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Drained and forgotten peat extraction sites: economic and carbon impacts of peat and water loss in spontaneously forested Lithuanian peatlands

Keywords: nature conservation, drained peatlands, soil carbon, rewetting, wetlands, ecosystem services

Introduction

Peatlands are globally important ecosystems that cover only around 3% of the Earth's land surface; however, they store nearly one-third of the world's soil carbon (United Nations Environment Programme [UNEP], 2022). This exceptional

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capacity results from the accumulation of partially decomposed organic material under persistently wet, oxygen-poor conditions, which slows microbial activity and allows carbon to build up over time (Craft, 2015).

Beyond carbon storage, peatlands provide a range of ecosystem services, including water regulation, nutrient retention, and support for specialized biodiversity (Joosten & Clarke, 2002; Tanneberger & Wichtmann, 2011). Their stable hydrological regimes help mitigate floods and droughts, while their organic soils are suitable for distinctive plant and animal communities. Peatlands also serve as valuable witnesses of historical nature development and are a part of local cultural heritage.

Despite these values, many peatlands across Europe have been drained and degraded due to agricultural expansion, forestry, and peat extraction (Joosten, 2009). Widespread drainage for peat mining and land use conversion has led to a loss of the acrotelm (the active peat-forming layer) and disrupted hydrological conditions and has triggered long-term carbon emissions (Leifeld & Menichetti, 2018). As an example, peat extraction has affected 4.2% of the raised bogs in the Baltic States (Hofer et al., 2012; Karofeld et al., 2016). The European Union's consumption of peat has drawn criticism for its unsustainable nature and lack of long-term resource management strategies (Patel et al., 2025). The cessation of peat extraction without subsequent restoration efforts can lead to the collapse of the peatland ecosystem, with degraded sites often remaining drained, resulting in continued peat decomposition, subsidence, and impaired vegetation recovery (Rydin et al., 2013). Natural recovery and regeneration of associated peatland vegetation is typically limited by persistent low water levels, altered nutrient regimes, and vegetation shifts toward non-peat-forming species (Boers et al., 2006; Manton et al., 2021). Although spontaneous tree colonization may stabilize the soil, it does not restore natural ecosystem processes and functions of peatland and thus may, in fact, increase greenhouse gas (GHG) emissions (Craft, 2015; Kamocki et al., 2025). In managed but continuously drained peatland forests, carbon accumulation in biomass and litter input does not compensate for carbon losses(Mander et al., 2024). Afforesting drained peatlands also fails to reestablish their native biodiversity and ecological functions (Haapalehto et al., 2017; Jurasinski et al., 2024). Moreover, such interventions may increase the vulnerability of these landscapes to wildfires (Kohlenberg et al., 2018; Zheng et al., 2023).

Recognizing the climate and ecological impacts of peatland degradation, the European Union has placed restoration at the core of several key policy instruments. The EU Biodiversity Strategy for 2030, the Soil Strategy, and the Nature Restoration Law all identify the rewetting of drained peatlands as a critical measure for meeting climate and biodiversity goals (Communication COM/2020/380, Communication COM/2021/699, Regulation (EU) 2022/869). Regulation (EU) 2018/841 highlights the importance of restoring organic soils, including peatlands, to enhance carbon removals in the land-use sector. Recent studies have emphasized that afforestation of drained peatlands, in the absence of hydrological restoration, is unlikely to deliver climate benefits and may even exacerbate GHG emissions (Jurasinski et al., 2024; Mander et al., 2024). Instead, rewetting and ecological restoration, such as through paludiculture or the reintroduction of peat-forming vegetation, are increasingly recognized as effective nature-based solutions (Wichmann & Nordt, 2024).

In this study, we assess the ecological condition and restoration potential of abandoned peat extraction sites in Lithuania. Focusing on forested post-extraction peatlands, we quantify peat volume loss, hydrological alterations, and associated carbon emissions. By evaluating degradation levels and the extent of ecosystem service loss, we aim to support site-specific restoration strategies that align with EU policy objectives. Our findings provide a basis for targeted rewetting efforts to reduce GHG emissions, improve ecological function, and contribute to national and European peatland restoration commitments.

Material and methods

Study area and spatial data analysis

Peatlands are an integral component of Lithuania's landscape, covering approx. 640,000 ha (10% of the country), and represent one of the country's most hydrologically and ecologically significant ecosystems (Valatka et al., 2018). Based on their geological origin and trophic status, peatlands in Lithuania comprise three main types: fens (78%), minerotrophic systems fed by mineral-rich groundwater, surface runoff, and precipitation; raised bogs (8%), oligotrophic peatlands elevated above the surrounding terrain and sustained purely by precipitation; and transitional mires (14%), which exhibit intermediate characteristics of both fens and bogs (Mitsch & Gosselink, 2015; Manton et al., 2021).

Historically, peat extraction has played a major role in the rural economy, beginning in the early 20th century and expanding rapidly during the Soviet industrial period (1950–1990) (Paavilainen & Päivänen, 1995). Currently, approx. 70% of Lithuania's peatlands have been drained and show evidence of human disturbance (Jarašius et al., 2015; Valatka et al., 2018). In total, peat extraction sites cover 20,533 hectares of which 60% are overgrown by secondary forests (Grigaliunas et al., 2023). The abandonment of drained and or extracted peatlands generally undergo spontaneous succession, typically colonized by pioneer woody species such as *Betula pubescens*, *Pinus sylvestris*, and *Salix* spp., resulting in the formation of secondary forests with altered hydrological regimes (Manton et al., 2021; Jarašius et al., 2022). Although these peatlands are degraded, they provide valuable opportunities for understanding hydrological recovery, vegetation succession, and ecosystem service restoration in peatland landscapes (Makrickas et al., 2023).

This study focuses on 33 abandoned peatland quarries (3,854 ha) in Lithuania, Northern Europe (Fig. 1).

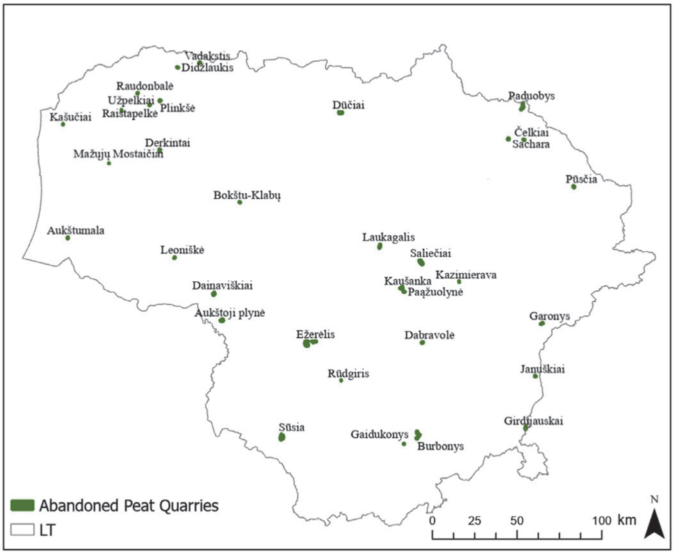

FIGURE 1. Distribution of abandoned peatlands in the territory of the country and location of the areas investigated during field research

Source: own work.

To identify and characterize degraded peatlands in forested areas across Lithuania, we first conducted a GIS-based spatial analysis to identify the spatial components of the peatlands (i.e., location, area, elevation). We used data from three national data sources: the Lithuanian mire and peatlands database (Agricultural Data Center [ŽŪDC], 2025), the cadastral database (Lithuanian State Forest Service [VMU], 2021), and the Lithuanian database of biodiversity (Valstybinė saugomų teritorijų tarnyba prie Aplinkos ministerijos [VSTT], 2025).

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The selection of the 33 abandoned peatland quarries was based on the presence of historical peat extraction data, spatial representation throughout Lithuania and a range of ecological conditions (i.e., peatland type, peat depth, water level, vegetation type, woody biomass, etc.) (Fig. 2).

FIGURE 2. Three samples of abandoned peatland quarries showing the range of ecological conditions found in Lithuania

Source: photos by J. Sendžikaitė.

Field investigations

The representative 33 abandoned peatland quarries were selected for field investigations, which were conducted between 2022 and 2023. At each site, we assessed peat depth, soil acidity (pH), carbon-to-nitrogen ratio (C : N), water table level (depth), and wood volume to determine the condition of the abandoned peatlands.

Peat depth was measured by applying a minimum of 10 sampling points along a standardized 100 m sampling transect using a standard peat corer following national peat survey guidelines (Saulėnas, 1993). We collected three samples at each site from the upper peat layer (5–15 cm) for laboratory analysis. The samples were analyzed for pH (measured in a 1 : 2.5 peat–water suspension), total organic carbon (by wet oxidation or spectrophotometry), and total Kjeldahl nitrogen, allowing us to calculate the C : N ratio. Trophic status (oligotrophic, mesotrophic, or eutrophic) was estimated based on the C : N and vegetation composition, following the classification system of Succow and Stegmann (2001), while the degree of peat decomposition was assessed in the field using the von Post humification scale (H1–H10).

Water table levels were recorded at the same locations as the peat depth measurements, and we supplemented the water table levels with long-term data from automated loggers at five sites (Aukštumala, Sachara, Pūsčia, Plinkšiai and Užpelkiai). Based on Koska et al. (2001), we classified site moisture regimes into six categories, from dry to lower eulittoral. For analysis, we used a threshold depth of 35 cm below the surface. Sites with an average water table deeper than this were considered to have unfavorable conditions for natural peat formation and thus considered degraded.

The analysis of wood volume on abandoned peatland quarries can help assess ecosystem recovery and carbon sequestration, as tree biomass reflects post--extraction succession. Increased wood volume also indicates peatland degradation, such as drying or nutrient enrichment, making it a useful but context-dependent indicator of peatland condition (Makrickas et al., 2023). Therefore, we used the cadastral database (VMU, 2021) to estimate the tree wood volume for each of the 33 abandoned peatland quarries.

Data analysis – principal component analysis

Using past statistics (Hammer, 2023) we normalized the five peatland characteristic data (peat depth, soil pH, C : N, water depth, and wood volume) and performed a multivariate principal component analysis (PCA) using a variance––covariance matrix. The PCA was performed to reduce the complexity of the dataset by transforming the five correlated environmental variables (C : N, pH, peat depth, water level and wood volume) into components that capture the main ecological gradients. We also performed a cluster analysis. These analyses produced a clearer visualization of site differences and identified key drivers like acidity, hydrology, and forest volume across peatland types.

Estimation of ecosystem service value

Peat

To evaluate the extent of peatland degradation, we estimated the volume of peat loss by comparing current and presumed natural historical surface elevations prior to peat extraction for each of the 33 sites. The analysis combined vector data representing peatland boundaries with raster-based surface elevation data.

Polygons delineating peatland areas in a shapefile format were used. For each site, a digital elevation model containing values representing the current peat surface altitude in meters above sea level was defined. All spatial data were projected to the Lithuanian Coordinate System of 1992 (LKS-92) to ensure geometric compatibility.

To estimate the original peat surface before drainage or subsidence, we used a two-meter buffer ring around each polygon. The outer buffer (expanded by 2 m) and the inner buffer (contracted by 2 m) defined a ring-shaped area approximating the undisturbed rim. The mean elevation value within this rim was taken as the reference historical surface level. The current average surface elevation was then calculated using raster values within each peatland polygon.

The difference between historical and current averages provided an estimate of surface lowering and thus the loss of peat through both extraction and subsequent subsidence following abandonment. Subsequently, we used the average peat market price of €116 per ton (t) to estimate the carbon loss value of each of the 33 peatlands (IndexBox, 2025).

We applied the following equation to estimate the value of peat loss: value [€] = = peat volume [m^3] × bulk density [$t \cdot m^{-3}$] × price [$€ \cdot t^{-1}$], where: bulk density is 0.1 $t \cdot m^{-3}$ and price is €116 per ton.

Water

To estimate the reduction in water retention capacity, we assumed that the field capacity of peat is up to 80% of its volume in water (Holden, 2005). Thus, every cubic meter of peat lost corresponds to 0.8 m^3 of water storage capacity lost. To provide an indicative economic value, we used a rate of €0.54 per m^3 of water, based on benefit transfer values from regional studies (e.g., Stachowicz et al., 2022; Makrickas et al., 2023). This allowed us to estimate the value of lost hydrological services. We emphasize that these estimates are general and should be treated as indicative rather than site-specific.

Carbon

Carbon loss from peat extraction was estimated by converting the volume of removed peat into dry mass, applying a carbon fraction, and expressing the result as both tons of carbon (t C) and carbon dioxide equivalents (t CO_2) using the following equations (Intergovernmental Panel on Climate Change [IPCC], 2014):

– Peat mass [kg] was calculated as: $M_{\text{peat}} = V \times \rho_{\text{peat}}$, where: V is peat volume [m^3] and ρ_{peat} is bulk density [$kg \cdot m^{-3}$].

– Carbon stock [t C] was then estimated as: $C = \frac{V \times \rho_{\text{peat}} \times fC}{1,000}$, where: *fC* is the carbon fraction of peat.
– Carbon dioxide equivalents [t CO_2] were derived as: $CO_2\,\text{eq.} = \frac{V \times \rho_{\text{peat}} \times fC}{1,000\left(\frac{44}{12}\right)}$,

where: ρ_{peat} is 100 kg·m^{-3} (mid-range of 60–150 kg·m^{-3}) (Parish et al., 2008) and carbon fraction (*fC*) is 0.50 (mid-range of 0.45–0.55) (Gorham, 1991; Joosten & Clarke, 2002).

It should be noted that this mid-range approach assumes uniform peat properties across the extracted peat quarries, as site-specific variability in bulk density or decomposition state was not available. It also represents carbon removed as stock (Turetsky et al., 2015). This stock-based approach is widely applied in peatland carbon accounting when direct flux data are lacking (Gorham, 1991; Joosten & Clarke, 2002; Turetsky et al., 2015).

Finally, we used the average carbon dioxide emission market price of €57.24 (VICAP) (from 1 January 2024 to 5 September 2025) to estimate the carbon loss value of each of the 33 peatlands (International Carbon Action Partnership [ICAP], 2025).

Rewetting

Rewetting represents a fundamental initial phase of peatland restoration, undertaken to enhance the provision of ecosystem services and their contributions to human well-being (Stachowicz et al., 2022). In drained peatlands, this process is primarily achieved through the closure of anthropogenic drainage networks. Therefore, we estimated the cost (€2,400 per ha) to rewet the 33 abandoned peatland quarries, following Stachowicz et al. (2022) and Makrickas et al. (2023).

Results and discussion

Peat properties and ecological status of studied sites

A total of 33 peatland sites (3,854 ha) were assessed, displaying a broad range of ecological conditions (Fig. 2). Despite historical peat extraction, all still contain at least 30 cm of peat and thus meet the formal definition of peatland. The mean peat depth varied from as little as 0.5 m (Saliečiai) to a maximum of 7 m (Užpelkiai), with the majority clustered around 2 m. This indicates that large volumes of peat are still present (Table 1).

The examination of water levels across 33 peatland sites indicates that the majority exhibit low hydrological conditions, with 14 sites (42%) falling into the lowest category, "2–", suggesting considerable drainage. Intermediate water levels (categories "2+" to "3+") are observed in 13 sites (39%), while only six peatlands (18%) demonstrate high water levels rated as "4+". Notably, all sites with a water level of "4+" have been classified as being in satisfactory condition, and several have undergone restoration. Notably, peatlands such as Aukštumala, Plinkšė, Pūščia, Sachara and Užpelkiai have undergone restoration, displaying higher water levels. This pattern suggests a clear relationship between restoration efforts and improved hydrological conditions, underlining the importance of active water level management in peatland conservation and carbon retention strategies (Table 1).

Soil acidity, measured as pH, ranged from very acidic (pH 2.73 in Plinkšiai) to near-neutral values (pH 7.00 in Girdijauskai), indicating diverse geochemical profiles. However, most pH samples were below 4.5, particularly in sites originally classified as raised bogs (Table 1).

The carbon-to-nitrogen ratio, a proxy for peat decomposition and quality, spanned from 20.6 (Paduobys) to 83.0 (Vadakstis), with higher values often associated with lower peat mineralization. Most sites also showed high C : N, suggesting low nutrient availability and slow decomposition. Peat decomposition ranged from weak (H3) in wetter areas to moderate or strong (H6–H7) in more degraded locations. Many samples fell in the H4–H5 range, which reflects ongoing aerobic decay due to low water tables (Table 1). Oligotrophic peatlands typically exhibit low pH values (< 4.2) and are dominated by acid-tolerant, nutrient-poor vegetation. Mesotrophic sites showed intermediate pH values (4.2–5.5) and supported a more diverse flora, including brown mosses and sedges (Jarašius et al., 2022). Eutrophic peatlands were identified by higher pH levels (> 5.5) and the presence of nutrient-demanding species such as *Carex*, *Phragmites*, and/or *Typha*. Together, these indicators provided insight into both the nutrient regime and the degree of peat decomposition at each site.

Aboveground woody biomass ranged widely, from 10.18 $m^3 \cdot ha^{-1}$ (Aukštumala) to 207.93 $m^3 \cdot ha^{-1}$ (Rūdgiris), reflecting both natural forest development and afforestation in some sites. Several sites in poor peatland condition (i.e., Sachara) were also recorded with high wood volumes. This raises concerns about the role of spontaneous tree encroachment in inhibiting restoration outcomes (Table 1).

TABLE 1. Overview of the peatland characteristic of the 33 extracted quarries in Lithuania

Peatland	Peatland type	Area [ha]	Mean peat depth [m]	pH	C : N	Water level	Wood volume [$M^3 \cdot ha^{-1}$]	Ecological condition	Restoration
Aukštoji plynė	raised bog	190	2.0	3.29	53.1	2−	124.82	bad	
Aukštumala	raised bog	66	2.0	3.06	55.0	3+	10.18	satisfactory	yes
Bokštų – Klabų	fen / transitional mire	48	2.0	3.55	47.2	2−	90.76	bad	
Burbonys	raised bog	225	1.6	3.13	64.5	2−	69.57	bad	
Čelkiai	fen	65	2.0	3.28	73.8	2−	130.75	bad	
Dabravolė	raised bog	71	2.0	2.95	60.0	2−	102.50	bad	
Dainaviškiai	raised bog	153	2.0	3.19	58.2	2+	206.96	satisfactory	
Derkintai	fen / transitional mire	75	2.0	6.05	25.0	4+	69.90	satisfactory	
Didžlaukis	fen / raised bog	63	1.4	3.03	72.8	2−	63.07	bad	
Dūčiai	fen / transitional mire	185	0.7	5.62	27.3	2−	64.65	bad	
Ežerėlis	fen / transitional mire	581	1.0	3.08	38.7	2−	82.43	bad	
Gaidukonys	fen	26	2.0	3.28	42.9	3+	157.13	satisfactory	
Garonys	raised bog	80	2.5	3.04	70.3	2+	54.47	bad	
Girdijauskai	fen	84	1.8	7.00	20.7	3−	17.79	bad	
Januškiai	fen	60	2.0	5.76	26.0	4+	75.75	satisfactory	
Kašučiai	raised bog	20	1.2	3.22	47.9	2−	121.41	bad	
Kaušanka	fen / raised bog	88	2.0	4.39	56.0	2−	110.20	bad	
Kazimierava	raised bog	19	2.0	2.82	56.1	3+	114.29	satisfactory	
Laukagalis	raised bog	144	1.7	4.48	46.9	2−	75.38	bad	
Leoniškė	raised bog	52	1.4	3.35	72.1	4+	125.46	satisfactory	
Mažieji Mostaičiai	fen	10	1.0	3.74	23.8	3−	148.50	satisfactory	
Paąžuolynė	raised bog	55	2.0	3.31	42.4	2+	119.32	satisfactory	
Paduobys	fen	268	1.5	5.56	20.6	2+	79.26	satisfactory	
Plinkšė	raised bog	70	2.0	2.73	68.2	3+	85.83	satisfactory	yes
Pūščia	raised bog	87	6.0	3.56	52.2	3+	73.42	satisfactory	yes
Raistapelkė	transitional mire	44	2.0	5.56	23.3	4+	41.78	satisfactory	
Raudonbalė	raised bog	36	2.0	3.06	61.1	2+	114.87	satisfactory	
Rūdgiris	raised bog	21	2.0	3.34	32.6	2+	207.93	satisfactory	
Sachara	raised bog	93	1.5	2.84	62.1	3+	121.04	satisfactory	yes
Saliečiai	fen	345	0.5	4.37	39.7	2−	94.42	bad	
Sūsia	fen	455	1.2	4.37	39.7	2−	60.10	bad	
Užpelkiai	raised bog	17	7.0	3.55	37.6	4+	23.45	satisfactory	yes
Vadakstis	raised bog	58	2.0	3.45	83.0	3+	71.23	bad	
Total area		3,854							

Source: own work.

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Peatland condition was classified as "satisfactory" for 17 sites and "bad" for 16, suggesting that nearly 50% of sites remain heavily degraded with deep drainage, heavily decomposed peat, and dominance of non-peat-forming vegetation. This was supported by water level data, where most degraded sites exhibited a low water table (2−), potentially limiting peat-forming processes, increasing GHG emissions and forming unnatural mire vegetation communities. The 16 peatlands deemed satisfactory were nonetheless moderately degraded but retained patches of semi-natural vegetation or higher water levels. None of the sites were in a good or near-natural condition. Restoration measures were reported in only a few sites, notably Aukštumala, Plinkšė, Pūsčia, Sachara, and Užpelkiai, highlighting the limited but targeted application of rewetting efforts (Table 1). Both the least disturbed sites and rewetted sites require further active restoration efforts to recover peat-forming processes.

Principal component analysis

The results of the PCA analysis showed that the first two principal components (PC1 and PC2) accounted for a cumulative 67.83% of the total variance, with PC1 explaining 37.98% and PC2 explaining 29.85%. The remaining components contributed progressively less, with PC3, PC4, and PC5 explaining 17.68%, 10.66%, and 3.83%, respectively (Table 2).

PC1 was primarily associated with C : N (loading = 0.617) and pH (loading = −0.682), indicating a strong gradient between organic matter quality and acidity. PC2 was dominated by peat depth (0.702) and water level (0.618), reflecting hydrological and vertical structural variation across sites. PC3 was most influenced by wood volume (0.749), suggesting a link to forest biomass accumulation. The remaining components (PC4 and PC5) showed mixed contributions but were less influential in explaining overall variance (Table 3).

TABLE 2. Summary result values from the principal component analysis

PC	Eigenvalue	Variance [%]
1	1.899	37.982
2	1.492	29.852
3	0.883	17.675
4	0.533	10.663
5	0.191	3.827

Source: own work.

TABLE 3. Summary result values from the principal component analysis loading values

Specification	PC1	PC2	PC3	PC4	PC5
C : N	0.617	0.023	−0.423	0.312	0.584
pH	−0.682	0.011	0.097	0.151	0.709
Peat depth	0.077	0.702	−0.050	−0.673	0.214
Water level	0.110	0.618	0.498	0.591	−0.097
Wood volume	0.368	−0.352	0.749	−0.280	0.317

Source: own work.

The biplot (Fig. 3) illustrates the spatial distribution of the sampling sites and variable loadings. Sites with high C : N and low pH values were clustered along the positive axis of PC1, while deeper peat and higher water levels aligned with a positive PC2. Wood volume showed a strong association with PC3 and was orthogonal to the hydrological gradient, indicating distinct ecological drivers.

Overall, the PCA revealed clear separation among peatland types based on chemical, hydrological, and structural attributes, supporting the classification of peatland condition and guiding restoration prioritization.

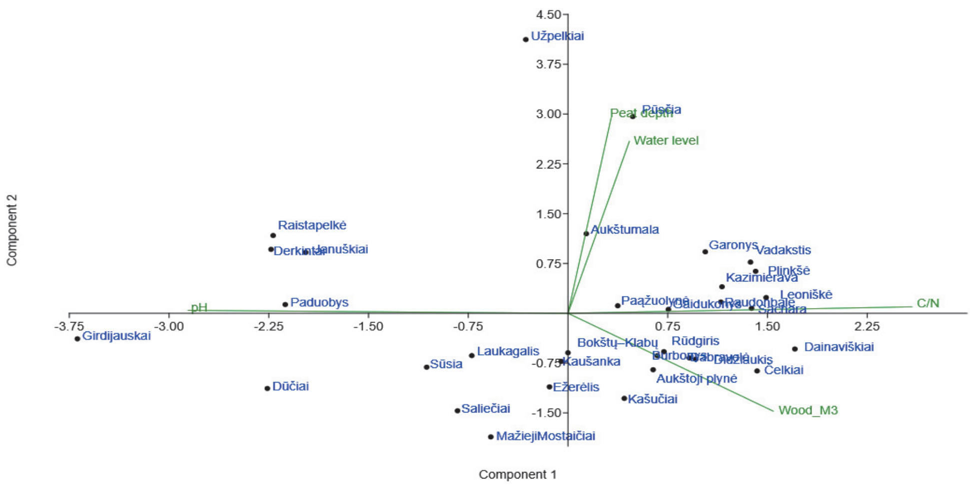

FIGURE 3. Results from principal component analysis based on variance-covariance matrix analysis of 5 variables representing 33 peatlands in Lithuania

Source: own work.

Visual inspection of the dendrogram from the hierarchical cluster analysis (Fig. 4) revealed distinct groupings among the peatland sites based on environmental variables. The hierarchical cluster analysis identified four major groupings among the 33 peatland sites, based on environmental variables such as C : N, water level, peat depth and wood volume. Dividing the dendrogram at a linkage distance of approximately seven revealed the following clusters:

- Cluster 1 (9 sites): Includes Paduobys through to Sūsia peatlands (see: Fig. 4). These sites share similar topographic, hydrological and pH characteristics, likely representing moderately degraded peatlands with spontaneously revegetated vegetation.
- Cluster 2 (2 sites): The Pūsčia and Užpelkiai peatlands, characterized by relatively intact peatland conditions, with consistent water regimes and a deeper peat depth.
- Cluster 3 (8 sites): Includes the Dainaviškas – Leoniškė peatlands. These sites appear to occupy an intermediate ecological position, possibly reflecting mixed land use impacts and variable restoration potential with similar C : N and wood volumes.
- Cluster 4 (14 sites): Includes the Kašučiai – Garonys peatlands. These peatlands are more ecologically distinct, showing signs of advanced degradation and disturbed hydrological regimes with increased seasonal variability and impaired water retention capacity.

This four-cluster PCA result provides a clearer ecological stratification of the former peatland quarry sites, thus offering a valuable framework for prioritizing conservation and restoration efforts based on shared site characteristics (Fig. 4).

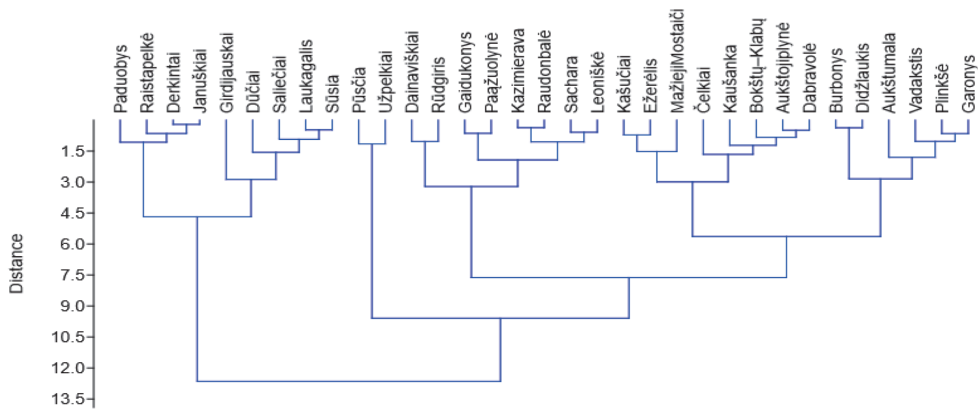

FIGURE 4. Results of the cluster analysis identified four main peatland clusters; from left to right, these represent clearer ecological stratification of the peatland sites

Source: own work.

Estimation of ecosystem service value associated with peat extraction

Peat

The assessment of the 33 abandoned Lithuanian peatland sites subjected to peat extraction revealed significant peat removal, surface subsidence, and volume reduction (Table 4). The average surface lowering ranges from 0.03 m (Dainaviškiai) to 4.97 m (Paduobys), with a mean lowering of approx. 1.81 m. These vertical losses reflect the cumulative effects of mechanical extraction, drainage, and compaction over time. The resulting peat volume losses are substantial, with site-specific estimates ranging from 33,261 m^3 (Mažieji Mostaičiai) to over 8.3 million m^3 (Saliečiai). Major extraction sites such as Saliečiai and Sūsia have each lost more than 12 million m^3 of peat, primarily due to their large surface areas and sustained extraction intensity. Collectively, the total peat volume loss across all surveyed peatlands exceeds 53.4 million m^3, underscoring the extensive alteration of peatland morphology and carbon storage capacity resulting from industrial-scale extraction activities. In addition to direct removal, long-term drainage and peat oxidation have contributed to continued surface subsidence, a process typically occurring at rates of approx. 0.5–2.0 cm annually in peatlands (Grzywna, 2017; Oleszczuk et al., 2022; Ghezelayagh et al., 2024). However, given that the lowering in the analyzed sites reaches 4.97 m, this natural subsidence component represents only a minor share of the total vertical loss.

Water

Peatland drainage and peat extraction lead to both physical removal of organic material and significant water volume loss, as peatland drainage lowers the water table and accelerates oxidation (Table 4). Across the 33 sites, estimated water volume losses range from 26.6 m^3 (Mažieji Mostaičiai) to over 6.6 million m^3 (Saliečiai). The total estimated water volume lost across all extraction sites is close to 62 million m^3, reflecting both direct hydrological drainage and secondary subsidence impacts. These losses illustrate the extensive hydrological disruption caused by peat extraction and emphasize the need for post-extraction rewetting and ecological restoration to mitigate further degradation and re-establish peatland functions.

Carbon

The analysis of the 33 abandoned peatland quarries revealed highly variable carbon losses and associated economic values (Table 4). Individual carbon stock losses ranged from as low as 5,355 t C at Leoniskė to over 666,352 t C at Paduobys.

This carbon loss translates into a wide range of estimated carbon values, from €19,636 at Leoniskė to more than €139.9 million at Paduobys. These results underline both the scale of past carbon emissions and the significant potential economic value of restoring and conserving remaining peat carbon stocks.

Rewetting

The rewetting cost estimates for the 33 abandoned peatland quarries show large variation across sites, reflecting differences in areas and degradation extents (Table 4). The largest peatlands, such as Paduobys (2.67 million m^2) and Plinkšė (3.5 million m^2), have correspondingly high estimated rewetting costs of €642,948 and €1.06 million, respectively. In contrast, smaller peatlands such as Mažieji Mostaičiai (101,278 m^2) and Kašučiai (19,583 m^2) require far lower investments of only €24,307 and €34,575, respectively. Several medium-sized sites, like Burbonys (2.24 million m^2) and Kazimierava (187,681 m^2), show intermediate costs (€539,780 and €45,043, respectively). These results highlight how peatland size strongly influences the estimated financial needs for restoration through rewetting.

Balance

The analysis of 33 abandoned peatland quarries revealed substantial peat, water, and carbon loss (Table 4). Across a total surveyed area of 3.85 million m^2, peat volume loss amounted to approx. 77.5 million m^3, accompanied by a water volume loss of 61.9 million m^3. The estimated carbon stock loss reached 3.87 million t C. This is equivalent to 14.2 million t CO_2 emissions. In economic terms, the total value of peat loss was estimated at €898.8 million, with additional losses of €33.5 million in water and €813.1 million in carbon. The costs associated with rewetting all 33 abandoned peatland quarries were estimated at €9.25 million, resulting in a net balance of approx. €42.97 million. These results highlight both the magnitude of the historic degradation and the considerable potential benefits of restoration for climate mitigation and ecosystem service recovery.

It should be noted that the extrapolation of peat loss and subsidence is a complex task due to its nonlinearity (Ikkala et al., 2021) and the different subsidence dynamics in forested versus agricultural peatlands (Liu et al., 2020). Moreover, the analysis of ecosystem services only focused on the once-off loss of peat extraction and rewetting, but not the scale and accumulated losses since abandonment or benefits of rewetting. As an example, the abandonment of peatland ranged from 1940 to 2020, and some peatlands are under restoration. Thus, our general estimates are a transient process.

TABLE 4. Estimated peatland extraction losses in terms of volume and monetary value for peat, water and carbon

Peatland	Area [m^2]	Average lowering [m]	Peat volume lost [m^3]	Water volume lost [m^3]	Carbon stock [t C]	CO_2 eq. [t CO_2]	Peat value [€]	Water value [€]	Carbon value [€]	Rewetting [€]	Balance [€]
Aukštoji plynė	1,897,398	0.99	1,884,403	1,507,522	94,220	345,477	21,859,073	814,062	19,775,104	455,376	814,532
Aukštumala	660,029	1.00	660,029	528,023	33,001	121,006	7,656,336	285,132	6,926,407	158,407	286,390
Bokštų – Klabų	479,576	0.50	239,788	191,830	11,989	43,962	2,781,541	103,588	2,516,358	115,098	46,496
Burbonys	2,249,084	2.68	6,020,396	4,816,317	301,020	1,103,749	69,836,588	2,600,811	63,178,605	539,780	3,517,392
Dabravolė	707,745	0.40	280,998	224,798	14,050	51,517	3,259,575	121,391	2,948,818	169,859	19,507
Dainaviškiai	1527519	0.03	4,8171	38,537	2,409	8,831	558,784	20,810	505,511	366,605	−334,142
Derkintai	753,770	3.35	2,527,243	2,021,794	126,362	463,332	29,316,019	1,091,769	26,521,129	180,905	1,522,216
Didžlaukis	628,759	0.66	412,802	330,242	20,640	75,681	4,788,508	178,331	4,331,988	150,902	127,287
Dūčiai	1,854,022	2.36	4,379,285	3,503,428	218,964	802,876	50,799,706	1,891,851	45,956,635	444,965	2,506,255
Ežerėlis	5,809,552	0.60	3,485,731	2,788,585	174,287	639,057	40,434,482	1,505,836	36,579,596	1,394,292	954,758
Garonys	803,448	2.68	2,1503,21	1,720,257	107,516	394,229	24,943,727	928,939	22,565,676	192,828	1,256,284
Geidukonys	262,586	0.83	217,177	173,741	10,859	39,816	2,519,249	93,820	2,279,073	63,021	83,336
Girdijauskai	837,204	2.95	2,468,046	1,974,437	123,402	452,479	28,629,331	1,066,196	25,899,908	200,929	1,462,298
Januškiai	603,841	3.51	2,120,003	1,696,002	106,000	388,671	24,592,035	915,841	22,247,514	144,922	1,283,758
Kašučiai	198,535	0.62	122,455	97,964	6,123	22,450	1,420,478	52,901	1,285,054	47,648	34,875
Kaušanka	878,596	2.24	1,971,236	1,576,989	98,562	361,397	22,866,339	851,574	20,686,340	210,863	1,117,562
Kazimierava	187,681	3.15	591,366	473,093	29,568	108,418	6,859,844	255,470	6,205,850	45,043	353,481
Laukagalis	1,441,621	0.87	1,246,935	997,548	62,347	228,607	14,464,446	538,676	13,085,455	345,989	494,326
Leoniškė	521,081	0.21	107,104	85,683	5,355	19,636	1,242,406	46,269	1,123,959	125,059	−52,882
Mažieji Mostaičiai	101,278	0.33	3,3261	26,609	1,663	6,098	385,828	14,369	349,044	24,307	−1,892
Čelkiai	649,624	2.78	1,805,635	1,444,508	90,282	331,036	20,945,370	780,035	18,948,510	155,910	1,060,916
Paąžuolynė	552,464	2.61	1,443,053	1,154,443	72,153	264,562	16,739,416	623,399	15,143,537	132,591	839,889
Paduobys	2,678,952	4.97	13,327,034	10,661,627	666,352	2,443,312	154,593,594	5,757,279	139,855,166	642,948	8,338,201
Plinkšė	697,250	0.50	349,546	279,637	17,477	64,084	4,054,733	151,004	3,668,168	167,340	68,221
Pūsčia	871,503	3.46	3014,593	2,411,674	150,730	552,680	34,969,276	1,302,304	31,635,424	209,161	1,822,387
Raistapelkė	442,392	2.54	1,121,856	897,485	56,093	205,675	13,013,528	484,642	11,772,863	106,174	649,850
Raudonbalė	356,677	0.29	104,145	83,316	5,207	19,093	1,208,077	44,990	1,092,903	85,602	−15,419
Rūdgiris	208,626	3.05	635,275	508,220	31,764	116,468	7,369,194	274,439	6,666,640	50,070	378,045
Sachara	925,314	0.87	801,704	641,363	40,085	146,980	9,299,763	346,336	8,413,155	222,075	318,196
Saliečiai	3,446,981	3.48	11,995,418	9,596,335	599,771	2,199,180	139,146,849	5,182,021	125,881,061	827,275	7,256,492
Sūsia	4,552,531	2.42	11,040,897	8,832,718	552,045	2,024,183	128,074,405	4,769,668	115,864,226	1,092,607	6,347,904
Užpelkiai	169,299	1.74	293,655	234,924	14,683	53,837	3,406,401	126,859	3,081,647	40,632	157,264
Vadakstis	580,904	1.00	580,346	464,277	29,017	106,398	6,732,015	250,710	6,090,208	139,417	251,681
Total	38,535,842	1.81	77,479,906	61,983,925	3,873,995	14,204,779	898,766,915	33,471,320	813,081,530	9,248,602	42,965,463

Source: own work.

Manton, M., Grigaliūnas, V., Jarašius, L., Sendžikaitė, J., Tamulaitytė, G., Grodzka-Łukaszewska, M. (2025). Drained and forgotten peat extraction sites: economic and carbon impacts of peat and water loss in spontaneously forested Lithuanian peatlands. *Sci. Rev. Eng. Env. Sci.*, *34* (4), 376–397. DOI 10.22630/srees.10809

Conclusions

This study highlights the scale of ecological and climate-related degradation associated with abandoned peat extraction sites in Lithuania. Despite the end of mining activities in many of these areas, they remain in a drained state that continues to drive peat loss, carbon emissions, and limited ecosystem function.

Our main findings are:

– Peat loss estimates from extraction at 33 abandoned peatland quarries totaled 77.5 million m^3, which equates to a current value of €899 million in revenue. Nonetheless, the abandoned peatland quarries still host peat deposits ranging from 0.5 m to 2 m in average depth. Thus, rewetting is needed.
– The drying and degradation of peatlands also reduced the water storage capacity across the 33 study sites, with an estimated loss of approx. 62 million liters of water, equaling approx. €33 million. This affects local hydrology and increases the vulnerability to drought, fire, flood and natural biodiversity.
– Soil carbon losses from these sites are substantial. We estimate approx. 14.2 t CO_2 emissions equaling €813 million were lost from peat extraction alone. These emissions are largely unaccounted for in land-use sector reporting and undermine climate targets.
– The rewetting of the 33 abandoned peatland quarries is estimated to cost approx. €9.2 million. Given these findings, we argue that rewetting and restoring Lithuania's drained peatlands should be a clear environmental priority. Blocking drainage ditches, raising water tables, and reintroducing peat-forming vegetation would help halt further degradation. Over a long timeframe, these sites could shift from being net carbon sources to functioning wetlands that support biodiversity and store water. This creates an opportunity to align restoration efforts with conservation policies and EU climate goals. Our results support current EU initiatives that call for the restoration of organic soils, particularly under the Nature Restoration Law and rules for the land use, land-use change and forestry (LULUCF) (Regulation (EU) 2018/841).

In conclusion, "drained and forgotten" peatlands are hotspots of avoidable carbon and water service loss. Restoration offers a clear, cost-effective path to reversing this trend. By quantifying peat loss, carbon emissions, and hydrological impacts, this study provides the evidence base needed to support targeted, science--based restoration strategies. We recommend prioritizing the rewetting of these areas within national and EU restoration programs, and monitoring outcomes to track improvements in carbon and water dynamics over time.

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Summary

Drained and forgotten peat extraction sites: economic and carbon impacts of peat and water loss in spontaneously forested Lithuanian peatlands. This study examines the condition and environmental impact of abandoned peatland quarries in Lithuania. Using spatial data and field investigations, we identified 33 abandoned peat quarry sites covering over 3,854 ha, which were abandoned between 1940 and 2020. Detailed field assessments were conducted at each abandoned peatland quarry to evaluate the peat depth, pH, carbon-to-nitrogen ratio, decomposition, water table levels, and wood volume. Despite past extraction, many sites still contain substantial peat layers along with significant carbon and water storage potential. However, ongoing drainage continues to drive peat loss and carbon dioxide emissions. We estimate that peat loss from extraction totaled 77.5 million m^3, which equates to a current value of €899 million in revenue. Nonetheless,

the abandoned peatland quarries still host peat deposits ranging from 0.5 m to 2 m in depth. The drying and degradation of the peatlands has also reduced the water storage capacity across the 33 study sites. This loss is estimated at approx. 62 million liters of water, which equals approx. €33 million. This substantially affects local hydrology and increases the vulnerability to drought, fire, flood and natural biodiversity. Carbon emissions from drained peat soils are also substantial. We estimate approx. 14.2 t CO_2 emissions equaling €813 million were lost from peat extraction alone. These emissions are often unreported if such areas are classified simply as “forests.” Our findings highlight the need for active restoration, particularly rewetting, to stop further degradation. Rewetting would reduce emissions, improve water retention, and support biodiversity recovery while offering clear opportunities to align peatland restoration with EU climate and nature goals.