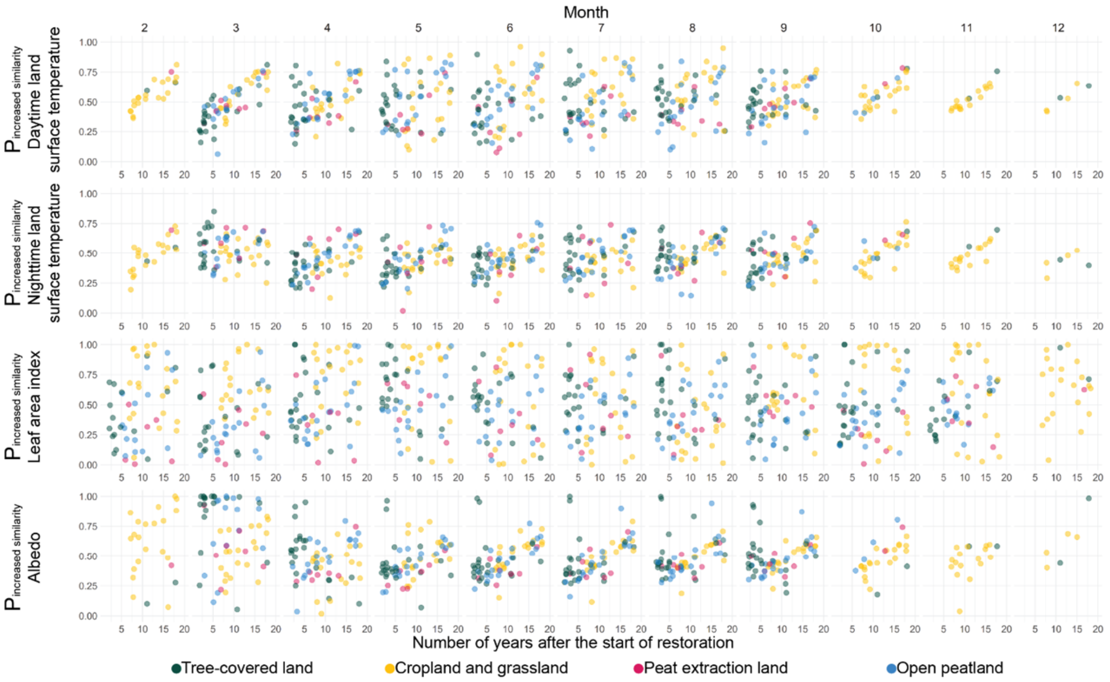

Figure 5. The monthly posterior probabilities (P) that restoration led to increased similarity between the restored and intact peatland versus the number of years that had passed after the start of restoration. Daytime land surface temperature indicates LST at 13:30, and nighttime land surface temperature shows LST at 22:30. Colors indicate the pre-restoration land cover type of restored peatlands.

a low probability of resembling intact sites. In other degraded peatlands (e.g. 4, 5, and 35), restoration decreased LAI and FPAR differences and increased their similarity with intact peatlands. In some peatlands (e.g. 18, 43, 40, 39, 27, 34, 30, and 33), albedo differences mostly increased in March (figures 4(p) and S3), bringing them closer to intact peatlands, as their albedo was lower than of the intact peatlands before restoration (figures 2(p) and S1).

3.3. Similarity between restored and intact peatlands increases based on the number of years since the restoration began

Following restoration, the similarity of LST and albedo between restored and intact peatlands tends to increase over time (figure 5). There was a linear relationship between similarity and the number of years since restoration began, with this increase in similarity being more pronounced in nighttime LST than in daytime LST during late spring and summer (table S14). The strongest relationships between albedo similarity and the number of years since restoration were observed during summer months. However, peatlands 44 and 45 did not follow this linear trend for albedo, resembling the intact site's albedo just three years after restoration began. Unlike LST and albedo, LAI and FPAR similarity did not show a linear relationship with the number of years since restoration.

4. Discussion

4.1. Site-specific variability in LST, LAI, FPAR, and albedo changes

The observed heterogeneity in LST, LAI, FPAR, and albedo differences between restored and intact peatlands across various sites and land cover types before restoration (figures 2 and S1) is a novel finding at this large scale. This heterogeneity highlights the challenges in addressing restoration needs and may be attributed to the variability in local conditions of degraded peatlands. Factors such as the density of drainage ditches (Bring *et al* 2022), ecological features of the catchment area (Similä *et al* 2014), duration and intensity of drainage (Loisel and Gallego-Sala 2022b) along with associated subsidence (Regan *et al* 2019), surface aerodynamic characteristics related to the vegetation and other micro topographical complexity (Hemes *et al* 2018, Lee *et al* 2021), soil fertility (Tuittila *et al* 2000) and acidity (Jarašius *et al* 2022) could contribute to these differences. Local conditions, combined with restoration methods, may explain the observed heterogeneity in restoration-induced changes in essential climate variables (figure 4). For instance, spontaneous revegetation may result in a more limited recovery of vegetation cover in peat extraction areas compared to more advanced methods, such as the moss layer transfer technique (Graf and Rochefort 2016, Allan *et al* 2024). To some extent, this heterogeneity in restoration-induced changes could also be attributed to changes in intact sites. Vegetation composition in intact peatlands may be altered by changes in climate conditions, such as reduced snow cover (Backéus *et al* 2023), rising temperatures, variations in precipitation patterns (Antala *et al* 2022), and fluctuating water table depths (Bragazza *et al* 2012, Oke *et al* 2020, Campbell *et al* 2021, Granlund *et al* 2022, Ma *et al* 2022b).

Our results could be partially influenced by data quality limitations. Although we excluded days without LST and albedo data due to cloud conditions, filtered outliers, and used data from the same dates for both restored and intact peatlands, some uncertainty may still arise from the varying quality of the data. For LAI and FPAR, we minimized these uncertainties by utilizing data records with a low mean absolute error that is comparable with high-quality LAI and FPAR retrievals of original MODIS Terra/Aqua/VIIRS LAI/FPAR products (Pu *et al* 2024).

Another limitation is the use of black-sky albedo, which represents directional-hemispherical reflectance at local noon in the absence of a diffuse component. While black-sky albedo allows for consistent spatial and temporal comparisons by minimizing atmospheric variability, it may underestimate total surface albedo (Liu *et al* 2009). As a result, the full radiative effects of restored peatlands may not be fully captured in our study.

Additionally, our results might be affected by spatial resolution limitation. We utilized satellite data with spatial resolution of 1 km and 0.5 km, where pixels covered peatlands by 60% and 90%, respectively. However, this is currently the only dataset available that provides global coverage, high temporal resolution, and a long historical record of studied essential climate variables since 2000.

4.1.1. Tree-covered land

Our findings revealed that tree-covered peatlands exhibited distinct thermal behavior, being cooler during the daytime and warmer at night than intact peatlands (figures 2(a) and (b)). While similar results have been observed by Li *et al* (2015), who reported daytime cooling and nighttime warming in forested land compared to open land; our results provide novel insights into thermal dynamics specifically for peatland ecosystems. In both our study and Li *et al* (2015), daytime cooling generally had a higher magnitude than nighttime warming. The lower albedo observed in degraded peatland compared to intact sites (figure 2(d)) likely contributed to nighttime warming (Bonan 2008) by increasing the absorption of solar radiation during the day. Consequently, degraded peatlands with lower albedo generally had higher nighttime LST than intact peatlands before restoration (figures 2(b), (d) and S1). In contrast, degraded sites with higher albedo, such as 53 and 72, often had lower nighttime LST than intact peatlands (figure S1).

Degraded tree-covered peatlands had lower albedo than intact sites during the growing season, with the largest difference occurring in early spring (figure 2(d)). After restoration, this large albedo difference between degraded and intact peatlands in early spring was narrowed (figure 4(d)). The pronounced albedo difference in early spring may be due to the longer-lasting snow cover in northern regions, where the albedo difference between open peatlands and forested areas becomes greater as solar radiation increases (Lohila *et al* 2010). This albedo difference between degraded and intact peatlands may lead to significant differences in absorbed energy and albedo-induced warming of forested land in spring (Lohila *et al* 2010). The albedo-induced daytime warming observed in our study across a large number of degraded peatlands highlights the significant impact of reduced albedo on energy absorption and surface warming during spring (figure 2(d)).

Significant restoration-induced changes in LAI and FPAR were observed at sites 44 and 45, where tree cover was notably reduced through clear-felling (table S1). At the same time, albedo increased in these peatlands. However, we did not observe overall cooling at these sites, which contrasts with the cooling typically observed during the transition from forests to wetlands, driven by increased surface albedo and reduced sensible and ground heat fluxes (Duveiller *et al* 2018). The lack of cooling may be due to the recent restoration of these sites (in 2020–2021). Despite the observed albedo change, the sensible and ground heat fluxes may not have had sufficient time to adjust to levels typical of intact peatlands. Similar patterns of increased albedo alongside rising daytime LST have been observed in non-peatland land covers, where the warming effect from reduced sensible heat flux offsets the cooling effect of higher albedo (Luyssaert *et al* 2014).

4.1.2. Cropland and grassland

We observed a restoration-induced decrease in daytime LST and an increase in nighttime LST differences between restored and intact peatlands, with a greater amplitude of change in daytime LST. The changes in daytime and nighttime LST differences varied across sites, which could be partially attributed to discrepancies in vegetation cover. For instance, a case study of three restored peatlands found that sites restored earlier exhibited smaller daytime cooling and nighttime warming than a more recently restored site, likely due to the presence of a mature, closed canopy cover (Hemes *et al* 2018). Overall, the transition from agricultural land to wetlands was previously found to result in increased sensible and ground heat flux, which outweighed the effect of decreased shortwave albedo (Duveiller *et al* 2018) and explains the higher magnitude of negative daytime LST change observed in our study.

This study included 20 restored former cropland and grassland sites with diverse pre-restoration contexts across a broad region, reflecting a range of environmental conditions. Some of our findings, such as those for site 51, which exhibited higher albedo, lower daytime temperature, and higher nighttime temperature compared to intact peatlands before restoration, agree with previous studies (Wang *et al* 2020, Worrall *et al* 2020). However, we also found that degraded peatlands could have predominantly lower albedo than intact peatlands, specifically sites 70 and 71 in our study. Moreover, the observed variations in albedo between degraded peatlands and intact sites did not consistently lead to the same patterns of daytime cooling and nighttime warming. The possible explanation for this inconsistency could be the difference in vegetation height between degraded and intact peatlands, which could affect overall surface roughness and, consequently, sensible heat flux and surface temperature (Worrall *et al* 2020).

4.1.3. Peat extraction land

The decrease in daytime LST difference between restored and intact peatlands was observed in most cases (figures 4(i) and S3). Interestingly, the largest decrease in daytime LST occurred in degraded peatlands with a high tree coverage before restoration. Tree cover varied between 38% and 61% of the total restored area for peatlands 9, 26, 29, 31, and 38 before restoration (table S1). These degraded sites also had higher LAI and FPAR values than intact peatlands during the growing season (figures 2(k) and S1). Tall vegetation may lower daytime and nighttime temperatures through enhanced turbulent heat fluxes (Lee *et al* 2021). After restoration, changes in vegetation cover, open water, and bare soil may affect the Bowen ratio by reducing latent heat flux (Wilson *et al* 2016) and explain the observed reduced daytime LST difference.

Most degraded sites had lower albedo than intact sites before restoration (figures 2(l) and S1). This lower albedo may be partly attributed to the greater presence of open water, which covered approximately 26% and 18% of the peatland area in restored sites 26 and 31, respectively, before restoration (table S1). Increased water bodies lead to decreased albedo and higher net radiation, which, in turn, may result in higher nighttime temperatures (Lee *et al* 2021) that we observed in peatlands 26 and 31.

4.1.4. Open peatland

We found complex patterns in LST differences between degraded and intact peatlands before restoration that could result from the interplay between vegetation cover, albedo, and heat fluxes. The findings from previous works are contradictory, and the physical mechanisms of complex LST patterns are poorly understood. Drained peatlands could (i) increase their temperature due to reduced latent heat flux (Kettridge and Waddington 2014), or (ii) increase their latent heat fluxes (Worrall *et al* 2020). Moreover, vegetation height and peat hydraulic properties could also change the sensible and latent heat fluxes in degraded peatlands (Schwärzel *et al* 2006, Worrall *et al* 2021).

Higher LAI and FPAR values in the degraded peatlands compared to the reference sites before restoration (figures 2(o) and S1) may be attributed to the increased coverage of vascular plants, particularly woody shrubs. This trend was observed in previous studies on degraded peatlands (Strack *et al* 2006, Harris *et al* 2020) and is known as shrubification, which may further progress to afforestation (Fay and Lavoie 2009). An increase in vascular plant and a decrease in *Sphagnum* moss coverage can occur because the deepened water table in degraded sites creates conditions outside the tolerance range for many peatland species (Harris *et al* 2020). Potential shrubification and lower albedo of shrubs (Salko *et al* 2024) might explain lower albedo in degraded peatlands 1, 3, 5, 25, and 33 (figure S1). Thus, restoration led to an increase in the albedo of these sites, making them more similar to intact peatlands. This effect was especially noticeable in spring, when snow cover amplifies the albedo contrast between open and shrub-covered areas, in a pattern comparable to what was observed earlier for tree-covered sites.

4.2. Restoration leads to increasing similarities between restored and intact peatlands over time

Nighttime LST and albedo data indicated that, on average, 11.82 ± 1.35 years after restoration, there is approximately a 0.5 probability of restored peatlands showing increased similarity to intact sites in May–September (figure 5, table S14). In other words, restored peatlands across wide-ranging geographical extent were more likely to be similar than different to intact peatlands after a post-restoration decade, aligning with the varying timelines reported in previous studies observed on local scale. In peat extraction sites, the re-establishment of C sink functions may take varying periods: 3 years (Strack *et al* 2016), 7 years (Wilson *et al* 2016), 14 years (Nugent *et al* 2018), or even more than 18 years (Schaller *et al* 2022). Re-vegetation may begin within 3–4 years following restoration (Tuittila *et al* 2000, Renou-Wilson *et al* 2019), with more than half of a restored site potentially revegetated within 10 years (González and Rochefort 2019). However, 15 years may still be insufficient time to re-establish peatland-specific vegetation in heavily degraded sites (Renou-Wilson *et al* 2019). 45–55 years might be enough for most restored sites to reach vegetation cover similar to the one at the reference site (Allan *et al* 2024). Likewise, in tree-covered peatlands, only minor changes in vegetation were observed within the first 5 years, with significant changes occurring only after 10 years (Haapalehto *et al* 2017, Ball *et al* 2023).

We demonstrated that multiple satellite-derived observations, such as albedo and LST, should be assessed together to ensure a more robust restoration assessment. In our study, sites 44 and 45 closely resembled intact sites in albedo after restoration, but not in nighttime LST. In these sites, a significant reduction in tree cover occurred during restoration in 2020–2021, due to clear-felling (table S1), which probably caused their albedo to become more similar to their treeless reference peatlands. Changes in albedo due to clear-felling should not be perceived as restoration progress as it is a short-term interim state that may also temporarily reduce water quality below the restoration site (Härkönen *et al* 2023). Meanwhile, nighttime LST showed that the thermal properties of these restored peatlands did not become substantially similar to the reference sites within such a short post-restoration period (figures 4(b) and S3).

However, the finding that restored peatlands resembling intact sites after a post-restoration decade should be interpreted with caution, as we did not model year-by-year changes in the restored sites. Based on the linear relationship we observed for nighttime LST and albedo in May–September, it might be projected that a high probability for restored peatlands showing increased similarity to intact sites may be reached within 52 ± 14 years (table S14). This projection is speculative, as it is based on the extrapolation of a linear relationship representing past climate conditions and without the availability of long-term data for validation.

4.3. Future directions

We observed the following changes in the difference between restored and intact peatlands caused by restoration: up to 3.18 °C (95% CI: 0.86–5.5) and −1.22 °C (95% CI: −3.08–0.81) in daytime and nighttime LST, respectively; up to −2.54 (95% CI: −3.05 to −2.03) in LAI; up to −0.29 (95% CI: −0.42 to −0.17) in FPAR; and up to −0.16 (95% CI: −0.24 to −0.09) in albedo. These changes may influence local and regional climate dynamics, especially in regions undergoing large-scale restoration efforts. As the number of restored peatlands continues to grow, particularly in Europe (Hering *et al* 2023) and Canada (Alamenciak *et al* 2023), it is crucial to consider these factors, especially in assessments of the climatic impacts of land-use change (Hemes *et al* 2018). For example, the restoration impact of peatlands was primarily considered in terms of biogeochemical impacts, focusing on the role of peatlands in reducing greenhouse gas emissions in the Sixth Assessment Report by the IPCC (Anon 2021). However, the potential biophysical impacts of restoration were not fully integrated into their climate projections, leaving a gap in the understanding of how restored peatlands influence local and regional climate dynamics.

Additionally, future research could examine how the restoration-induced changes in degraded peatlands can inform the land-use components of Nationally Determined Contributions (UNFCCC 2024). This would help ensure that the climatic benefits of restoration are more fully reflected in national mitigation and adaptation planning. In particular, the observed linear relationships between albedo, nighttime LST, and time since restoration could support projections of long-term climate effects, aiding the integration of peatland restoration into land-use scenario planning.

Future studies could also compare our observed changes in the difference between restored and intact peatlands caused by restoration with results obtained from other countries and regions. In tropical peatlands, for instance, limited climate resistance may restrict the recovery of biophysical properties and reveal how climate influences restoration outcomes (Girkin *et al* 2022).

5. Conclusions

Leveraging more than 20 years of satellite data, we used essential climate variables to reveal changes in restored peatlands and assess whether they return to their original, natural state in Finland, Estonia, Latvia, Lithuania, the UK, Canada, and the USA. The results of this study indicate that:

- Degraded peatlands generally exhibited lower LST and albedo, higher nighttime LST and increased LAI and FPAR compared to their respective intact counterparts. These differences persisted both before and after restoration.
- Restoration led to notable shifts in LST, LAI, FPAR, and albedo, modifying their differences relative to intact peatlands. Predominantly, we observed: (i) decreased differences in daytime LST, (ii) increased differences in nighttime LST, (iii) changes in LAI and FPAR varied across sites, but both exhibited similar patterns of change, (iv) differences in albedo were the most noticeable in winter and early spring.
- Over time, restored peatlands tended to become more similar to intact sites in terms of LST and albedo, following a linear relationship with the number of years since restoration began. We found that it might take over a decade and around fifty years after restoration to reach a 0.5 and 1 probability, respectively, that restored peatlands exhibited increased similarity to intact sites.

The observed restoration-induced changes in climate variables may have significant implications for regional and local climate dynamics, particularly in regions undergoing large-scale peatland restoration, such as North America and Europe. Therefore, we highlight the need to integrate potential biophysical impacts of restoration into climate projections.

Data availability statement

We acknowledge the use of freely available LST and albedo imagery from NASA's MODIS AppEEARS application (https://appeears.earthdatacloud.nasa.gov/). All other data are available in the main text or the supplementary data.

The data that support the findings of this study are openly available at the following URL/DOI: https://zenodo.org/records/8076540.

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References

Ahmad S, Liu H, Günther A, Couwenberg J and Lennartz B 2020 Long-term rewetting of degraded peatlands restores hydrological buffer function *Sci. Total Environ.* **749** 141571

Alamenciak T, Pomezanski D, Shackelford N, Murphy S D, Cooke S J, Rochefort L, Voicescu S, Higgs E and Pelletier F 2023 Ecological restoration research in Canada: who, what, where, when, why, and how? *Facets* **8** 1–11

Allan J M, Guêné-Nanchen M, Rochefort L, Douglas D J T and Axmacher J C 2024 Meta-analysis reveals that enhanced practices accelerate vegetation recovery during peatland restoration *Restor. Ecol.* **32** e14015

Anon 2021 AR6 climate change 2021: the physical science basis (IPCC) (available at: www.ipcc.ch/report/sixth-assessment-report-working-group-i/)

Antala M, Juszczak R, van der Tol C and Rastogi A 2022 Impact of climate change-induced alterations in peatland vegetation phenology and composition on carbon balance *Sci. Total Environ.* **827** 154294

Armstrong L, Peralta A, Krauss K W, Cormier N, Moss R F, Soderholm E, McCall A, Pickens C and Ardón M 2022 Hydrologic restoration decreases greenhouse gas emissions from shrub bog peatlands in Southeastern US *Wetlands* **42** 1–10

Backéus I, Gunnarsson U and Strömquist L 2023 Bog vegetation re-mapped after 63 and 103 years:expansion of Rhynchospora alba (Studies on Skagershultsmossen 2) *Mires Peat* **29** 16

Ball J, Gimona A, Cowie N, Hancock M, Klein D, Donaldson-Selby G and Artz R R E 2023 Assessing the potential of using Sentinel-1 and 2 or high-resolution aerial imagery data with machine learning and data science techniques to model peatland restoration progress—a Northern Scotland case study *Int. J. Remote Sens.* **44** 2885–911

Bonan G B 2008 Forests and climate change: forcings, feedbacks, and the climate benefits of forests *Science* **320** 1444–9

Bragazza L, Parisod J, Buttler A and Bardgett R D 2012 Biogeochemical plant–soil microbe feedback in response to climate warming in peatlands *Nat. Clim. Change* **3** 273–7

Bring A, Thorslund J, Rosén L, Tonderski K, Åberg C, Envall I and Laudon H 2022 Effects on groundwater storage of restoring, constructing or draining wetlands in temperate and boreal climates: a systematic review *Environ. Evid.* **11** 1–30

Burdun I *et al* 2023 Hidden becomes clear: optical remote sensing of vegetation reveals water table dynamics in northern peatlands *Remote Sens. Environ.* **296** 113736

Bürkner P-C 2017 brms: an R package for Bayesian multilevel models using Stan *J. Stat. Softw.* **80** 1–28

Campbell C, Granath G and Rydin H 2021 Climatic drivers of Sphagnum species distributions *Front. Biogeogr.* **13** 1–17

Chasmer L, Baker T, Carey S K, Straker J, Strilesky S and Petrone R 2018 Monitoring ecosystem reclamation recovery using optical remote sensing: comparison with field measurements and eddy covariance *Sci. Total Environ.* **642** 436–46

Duveiller G, Hooker J and Cescatti A 2018 The mark of vegetation change on Earth's surface energy balance *Nat. Commun.* **9** 1–12

Evans C D *et al* 2021 Overriding water table control on managed peatland greenhouse gas emissions *Nature* **593** 548–52

FAO 2023 Standards of practice to guide ecosystem restoration *A Contribution to the United Nations Decade on Ecosystem Restoration* Summary Report

Fay E and Lavoie C 2009 The impact of birch seedlings on evapotranspiration from a mined peatland: an experimental study in southern Quebec, Canada *Mires Peat* **5** 1–7 (available at: http://mires-and-peat.net/pages/volumes/map05/map0503.php)

Fluet-Chouinard E *et al* 2023 Extensive global wetland loss over the past three centuries *Nature* **614** 281–6

French N H F, Whitley M A and Jenkins L K 2016 Fire disturbance effects on land surface albedo in Alaskan tundra *J. Geophys. Res.* **121** 841–54

Gatis N, Benaud P, Anderson K, Ashe J, Grand-Clement E, Luscombe D J, Puttock A and Brazier R E 2023 Peatland restoration increases water storage and attenuates downstream stormflow but does not guarantee an immediate reversal of long-term ecohydrological degradation *Sci. Rep.* **13** 1–14

Girkin N T, Cooper H V, Ledger M J, O'Reilly P, Thornton S A, Åkesson C M, Cole L E S, Hapsari K A, Hawthorne D and Roucoux K H 2022 Tropical peatlands in the Anthropocene: the present and the future *Anthropocene* **40** 100354

Global Climate Observing System 2024 Essential climate variables (available at: https://gcos.wmo.int/site/global-climate-observing-system-gcos/essential-climate-variables)

Goldstein A *et al* 2020 Protecting irrecoverable carbon in Earth's ecosystems *Nat. Clim. Change* **10** 287–95

González E and Rochefort L 2019 Declaring success in Sphagnum peatland restoration: identifying outcomes from readily measurable vegetation descriptors *Mires Peat* **24** 1–16

Graf M D and Rochefort L 2016 A conceptual framework for ecosystem restoration applied to industrial peatlands *Peatland Restoration and Ecosystem Services* (Cambridge University Press) pp 192–212 (available at: www.cambridge.org/core/books/peatland-restoration-and-ecosystem-services/conceptual-framework-for-ecosystem-restoration-applied-to-industrial-peatlands/10D58A8517E49D996696CB8F8F3A81FA)

Granlund L, Vesakoski V, Sallinen A, Kolari T H M, Wolff F and Tahvanainen T 2022 Recent lateral expansion of Sphagnum bogs over central fen areas of boreal Aapa mire complexes *Ecosystems* **25** 1455–75

Haapalehto T, Juutinen R, Kareksela S, Kuitunen M, Tahvanainen T, Vuori H and Kotiaho J S 2017 Recovery of plant communities after ecological restoration of forestry-drained peatlands *Ecol. Evol.* **7** 7848–58

Härkönen L H, Lepistö A, Sarkkola S, Kortelainen P and Räike A 2023 Reviewing peatland forestry: implications and mitigation measures for freshwater ecosystem browning *For. Ecol. Manage.* **531** 120776

Harris L I, Roulet N T and Moore T R 2020 Drainage reduces the resilience of a boreal peatland *Environ. Res. Commun.* **2** 065001

Hemes K S, Eichelmann E, Chamberlain S D, Knox S H, Oikawa P Y, Sturtevant C, Verfaillie J, Szutu D and Baldocchi D D 2018 A unique combination of aerodynamic and surface properties contribute to surface cooling in restored wetlands of the Sacramento-San Joaquin Delta, California *J. Geophys. Res.* **123** 2072–90

Hering B D *et al* 2023 Securing success for the nature restoration law *Science* **382** 1248–51

Howie S A, Whitfield P H, Hebda R J, Munson T G, Dakin R A and Jeglum J K 2009 Water table and vegetation response to ditch blocking: restoration of a raised bog in southwestern British Columbia *Can. Water Resour. J.* **34** 381–92

Hu S, Niu Z, Chen Y, Li L and Zhang H 2017 Global wetlands: potential distribution, wetland loss, and status *Sci. Total Environ.* **586** 319–27

Humpenöder F, Karstens K, Lotze-Campen H, Leifeld J, Menichetti L, Barthelmes A and Popp A 2020 Peatland protection and restoration are key for climate change mitigation *Environ. Res. Lett.* **15** 104093

IUCN 2021 Science-based ecosystem restoration for the 2020s and beyond *Science Task Force for the UN Decade on Ecosystem Restoration*

Jarašius L *et al* 2022 *Handbook for Assessment of Greenhouse Gas Emissions from Peatlands. Applications of Direct and Indirect Methods by LIFE Peat Restore* (Lithuanian Fund for Nature)

Kettridge N and Waddington J M 2014 Towards quantifying the negative feedback regulation of peatland evaporation to drought *Hydrol. Process.* **28** 3728–40

Klimkowska A *et al* 2019 Are we restoring functional fens?—The outcomes of restoration projects in fens re-analysed with plant functional traits *PLoS One* **14** e0215645

Lee S-C, Black T A, Nyberg M, Merkens M, Nesic Z, Ng D and Knox S H 2021 Biophysical impacts of historical disturbances, restoration strategies, and vegetation types in a peatland ecosystem *J. Geophys. Res.* **126** e2021JG006532

Lees K J *et al* 2019 A model of gross primary productivity based on satellite data suggests formerly afforested peatlands undergoing restoration regain full photosynthesis capacity after five to ten years *J. Environ. Manage.* **246** 594–604

Leifeld J and Menichetti L 2018 The underappreciated potential of peatlands in global climate change mitigation strategies *Nat. Commun.* **9** 1–7

Li Y, Zhao M, Motesharrei S, Mu Q, Kalnay E and Li S 2015 Local cooling and warming effects of forests based on satellite observations *Nat. Commun.* **6** 1–8

Liu J *et al* 2009 Validation of Moderate Resolution Imaging Spectroradiometer (MODIS) albedo retrieval algorithm: dependence of albedo on solar zenith angle *J. Geophys. Res.* **114** 1106

Lohila A, Minkkinen K, Laine J, Savolainen I, Tuovinen J-P, Korhonen L, Laurila T, Tietäväinen H and Laaksonen A 2010 Forestation of boreal peatlands: impacts of changing albedo and greenhouse gas fluxes on radiative forcing *J. Geophys. Res.* **115** 4011

Loisel J *et al* 2021 Expert assessment of future vulnerability of the global peatland carbon sink *Nat. Clim. Change* **11** 70–77

Loisel J and Gallego-Sala A 2022 Ecological resilience of restored peatlands to climate change *Commun. Earth Environ.* **3** 1–8

Luyssaert S *et al* 2014 Land management and land-cover change have impacts of similar magnitude on surface temperature *Nat. Clim. Change* **4** 389–93

Ma L, Zhu G, Chen B, Zhang K, Niu S, Wang J, Ciais P and Zuo H 2022a A globally robust relationship between water table decline, subsidence rate, and carbon release from peatlands *Commun. Earth Environ.* **3** 1–14

Ma X-Y, Xu H, Cao Z-Y, Shu L and Zhu R-L 2022b Will climate change cause the global peatland to expand or contract? Evidence from the habitat shift pattern of Sphagnum mosses *Glob. Change Biol.* **28** 6419–32

Mander Ü, Espenberg M, Melling L and Kull A 2023 Peatland restoration pathways to mitigate greenhouse gas emissions and retain peat carbon *Biogeochemistry* **167** 1–21

McCarter C P R and Price J S 2013 The hydrology of the Bois-des-Bel bog peatland restoration: 10 years post-restoration *Ecol. Eng.* **55** 73–81

Montanarella L, Scholes R and Brainich A 2018 The IPBES assessment report on land degradation and restoration

Nelson C R *et al* 2024 *Standards of Practice to Guide Ecosystem restoration—a Contribution to the United Nations Decade on Ecosystem Restoration 2021–2030* (Rome)

Nichols J E and Peteet D M 2019 Rapid expansion of northern peatlands and doubled estimate of carbon storage *Nat. Geosci.* **12** 917–21

Noon M L *et al* 2021 Mapping the irrecoverable carbon in Earth's ecosystems *Nat. Sustain.* **5** 37–46

Nordbeck R and Hogl K 2024 National peatland strategies in Europe: current status, key themes, and challenges *Reg. Environ. Change* **24** 1–12

Nugent K A, Strachan I B, Strack M, Roulet N T and Rochefort L 2018 Multi-year net ecosystem carbon balance of a restored peatland reveals a return to carbon sink *Glob. Change Biol.* **24** 5751–68

Oke T A and Hager H A 2020 Plant community dynamics and carbon sequestration in Sphagnum-dominated peatlands in the era of global change *Glob. Ecol. Biogeogr.* **29** 1610–20

Page S E and Baird A J 2016 Peatlands and global change: response and resilience *Annu. Rev. Environ. Resour.* **41** 35–57

Pan Y *et al* 2011 A large and persistent carbon sink in the world's forests *Science* **333** 988–93

Pörtner H O *et al* 2023 Overcoming the coupled climate and biodiversity crises and their societal impacts *Science* **381** 380

Pu J, Yan K, Roy S, Zhu Z, Rautiainen M, Knyazikhin Y and Myneni R B 2024 Sensor-independent LAI/FPAR CDR: reconstructing a global sensor-independent climate data record of MODIS and VIIRS LAI/FPAR from 2000 to 2022 *Earth Syst. Sci. Data* **16** 15–34

Regan S, Flynn R, Gill L, Naughton O and Johnston P 2019 Impacts of groundwater drainage on peatland subsidence and its ecological implications on an Atlantic raised bog *Water Resour. Res.* **55** 6153–68

Renou-Wilson F, Moser G, Fallon D, Farrell C A, Müller C and Wilson D 2019 Rewetting degraded peatlands for climate and biodiversity benefits: results from two raised bogs *Ecol. Eng.* **127** 547–60

Salko S-S, Hovi A, Burdun I, Juola J and Rautiainen M 2024 Hyperspectral characterization of vegetation in hemiboreal, boreal and Arctic peatlands using a geographically extensive field dataset *Ecol. Inform.* **82** 102772

Schaller C, Hofer B and Klemm O 2022 Greenhouse gas exchange of a NW German peatland, 18 years after rewetting *J. Geophys. Res.* **127** e2020JG005960

Schwärzel K, Šimůnek J, Van Genuchten M T and Wessolek G 2006 Measurement modeling of soil-water dynamics evapotranspiration of drained peatland soils *J. Plant Nutr. Soil Sci.* **169** 762–74

Similä M, Aapala K and Penttinen J 2014 Ecological restoration in drained peatlands—best practices from Finland

Smith P *et al* 2019 Land-management options for greenhouse gas removal and their impacts on ecosystem services and the sustainable development goals *Annu. Rev. Environ. Resour.* **44** 255–86

Stan Development Team 2022 Stan modeling language users guide and reference manual, version 2.30 (available at: https://mc-stan.org/)

Stan Development Team 2024 RStan: the R interface to Stan.R package version 2.26.24 (available at: https://mc-stan.org/)

Strack M, Cagampan J, Hassanpour Fard G, Keith A M, Nugent K, Rankin T, Robinson C, Strachan I B, Waddington J M and Xu B 2016 Controls on plot-scale growing season CO_2 and CH_4 fluxes in restored peatlands: do they differ from unrestored and natural sites? *Mires Peat* **17** 1–18

Strack M, Waddington J M, Rochefort L and Tuittila E-S 2006 Response of vegetation and net ecosystem carbon dioxide exchange at different peatland microforms following water table drawdown *J. Geophys. Res.* **111** 1–10

Taillardat P, Thompson B S, Garneau M, Trottier K and Friess D A 2020 Climate change mitigation potential of wetlands and the cost-effectiveness of their restoration *Interface Focus* **10** 20190129

The European Parliament and The Council of the European Union 2024 Regulation (EU) 2024/1991 of the European parliament and of the council of 24 June 2024 on nature restoration and amending regulation (EU) 2022/869 (available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32024R1991&qid=1722240349976)

Toca L, Artz R R E, Smart C, Quaife T, Morrison K, Gimona A, Hughes R, Hancock M H and Klein D 2023 Potential for peatland water table depth monitoring using Sentinel-1 SAR backscatter: case study of forsinard flows, Scotland, UK *Remote Sens.* **15** 1900

Tuittila E-S, Vasander H and Laine J 2000 Impact of rewetting on the vegetation of a cut-away peatland *Appl. Veg. Sci.* **3** 205–12

UNFCCC 2024 2024 NDC synthesis report (available at: https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs/2024-ndc-synthesis-report)

Wan Z 2013 Collection-6 MODIS land surface temperature products users' guide

Wang M, Wu J, Lafleur P M and Luan J 2020 *Investigation of the Climatological Impacts of Agricultural Management and Abandonment on a Boreal Bog in Western Newfoundland* vol 711 (Canada Science of The Total Environment)

Wilson D, Farrell C A, Fallon D, Moser G, Müller C and Renou-Wilson F 2016 Multiyear greenhouse gas balances at a rewetted temperate peatland *Global. Change Biol.* **22** 4080–95

Worrall F, Boothroyd I M, Gardner R L, Howden N J K, Burt T P, Smith R, Mitchell L, Kohler T and Gregg R 2019 The impact of peatland restoration on local climate: restoration of a cool humid island *J. Geophys. Res.* **124** 1696–713

Worrall F, Boothroyd I M, Howden N J K, Burt T P, Kohler T and Gregg R 2020 Are peatlands cool humid islands in a landscape? *Hydrol. Process.* **34** 5013–25

Worrall F, Morrison R, Evans C, Kaduk J, Page S, Cumming A, Rayment M and Kettridge N 2021 Are peatlands in different states with respect to their thermodynamic behaviour? A simple test of peatland energy and entropy budgets *Hydrol. Process.* **35** e14431