Journal of Environmental Management 341 (2023) 117952

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Trading wood for water and carbon in peatland forests? Rewetting is worth more than wood production

Evaldas Makrickas[a], Michael Manton[a,*], Per Angelstam[b,c], Mateusz Grygoruk[d]

[a] Vytautas Magnus University, Faculty of Forest Sciences and Ecology, Studentu Str. 11, Akademija, Kauno r., 53361, Lithuania
[b] Inland Norway University of Applied Sciences, Faculty of Applied Ecology, Agricultural Sciences and Biotechnology, 2480, Evenstad, Norway
[c] Swedish University of Agricultural Sciences (SLU), Faculty of Forest Sciences, School for Forest Management, PO Box 43, 73921, Skinnskatteberg, Sweden
[d] Institute of Environmental Engineering, Warsaw University of Life Sciences-SGGW, ul. Nowoursynowska 166, 02-787, Warsaw, Poland

ARTICLE INFO

Keywords:
Carbon storage
Economic indicators
Environmental indicators
Ecosystem services
Forest management
Water retention
Wetlands

ABSTRACT

While traditional forest management systems aim at maximizing timber production, sustainable forest management focuses on the multiple benefits of entire forest landscapes. The latter is now at the top of policy agendas. This calls for learning through evaluation to support the implementation of policies aiming towards multi-functional forest landscapes. The aim of this study is to quantify the economic trade-offs among natural, current, and re-wetted peatland forests using seven indicators, *viz.* drainage maintenance, rewetting, water retention, wood production, and three types of carbon sequestration as economic indicators. We discuss ways to adapt to and mitigate effect of forest draining on climate change toward securing multi-functional forest landscapes. The cost benefit analysis showed that in a potential natural state, Lithuania's peatland forests would deliver an economic benefit of ~€176.1 million annually. In contrast, compared to natural peatland forests, the drainage of peatland forests for wood production has caused a loss of ~€309 million annually. In comparison, peatland forest rewetting is estimated to increase the economic value by ~€170 million annually. This study shows that satisfying different ecosystem services is a balancing act, and that a focus on wood production has resulted in net losses when foregone values of water storage and carbon sequestration are considered. Valuation of different sets of ecosystems service benefits and disservices must be assessed, and can be used as a tool towards creating, implementing and monitoring consequences of policies on both sustainability and biodiversity.

1. Introduction

Landscapes are social-ecological systems that provide goods, services and benefits required for human well-being. Society has become more environmentally aware of the critical issues arising from intensive landscape management, as well as the role societal commitment contributes towards landscape conservation and improving environmental quality (Bibri, 2021). Nevertheless, the increasing human footprint on forest landscapes illustrates that the demands for benefits may exceed their capacity (Felton et al., 2020; Lindahl et al., 2017). This represents a wicked problem (Nikolakis and Innes, 2020), which requires knowledge production, learning, and to transform traditional habits and routines to meet current and future needs (Angelstam et al., 2018). For a long time, land management has been related to the yield of crops, wood and other renewable goods at the expense of natural patterns and processes that support biodiversity conservation, and provide other benefits for human well-being (Angelstam et al., 2022).

This has triggered shifts in policies that promote conservation, restoration, and sustainable use of forest landscapes (Convention on Biological Diversity, 2010, 2022; European Commission, 2013, 2019, 2020, 2021). Additionally, under the Paris Agreement (United Nations, 2015), EU member states have committed to significantly reducing greenhouse gas (GHG) emissions, which led to legislative amendments that propose to reduce carbon emissions by 55% by 2030. According to FAO (2022), there are three interrelated forest management pathways that can sustain both economic benefits and environmental recovery of forest ecosystems. These are (1) halting deforestation and maintaining existing natural forests; (2) restoring degraded forest land; and (3) sustainably using forests and building green value chains. As outlined in the EU's forest strategy (European Commission, 2021), this includes

---

* Corresponding author.

E-mail addresses: evaldas.makrickas@vdu.lt (E. Makrickas), michael.manton@vdu.lt (M. Manton), per.angelstam@inn.no (P. Angelstam), mateusz_grygoruk@sggw.edu.pl (M. Grygoruk).

https://doi.org/10.1016/j.jenvman.2023.117952
Received 6 February 2023; Received in revised form 12 April 2023; Accepted 14 April 2023

improving water quality, water retention, nutrient filtration, carbon storage, and the maintenance of biodiversity by applying closer-to-nature forest management (Larsen et al., 2022). Thus, the sustainable management of forests is not only about the production of timber, but entails maintaining multi-functional forest landscapes . Moreover, this policy development has triggered a hot debate on how to manage forests sustainably for the future (Larsen et al., 2022; Tadesse et al., 2022).

The ecosystem services approach emphasizes that forest landscapes provide an important range of goods, services and values, and that improved landscape management is needed to safeguard their benefits (TEEB, 2010). Peatlands sequester and store more carbon than any other type of terrestrial ecosystem, including the global above-ground carbon stock of forest ecosystems (Dunn and Freeman, 2011). However, peatland forests have sustained unprecedented degradation and loss in the drive for timber production (Manton et al., 2021; Tanneberger et al., 2021). This includes the draining of peatlands which impairs hydrological processes (Stachowicz et al., 2022), modifies energy flows, nutrient cycles, and GHG emissions (Escobar et al., 2022), and causes losses in biodiversity (Lõhmus et al., 2015; Tanneberger et al., 2021), peat subsidence and negatively impacts on human well-being (Joosten et al., 2017; Tanneberger et al., 2017). GHG emissions from drained peatlands are estimated to constitute about five percent of the global CO_2 emissions caused by human activities (IPCC, 2014; Tanneberger et al., 2017). The disservices of drained peatlands continue to increase until they are re-wetted and restored. Rewetting peatland forests is key towards mitigating climate change, conserving biodiversity, and improving human well-being (Joosten et al., 2016; Kløve et al., 2017; Nyberg et al., 2022). Thus, producing knowledge on the maintenance of peatlands, including natural, drained, re-wetted states is a management priority towards a sustainable future for forest ecosystem resilience (FAO, 2020).

The aim of this study is to quantify the economic trade-offs among natural, current, and re-wetted peatland forests using seven indicators, *viz.* drainage maintenance, rewetting, water retention, wood production, and three types of carbon sequestration as economic indicators. We discuss the opportunity to shift from wood production to rewetting, the sensitivity of the analysis and new portfolios of management and governance drivers.

2. Materials and methods

2.1. Case study area and framework

Lithuania was chosen as a case study (e.g., Yin, 2014) because it is a country that is at the crossroad between continuing traditional forest management for sustained yield wood production and meeting European Commission's policy (e.g., European Commission, 2019, 2021) supporting the development of multi-functional forest that deliver a variety of ecosystems services.

Lithuania has two main social-ecological system gradients. First, it is located in the hemi-boreal forest transition zone (Fig. 1) between the temperate ecoregion to the south and the boreal ecoregion to the north (Ahti et al., 1968; Manton et al., 2022). The Lithuanian landscape is relatively flat, ranging from sea level to 293 m in altitude (National Land Service, 2017). Peatlands cover ~10% (650 000 ha) of the country, and of these ~70% are drained (470 000 ha) (Jarašius et al., 2015; Valatka et al., 2018). Second, Lithuania's occupation by the USSR from WW2 to 1990 triggered the prohibition of private land ownership and creation of cooperative state-owned farms (Plakans, 2011). This led to industrialized agriculture and forestry, and created an invasive freshwater drainage network to enhance production of food, feed, and fiber (Povilaitis et al., 2011). In 1990, Lithuania regained its independence and began the transition to an open market economy through the restitution of private land ownership (Brukas, 2015).

Lithuania's total forest land area is ~2 200 200 ha (~34% of the country) (State Forest Service, 2021b). Scots pine (*Pinus sylvestris)* forms the dominant species (34%) followed by silver birch (*Betula pendula*) 22%, Norway spruce (*Picea abies*) 21%, alder (*Alnus glutinosa* and *A. incana*) 14%, aspen (*Populus tremula*) 5%, oak (Q*uercus robur*) 2%, ash

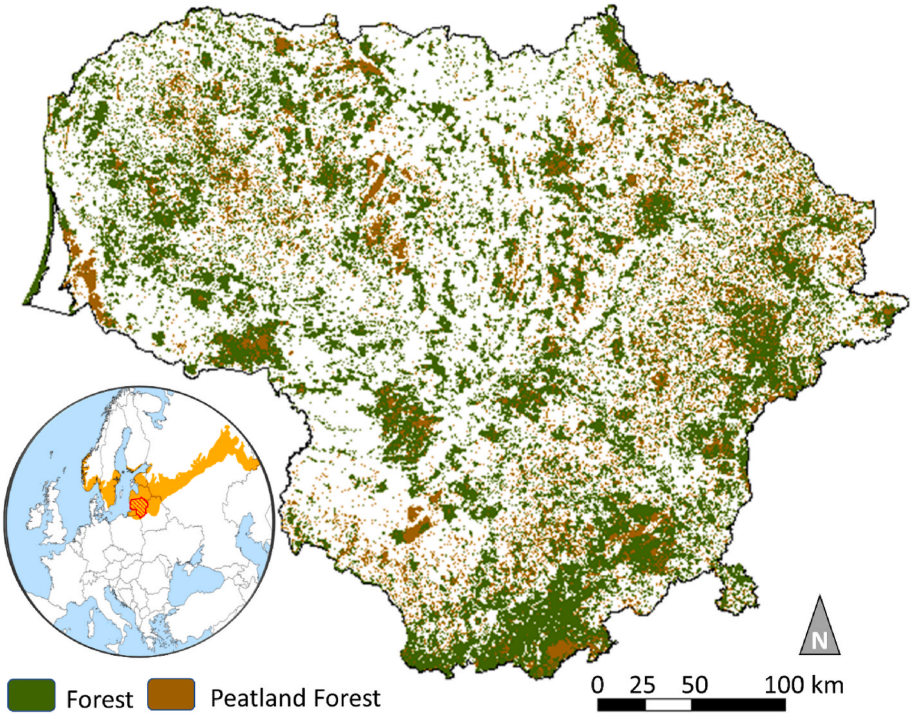

Fig. 1. Map showing Lithuania's forests, and both semi-natural and drained peatland forests (State Forest Service, 2021a). The insert map shows Lithuania's position (red) in the European hemiboreal forest zone (orange). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(*Fraxinus excelsior*) 1%, and other species 1%. The mean growing stock volume is 238 m^3/ha, total growing stock volume 552 million m^3, and ~7.2 million m^3 of timber is harvested annually (State Forest Service, 2020). In total, the forestry sector contributes 4.4% to Lithuania's GDP (State Forest Service, 2021b).

We used a five-step process (Fig. 2) to 1) identify the area of peatland forest, the area of peatland forest affected by drainage and the length of the drainage ditch networks, 2) estimate the costs of maintaining the drainage system vs. rewetting construction costs, 3) quantify the economic value of wood, water and carbon for three peatland forest states and, 4) undertake a cost benefit analysis of peatland forest area, and 5) to discuss the economic trade-offs of natural vs. current vs. rewetted peatland forests.

2.2. *Analyses of peatland forests and drainage*

We used three Lithuanian spatial data sets to identify the current amount of peatland forest and the area of undrained (natural) and drained peatland forests, using GIS. We applied five approaches using three data sets to identify the state of Lithuania's different peatlands (Table 1).

2.3. *Estimation of drainage maintenance and rewetting costs*

Regardless of the action taken by management, in terms of business as usual for wood production or the rewetting of peatland forests, a range of management costs are involved. For instance, wood production needs the drainage systems of peatland forests to be maintained to acquire optimal soil moisture for sustained maximum tree growth (Finér et al., 2018; Povilaitis et al., 2015). Whereas, the restoration of drained peatlands, first and foremost requires the re-creation of the topsoil with high-water saturation (Andersen et al., 2017). This is an inherent initial restoration action. Rewetting usually implies the blocking of ditches and/or the construction of barriers that reduces the drainage influence of ditches and drains. Therefore, we analyzed both the cost to maintain the drainage system of peatland forests, and the cost of rewetting drained peatlands through ditch blocking.

Because the hydrological waterways and drainage data (National Land Service, 2021) provides the best available spatial data on waterways and drainage for Lithuania, we used the results from approach 3 (Table 1) to calculate the total, average and maximum length of the non-natural drains that intersect the National forest database (State Forest Service, 2021a). There was no other available spatial data identifying waterways and drains data.

2.3.1. *Maintenance of the peatland forest drainage*

The continuous succession of trees, bushes, and shrubs; land subsidence, rubbish dumping, and beaver (*Castor fiber*) activity, diminish the efficiency of forest draining systems. Therefore, we estimated the ongoing maintenance cost of the current forest peatland drainage system. First, we obtained the current costs of ditch maintenance from three contractors (Table 2). Second, we used the hydrological waterways and drains data (National Land Service, 2021) that intersected the peatland forests (see Table 1, approach 2) to calculate the drainage maintenance costs using the following Formula (1).

$$\text{Dr cost} = \text{M cost} \cdot \text{L} / \text{A} / 25 \qquad (1)$$

Where: Dr cost – different drainage maintenance costs; M cost - average maintenance cost €/km (cleaning of drainage dich); L - total length of drainage in kilometers (drainage length in peatland forests – 13 626 km (National Land Service, 2021). The average drainage maintenance cost was divided by area – 143 818 ha of drained peatland forests - A and subsequently multiplied by 1 time every 25 years representing the reoccurrence of drainage maintenance (Finér et al., 2018). For comparison between actions, we estimated the average ditch maintenance cost €/ha/yr. We assumed that the average drainage ditch size was 4 m wide and 2 m deep as this was the dimension specified by the three contractors providing the quotations for forest drainage maintenance.

2.3.2. *Rewetting drained peatlands – dam construction costs*

Rewetting peatlands is often the first step of restoration that aims to improve the delivery of ecosystem services and their benefits for human well-being (Stachowicz et al., 2022). Rewetting drained forest peatlands requires the blocking of man-made drains. This can be achieved by building hydrotechnical constructions (Fig. 3) that retain water (for instance ditch blocks, peat dams, spillways and sheet-piles) that slow-down surface runoff and increase water levels in the ditches (Landry and Rochefort, 2012; Stachowicz et al., 2022).

To estimate dam construction costs, we used a quotation from a professional dam building contractor in Lithuania provided during the spring of 2022, and additionally used the estimated average, cross-sectorial ditch block construction cost following Stachowicz et al. (2022) (Table 2). Using the average cost of dam construction, we calculated the cost of rewetting Lithuania's drained peatland forests using the following Formula (2).

$$\text{D cost yr} = (\text{DC cost} \cdot \text{n} / 2.5\%) / \text{t} \qquad (2)$$

Where: D cost yr - dam construction cost per year; DC cost - average dam construction cost €/unit; n - number of dams needed for rewetting of all peatland forests (length of drainage in peatland forests 13 626 km/ average frequency of dams for rewetting 0.062 km; 2.5% - annual depreciation rate for 40 years period of dam (for hydrotechnical installations); t – hydrotechnical construction ageing time (depreciation 40 years) (Szałkiewicz et al., 2018).

2.4. *Estimating the value of wood, water and carbon in peatland forests*

2.4.1. *Assumptions*

We estimated the potential value of stored wood, water and carbon

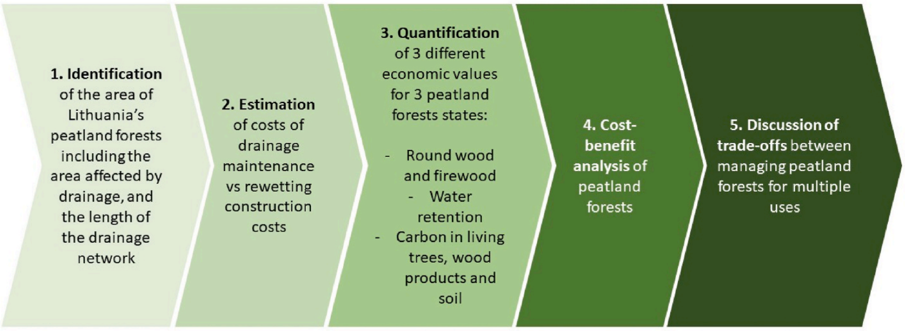

Fig. 2. The step-wise framework applied in this study to assess the trade-offs between peatland forest benefits delivered by wood production, water retention and carbon sequestration and emissions.

Table 1

Different data sources and analyses used to identify peatland forests and their characteristics in Lithuania.

Approach	Source	GIS analysis process	GIS result	Secondary analysis process	Final results
1. National forest database	State Forest Service (2021a)	Attribute selection and export All peatland - Forest site type = P*	Layer of natural and drained peatland forests	Drained vs. non-drained peatlands using attribute data Forest site type = P* vs. P*n	A. Total forest peatland area. B. Total drained peatland area
2. National forest database and Hydrological waterways and drains	State Forest Service (2021a) and National Land Service (2021)	Select non-natural hydrological features from the attribute table ("TIPAS" type = 2,3,4 and 9999). Intersect selection with all peatland forests (results of Approach 1)	Layer of forest peatland intersected with non-natural drainage	Drained vs. non-drained peatlands using attribute data Forest site type = P* vs. P*n, and the match of P*n from Approaches 1 and the outcome of this approach	A. Total drained peatland area B. Matching drained forest peatland area from Approaches 1 and 2 (this approach)
3. Hydrological waterways and drains and National forest database	National Land Service (2021) and State Forest Service (2021a)	Select non-natural hydrological features from the attribute table ("TIPAS" Type = 2,3,4 and 9999). Buffer selected features by 100m. Intersect 100m drainage buffer with all peatland forests (results of Approach 1)	Layer of forest peatland intersected with an area affected by non-natural drainage (100m)	Drained vs. non-drained peatlands using attribute data Forest site type = P* vs. P*n, and the match of P*n from Approach 1 and the outcome of this approach	A. Total drained peatland area. B. Matching drained forest peatland area from Approaches 1 and 3 (this approach)
4. National peatland database	VšĮ Gamtos paveldo fondas (2018)	Attribute selection and export of forest peatland - "Land use type" = "m0"	Layer of natural and drained peatland forests	Drained vs. non-drained peatlands using attribute data "Melioration" = "Mg" or "Md"	A. Total forest peatland area B. Total drained peatland area
5. National peatlands database and National forest database	VšĮ Gamtos paveldo fondas (2018) and State Forest Service (2021a)	Intersect the peatland forests from the National Peatland database (results of approach 4) with the Peatland of the National Forest database (Results of Approach 1)	Layer of peatland forests intersected with the national peatland database	Drained vs. non-drained peatlands using attribute data. A peatland was considered drained when both datasets indicated drainage	A. Total forest peatland area B. Total drained peatland area

Table 2

Cost quotations for the maintenance and rewetting of drained peatlands. A drainage maintenance frequency of 25 years was applied (Finér et al., 2018).

Action	Source	Ditch size	Activity	Cost €/km
Drainage maintenance	Small partnership "Dirginta"	4 m width x 2 m depth	Cutting bushes, small trees	850
	Private limited company "Melsvita"	4 m width x 2 m depth	Cutting bushes, small trees	1 100
	Private limited company "Sistela"	4 m width x 2 m depth	Cutting bushes, small trees	1 550
			Cleaning ditches with machinery (bushes, trees and excavation <40 cm).	2 453
Average maintenance cost/km				**€1 488**
Rewetting (dam construction – blocking)	Stachowicz et al. (2022)	(±1–5) m width (±2–3) m depth)	Wood and peat dams	1 114
	Private limited company "Sistela"	4 m width x (0,5–1) m depth	Wood and peat	196
			Wood and rocks	3 153
Average rewetting (construction) cost/dam				**€1 487**

for Lithuania's peatland forests using three different alternative states of peatland forests, *viz.*; **i**) natural peatland forests not impacted by drainage (Natural), **ii**) the current mix of drained and undrained peatland forests (Current), **iii**) rewetted peatlands – a hypothetical analysis of rewetting all the drained peatland forests in combination with the natural undrained forests (Rewetted).

We used Lithuania's National forest database ((State Forest Service, 2021a) see Table 1, approach 1) as the most reliable data source to estimate values of stored wood, water, and carbon in each of the three peatland forest states (Manton et al., 2021; Mozgeris et al., 2021). In addition, the National forest database contains a wide range of forest data (i.e., forest harvesting volume and species, stand age and area, drained and non-drained forest stands and carbon storage) that was used in the analysis.

2.4.2. *Wood volume*

As traditional forest management is based on wood production (Angelstam et al., 2021, 2022; Mozgeris et al., 2021), we estimated the value of the standing timber volume of Lithuania's peatland forests for the three broad peatland forest states (natural, current and rewetted). To do this we used forest stand characteristics (i.e., tree species, area, site type, age and standing wood volume (for wood production) contained within the National forest database (State Forest Service, 2021a). In addition, we reviewed the sales value data of raw wood (round logs and firewood in Lithuania for each tree species for the years 2021–22 (https://emps.baltpool.eu/; https://giriuaukcionai.lt/; https://www.volimeda.lt/lt/pirkimai Accessed 22-4-2022) and calculated the weighted average wood value per hectare for Lithuania's peatland forests. Scots pine, Norway spruce, birch, oak, ash and aspen were calculated as round wood and all other tree species were counted as firewood. Analyzing the peatland forest by tree species and possible product type (i.e., round wood or firewood) we estimated the mean sales price of raw wood from peatland forest to be €42/m^3. The price of wood was stable over the past twenty years with price increases matching inflation.

We assumed that all of Lithuania's forest stands have reached harvesting age, which is ~100 years of age (Ministry of the Environment, 1994; Parliment of the Republic of Lithuania, 2010), and calculated the total volume of today's forest stands and projected the yearly growth

Fig. 3. Peatland rewetting and restoration using ditch blocking to raise the water table and water storage capacity in Aukštumala raised bog, Lithuania, photos by L. Jarašius and J. Sendžikaitė.

increment of wood volume (m^3) for each of the three peatlands states; natural, current, rewetted. We applied Formula (3).

$$WV = A \cdot V \text{ (natural, current, rewetted)} \cdot W \text{ price} / A / 100 \tag{3}$$

Where: WV – Wood value, €/ha/yr; A – area of drained and non-drained peatland forests, 302 585 ha; V natural - wood volume in natural peatland forest stands, m^3/ha; V current volume in current peatland forest stands, m^3/ha; V drain - wood volume in drained peatland forest stands, m^3/ha; V rewet - wood volume m^3/ha in rewetted peatland forest stands; W price - market wood price, €/m^3; 100 - time scale in years'; 0.72 – volume reduction in rewetted peatland forests (Laine et al., 2011). As rewetting of peatland forests, raises the water table, and reduces the growing conditions of trees, often ending in mortality due to an overabundance of water (Maanavilja et al., 2014). Therefore, we estimated the wood volumes in option R – rewetted peatland forests by applying a 72% reduction in forest stand volume (Laine et al., 2011) between the difference of Option Current – (Current – Natural) · 0.72.

The three options used were as follows:

1. Natural WV = A · V natural · W price / A / 100, not impacted by drainage all peatland forests
2. Current WV = A · V current · W price / A / 100, situation natural and drained forests peatlands
3. Rewetted WV = V current - ((V current - V natural) · 0.72) / A / 100), all drained and natural peatlands rewetted

2.4.3. *Water storage*

High water saturation of peatlands is a key element that supports and facilitates multiple ecological functions. The loss of stored water caused by artificial drainage disrupts the natural processes of peatlands and their ability to function and provide ecosystem services like CO_2 sequestration (Joosten, 2009; Komulainen et al., 1999), flood prevention (Lõhmus et al., 2015; Tolvanen et al., 2013), water and organic matter storage (Mustamo et al., 2016) and water filtering (Wallage et al., 2006). Artificially lowered water tables within peatlands increases the decomposition of peat (Jarašius et al., 2015), causes the reduction of typical peatland vegetation species growth and increases CO_2 emissions (Jarašius et al., 2022; Joosten et al., 2017). The rewetting and raising of the water level in peatlands, together with selective vegetation harvesting, can deliver a range of benefits including improved peat structure, carbon sequestration, water storage and filtration and thus overall peatland functioning (Laine et al., 2011; Pakalne et al., 2021).

To estimate the water storage capacity for the three peatland forest states, we assume that rewetted peatland forests will store more water than drained peatland forests, due to the reduction of draining network functionality, restored moss layers in rewetted peatland, in contrast to drained peatlands (strong drainage and the loss of the moss layer, respectively). Additionally, an increased water table (Price et al., 2003) and higher porosity (McCarter and Price, 2014) as well as lower bulk density (Mustamo et al., 2016) are characteristics of rewetted peatlands compared to drained sites. This allows for more water to be retained in the topsoil. To estimate water retention (water storage W in peatland forests, m^3) in the three peatland forest states we used following Formula (4).

$$W = A \cdot l \cdot p \cdot 10\,000 \cdot 0.53 \,/\, A \,/\, 0.025 \quad (4)$$

Where: A – total area of peatland forests, ha; l – water table level (we assumed the mean depth of peatlands in Lithuania was 3 m and adjusted the water level as required to distinguish the rise in the water table of peatlands (Menberu et al., 2016)); p – effective porosity coefficient (we assumed to be constant for all peatlands - 0.87 (Stachowicz et al., 2022)); 10 000 is used to convert area of peatlands to m^2, 0.025 - depreciation rate. Thus, the three rewetting options used were as follows.

1. Natural (W = (drained peatland forest area ha · 2.9 · 0.87 · 10 000) + (non-drained forest peatland area · 2.9 · 0.87 · 10 000)) · 0.53 / A / 0.025
2. Current (W = (drained peatland forest area ha · 2.4 · 0.87 · 10 000) + (non-drained peatland forest area ha · 2.9 · 0.87 · 10 000)) · 0.53 / A / 0.025
3. Rewetted (W = (drained peatland forest area ha · 2.5 ·0.87 · 10 000) + (non-drained peatland forest area ha · 2.9 · 0.87 · 10 000)) · 0.53 / A / 0.025

Subsequently, we estimated the value of water retention as an ecosystem service for each of the three peatland forest states by multiplying the volume (m^3) of water by the unit value of water retention, which was estimated as €0.53/$m^{3/}$yr based on market costs of water retention (see, Stachowicz et al., 2022).

2.4.4. *Carbon in peatland forests*

Carbon accounting requires the consideration of both sequestration (uptake) and emissions (respiration) from multiple sources (Jarašius et al., 2022; Maljanen et al., 2010). Peatland forests sequester and store carbon in the soil, in trees and also in products made from wood. Therefore, first we estimated both the carbon sequestration, accumulation and emissions from peatland forest soil, second the accumulation of carbon in living trees (natural above ground carbon in living trees) and third, the carbon stored in wood products created after raw wood processing for each of the three peatland forest states.

2.4.4.1. Peatland forest soils. Soil carbon sequestration and emission were estimated for three forest peatland options using the updated greenhouse gas emission site types (GEST) and measurements for in the Baltic States (Couwenberg et al., 2011; Jarašius et al., 2022). To analyze the water level indicators for the GEST vegetation of "*Forested Peatlands*" we first allocated each GEST into the three peatland forest options. The allocation of the GESTs by water level was as followed; Natural peatland forest = +4 to +5, Drained peatland forests = −3 to −2, and rewetted peatland forests = +2 to +3. The mean CO_2 emissions rate (t CO_2-eq./ha/yr) was estimated respectively. The mean CO_2 emissions rate (t CO_2-eq./ha/yr) were natural peatland forest −0.77, drained peatland forests 29.81, and rewetted peatland forests 11.33. Subsequently, we used the average CO_2 emission market price of €67.81 (V_{ICAP}) (May 1st, 2021, to April 30th, 2022), to estimate the value of carbon stored in the each of the three peatland forest states (International Carbon Action Partnershi p, 2022). We applied 3 Formulas (5), (6) and (7) to estimate the soil CO_2 emission value €/ha/yr for each of the three peatland forest options.

$$\text{Natural } Cs\,n = A \cdot Aln \cdot V_{ICAP} \,/\, A \quad (5)$$

$$\text{Current } Cs\,cr = (An \cdot Aln) + (Ad \cdot Ald) \cdot V_{ICAP} \,/\, A \quad (6)$$

$$\text{Rewetted } Cs\,rw = (An \cdot Aln) + (Ad \cdot Alr) \cdot V_{ICAP} \,/\, A \quad (7)$$

Where: Cs n – soil carbon in natural peatland forests, €/ha/yr; Cs cr - soil carbon in current peatland forests, €/ha/yr; Cs rw - soil carbon in rewetted peatland forests, €/ha/yr; A – total area of peatland forests 302 585 ha; An – area of natural undrained peatland forests – 158 767 ha; Ad – area of drained peatland forests – 143 818 ha, Aln – average emission value for natural undrained peatlands −0.77 forests t CO_2-eq./ha/yr; Ald - average emission value for drained peatland forests 29.81 t CO_2-eq./ha/yr; Alr - average emission value for rewetted peatland forests 11.33 t CO_2-eq./ha/yr (Jarašius et al., 2022). V_{ICAP} – average CO_2 emission market price of €67.81 (International Carbon Action Partnership, 2022).

2.4.4.2. Living trees. The estimation of the values of carbon in living tree required three steps. First, using the wood volumes acquired in section 2.4.2 (Value of wood in Lithuania's forests), we estimated the fixed living carbon stored with in each of the three peatland forest states, respectively. Second, we converted the estimated value of living tree carbon sequestration in the three peatland forest states respectively, by multiplying the amount of t C/ha/yr by 3.67 to get value of stored t CO_2/ha/yr (Jarašius et al., 2022; Penman et al., 2003). Third, we used the average European CO_2 emission market price €67.81 (V_{ICAP}) (May 1st, 2021, to April 30th, 2022), to calculate the estimated value of carbon stored in the each of the three peatland forest states (International Carbon Action Partnership, 2022). We expressed the result as €/ha/yr. To do this we applied Formula (8) following Penman et al. (2003):

$$C = (V \cdot D \cdot BEF) \cdot (1 + R) \cdot CF \,/\, A \cdot 3.67 \cdot V_{ICAP} \,/\, 100 \quad (8)$$

C - Fixed carbon in wood biomass tons of carbon; V – tree volume m^3/ha; D - Basic wood density, tons dry mass m-3; BEF - Biomass expansion factor for conversion of stem biomass to above ground tree biomass per species, dimensionless; R - Root shoot ratio, dimensionless; CF - Carbon fraction (Penman et al., 2003) Standard value 0,5 tons C (tons dry mass)-1; A – total area of peatland forests, ha; 3.67 – Carbon transfer rate to CO_2 (Valatka et al., 2018); V_{ICAP} – average European CO_2 emission market price €67.81 (International Carbon Action Partnership, 2022). The amount of carbon in living trees of peatland forests was reported as (t C/ha/yr).

2.4.4.3. Wood processing, short-lived and long-lived products. As the forest industry stresses the importance of carbon captured and stored in wood products (i.e., building material and furniture), we estimated both the amount of carbon lost through timber drying, milling and processing, and the amount of carbon stored in wood products after processing for each of the three peatland forest states. As wood is dried before use, we first converted the estimated living tree volumes (m^3) from the peatland forest data (State Forest Service, 2021a) into dry weight mass by multiplying the live wood volume by 0.45 for each of the three peatland forest states (Heath et al., 2008). Second, as the processing of raw wood for product is estimated to produce (1) waste wood residues and (2) short-lived products (bioenergy, pellets, and pulp and paper (Jasinevičius, 2018)) of ~40–60% (i.e., fast carbon release) (Sokka et al., 2015), we multiplied the dry wood mass by 0.5 (mean value) to account for these losses. Finally, (3) given that the life span of long-lived wood products (construction lumber, plywood, and panels) vary we divided the amount of carbon stored for 30 years (the medium-long lifespan of products (Pussinen et al., 1997)) to estimate the yearly amount of carbon stored. It should be noted that timber drying, milling and processing of raw wood is a disservice as it reduces the long-term storage of carbon (Jasinevičius, 2018).

Counting carbon stock in wood products for the three peatland forest options, firstly we counted the carbon in round wood products. We followed Formulas (9) and (10) presented by Penman et al. (2003) to estimate the dry wood mass value for round wood and CO_2 ratio in dry round wood.

$$\text{EWPn, cr, rw} = \text{C n, cr, rw (results from Formula (8)) - CWS n, cr, rw} \tag{9}$$

$$\text{CWS n, cr, rw} = (\text{V n} \cdot \text{D} \cdot \text{BEF}) \cdot (1 + \text{R}) \cdot \text{CF} \cdot 0.5 \cdot 0.45 \,/\, \text{A} \,/\, 30 \cdot 3.67 \cdot V_{ICAP} \tag{10}$$

Where: EWP n, cr, rw – carbon emission value form wood processing for the three peatland forest states Natural, Current and Rewetted, €/ha/year; C n, cr, rw – tons of carbon in live trees for the three peatland forest states natural, current, rewetted, t/ha; CWS n, cr, rw – carbon storage after wood processing for the three peatland forest states natural, current, rewetted, t/ha; V n, cr, rw – tree volume m^3/ha for the three peatland forest states natural, current, rewetted, V – tree volume m^3/ha; D – Basic wood density, tons dry mass m^3; BEF – Biomass expansion factor for conversion of stem biomass to above ground tree biomass per species, dimensionless; R - Root shoot ratio, dimensionless; CF – Carbon fraction (Penman et al., 2003) Standard value 0.5 tons C (tons dry mass) -1; 0.5 - dry weight mass value of round wood products; 0.45 - CO_2 ratio in dry round wood; A – total area of peatland forests, ha; 3.67 – Carbon conversion rate to CO_2 (Valatka et al., 2018); V_{ICAP} – average European CO_2 emission market price €67.81 (International Carbon Action Partnership, 2022).

2.5. *Cost benefit analysis of peatland forest*

Finally, we analyzed the tradeoffs between peatland forest ecosystem services for natural peatland forests, current peatland forests, and rewetted peatland forests. We use market value methods (de Groot et al., 2012) to estimate the value tradeoffs of seven peatland forest economic indicators using drainage maintenance, rewetting, wood (value of sawlogs and firewood), water retention and three types of carbon accumulation and emissions. As the harvesting of peatland forests is discouraged and other goods, services and benefits must be obtained from forests (European Commission, 2021), we assume that both the natural and rewetted peatlands will not be harvested, thus the peatland forest options contain a value for wood but were not considered for the emission of carbon during wood processing. We used Formulas (11), (12) and (13) for counting cost benefit as €/ha/yr for the three options:

Table 3
Results of five approaches using 3 spatial datasets to identify Lithuania's total peatland forest area, and the area and proportion of drained peatlands.

Approach	Total peatland forest area (ha)	Drained peatland forest area (ha)	Proportion (%) of drained peatland forest (b/a)
	a	b	c
1. National forest database	302 585	143 818 P*n	47.5
2. National forest database and Hydrological waterways and drains	302 585	86 768 P** (59 063 P*n)	28.7
3. Hydrological waterways and drains and National forest database	302 585	144 012 P** (95 820 P*n)	47.6
4. National peatland database	301 171	150 912	50.1
5. National peatlands database and National forest database	228 184	112 444	49.3

P*n indicates drained peatlands and P** undrained peatland according to the National forest database.

$$\text{Natural CB} = (\text{Wv} + \text{Wr} + \text{Cs}_{\text{accumulation}} + \text{Ct}) \tag{11}$$

$$\text{Current CB} = (\text{Wv} + \text{Wr} + \text{Ct}) - (\text{Mc} + \text{Cs}_{\text{emission}} + \text{Cwp}) \tag{12}$$

$$\text{Rewetted CB} = (\text{Wv} + \text{Wr} + \text{Ct}) - (\text{Rc} + \text{Cs}_{\text{emission}} + \text{Cwp}) \tag{13}$$

Where: Natural CB - cost benefit value for natural peatland forests; Where: Current CB - cost benefit value for current peatland forests; Where: Rewetted CB - cost benefit value for rewetted peatland forests; Wv - Wood volume benefit; Wr -water retention benefit; $Cs_{accumulation}$ – carbon accumulation in the soil benefit; $Cs_{emission}$ - carbon emission cost in the soil current and rewetted peatland forests; Ct - carbon accumulation benefit from live trees; Mc – drainage maintenance cost; Rc – rewetting of drained peatland forests cost; Cwp – cost for harvested wood product CO_2 emission. The result was then times by total peatland area to estimate the total amount.

3. Results

3.1. *Peatland forests and drainage*

The analysis of peatland forest data showed mismatches in peatland forest area and the area of drained peatland forests among the five different approaches used (Tables 1 and 3). According to the analysis of Approach 1, the Lithuanian National forest database (State Forest Service, 2021a), there are 302 585 ha of peatland forest of which 143 818 ha (47.5%) are drained. This was the largest area of forest peatland out of the five peatland forest identification approaches.

The area of drained peatland forest using Approach 2, National forest database (State Forest Service, 2021a), intersected with non-natural watercourses (National Land Service, 2021) showed the smallest area of drained peatland forest (86 768 ha). Further spatial analysis of Approach 2 showed that only 59 063 ha these drained peatlands matched the peatland data from Approach 1. The results of Approach 3 (Lithuanian National forest database and non-natural watercourses) with the addition of a 100 m buffer, indicated that 144 012 ha of peatland forests were impacted by drainage. Further spatial analysis of Approach 3 showed that only 95 820 ha of these drained peatlands matched the National forest database. In addition, based on Approach 3, we estimated that the total length of non-natural drainage that impacts peatland forest was 13 626 km. Approach 4 analysis results of the National peatland database (VšĮ Gamtos paveldo fondas, 2018) was only 1 414 ha less in total peatland forest areas compared to the National forest database (State Forest Service, 2021a). Finally, peatland analysis Approach 5, that intersected the National forest data, and the National peatlands data, indicated a 74 401 to 72 987 ha difference in total peatland forest area, respectively (Table 3).

3.2. *Drainage maintenance and rewetting costs*

3.2.1. *Maintenance of the peatland forest drainage*

The average drainage maintenance cost to remove bushes, trees, rubbish, beaver dams and accumulated matter in a ditch 4 m wide x 2 m deep was on average €1 488/km. This equates to an average drainage cleaning price of €5.64 ha/yr, which totals €811 000 annually for Lithuania's drained peatland forests. We estimate the total lifetime drainage maintenance cost over 25 years to be ~$€20.3 \bullet 10^6$.

3.2.2. *Rewetting drained peatlands – dam construction costs*

We estimated that ~220 000 dams need to be constructed to rewet Lithuania's peatland forests. The rewetting analysis showed that the cost of the construction of one dam varied from €196 to €3 153 per dam with an average cost of €1 487. Rewetting all drained peatland forests in

Lithuania using the least expensive option (wood and peat ditch dam) would cost €7.49/ha/yr, whereas the most expensive option would cost €120.46/ha/yr (ditch dam from wood and rocks) and the average price was €56.81/ha/yr based on a 40-year life span. Based on the average price the total cost of dam construction for rewetting Lithuania's drained peatland forest was estimated at ~€$326.8 \bullet 10^6$.

3.3. *Value of wood, water, and carbon*

3.3.1. *Wood volume*

The maximum volume of raw wood in Lithuania's current peatland forests was estimated at 55 million m^3, delivering a wood value of €76.57/ha/yr. This is more than both the estimations for both natural peatland forest (€61.32/ha/yr) and rewetted peatland forests (€65.11/ha/yr) (Table 4).

3.3.2. *Water storage*

The results of the water storage analysis showed that natural peatland forests under natural conditions, would have delivered the largest storage capacity ~7.6 billion m^3 of water. The results for the current peatland forests, show that ~626 million m^3 of water has been lost due to forest drainage. In comparison, the rewetting of all drained peatland forests was estimated to increase the water storage capacity by 125 million m^3 of water compared to the current situation.

In terms of monetary value, our results show that natural peatland forests under natural conditions (i.e., pristine condition with no drainage) would store water with an estimated value of >€101 billion. In comparison, the current peatland forests indicates that through the drainage of peatland forests we have lost ~€8.3 billion in water. In comparison, rewetting all the drained peatlands would deliver a benefit of ~€1.6 billion in terms of water value (Table 4).

3.3.3. *Carbon in the soil*

The CO_2 soil analysis showed that the natural peatland forests (under natural conditions), would accumulate ~232 000 tons of CO_2/yr. The results of the current peatland forests estimates that ~4.4 million tons of CO_2/yr has been lost due to forest drainage. In comparison, the rewetting of all drained peatland forest was estimated to increase the soil carbon storage capacity by ~2.7 million tons of CO_2/yr compared to the current peatland forest situation.

In terms of monetary value, our results estimate that natural peatland forests would accumulate ~€15.7 million of carbon in the soil annually. In comparison, the drainage of peatlands forests has lost ~€298 million annually. Whereas, rewetting all drained peatland forests was estimated to deliver a benefit of ~€180 million in terms of CO_2 accumulation compared to the current peatland situation (Table 4).

3.3.4. *Carbon in live trees and wood products*

The results of the analysis of carbon in live trees showed that the natural peatland forests, would accumulate ~1.97 tons of CO^2/ha/yr, but wood processing would emit ~0.5 tons of CO_2/ha/yr. In comparison the current peatland forests would accumulate ~2.46 tons of CO_2/ha/yr, but wood processing would emit ~0.62 tons of CO_2/ha/yr. Estimations for rewetted peatland forests show that ~2.06 tons of CO_2/ha/yr would be sequestered but wood processing would emit ~0.52 tons of CO_2/ha/yr into the atmosphere.

In terms of monetary value, our results estimated that natural peatland forests would store the least amount of carbon in living trees with a CO_2 market value of ~€40.6 million annually. In comparison, the drainage of peatland forests improved the CO_2 market value to ~€50.6 million annually for current peatland forests. In contrast, rewetting all the drained peatlands was estimated to reduce the CO_2 storage market value to a total of €42.4 million annually (Table 4). The post processing CO_2 market value follows the same trend; natural peatland forests €30.4 million annually, current peatland forests €37.9 million annually and rewetted peatland forests €31.8 million annually.

3.4. *Cost benefit analysis of drainage action, wood, water and carbon*

The cost benefit analysis of seven economic indicators showed that Lithuania's peatland forests in a natural state would deliver a benefit of €176.1 million annually (€582/ha/yr). However, estimates show that the current state of Lithuanian's peatland forests is a disservice at a cost of -€132.9 million annually (-€439/ha/yr). In comparison, the estimates of rewetting of all Lithuania's drained peatland forest would deliver a benefit of €37.1 million annually (€122/ha/yr) (Fig. 4, Table 4).

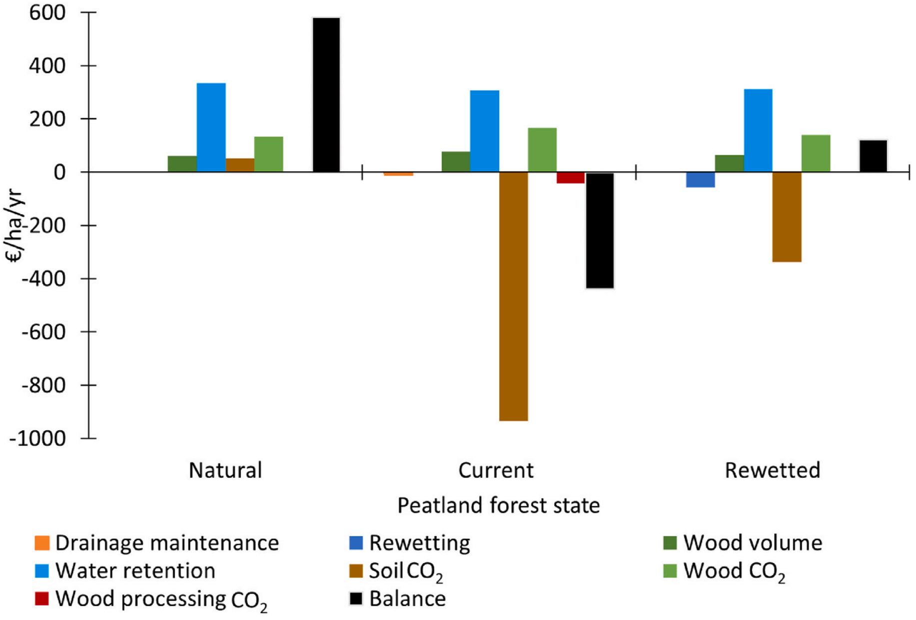

Fig. 4. Histogram of the cost benefit analysis, showing economic benefits and disservices of seven ecosystem services indicators for three peatland forest states (natural, current, and rewetted) in Lithuania. The black bar indicates the balanced value of the combined indicators for each peatland forest state.

Table 4
Estimated quantity and economic market value of five indicators for three peatland forest states (Natural, Current and Rewetted) in Lithuania. For soil CO_2 emissions, a positive tons/ha/yr value is an emission, whereas a negative value is the sequestration of carbon.

Indicator	Peatland forest state	Quantity				Estimated value €	
		m^3/ha	total m^3	tons/ha/yr	tons/yr	ha/yr	Total/yr
Wood	Natural	146	$44.2 \bullet 10^6$	NA	NA	61	$1.86 \bullet 10^9$
	Current	182	$55.2 \bullet 10^6$	NA	NA	77	$2.32 \bullet 10^9$
	Rewetted	153	$46.2 \bullet 10^6$	NA	NA	64	$1.95 \bullet 10^9$
Water	Natural	25 230	$7.6 \bullet 10^9$	NA	NA	334	$101.2 \bullet 10^6$
	Current	23 162	$7.0 \bullet 10^9$	NA	NA	307	$92.9 \bullet 10^6$
	Rewetted	23 576	$7.1 \bullet 10^9$	NA	NA	312	$94.5 \bullet 10^6$
Soil CO_2 emissions	Natural	NA	NA	−0.77	$-0.23 \bullet 10^6$	52	$15.7 \bullet 10^6$
	Current	NA	NA	14.52	$4.2 \bullet 10^6$	−933	$-282.4 \bullet 10^6$
	Rewet	NA	NA	11.33	$1.5 \bullet 10^6$	−338	$-102.3 \bullet 10^6$
Wood CO_2 sequestration	Natural	NA	NA	1.97	597 534	134	$40.6 \bullet 10^6$
	Current	NA	NA	2.46	745 760	167	$50.6 \bullet 10^6$
	Rewetted	NA	NA	2.06	624 735	140	$42.4 \bullet 10^6$
Processed wood retained CO_2	Natural	33	$9.9 \bullet 10^6$	1.48	448 150	100	$30.4 \bullet 10^6$
	Current	41	$12.4 \bullet 10^6$	1.85	559 581	125	$37.9 \bullet 10^6$
	Rewetted	34	$10.4 \bullet 10^6$	1.55	468 812	105	$31.8 \bullet 10^6$

4. Discussion

4.1. *From wood production to rewetting*

4.1.1. *Potential reward of multi-functional peatland forests*

Our attempt towards a cost benefit tradeoff analysis of wood, water and carbon in Lithuania's peatland forests showed that increased wood production through the drainage of peatland forests incurred a loss of ~€308.9 million annually, corresponding to ~6.6% of the country's annual GDP. This loss emerged from lost water retention and decreased ecosystem carbon stock. This estimated economic loss is greater than Lithuania's State Forest company largest ever profit €205.9 million (~4.4% of Lithuania's GDP) recorded in 2020 (State Forest Service, 2021b).

By draining Lithuania's peatland forests, the forest industry has gained ~€4.6 million (€15/ha/yr for wood production based on a 100-year rotation), and ~€10 million (€32/ha/yr) for the sequestration of CO_2 in wood. However, considering the additional indicators, the drainage of peatland forests has lost ~€8.3 million in water storage, ~€298.1 million in soil carbon emissions and ~€7.5 million in wood processing carbon emissions annually. Thus, the drainage of peatland forests for wood has come at an economic loss, not to mention environmental degradation and disservice to other ecosystems services.

In comparison, rewetting of all Lithuania's drained peatland forests is estimated to save a total of ~€170 million annually compared to the current peatland forest situation using the seven indicators (drained maintenance costs, rewetting costs, wood, water storage, and CO_2 in the soil, raw wood, and processed wood emissions). The rewetting of drained peatland forests was estimated to deliver a shortfall of ~€139 million annually compared to the natural peatland state with no drains. However, it is predicted that the benefits gained would increase yearly as the condition of the rewetted peatland improves.

The rewetting of all Lithuania's peatland forests would record a ~€3.8 million decrease in wood production annually (€12/ha/yr based on a 100-year rotation). However, considering the additional indicators of water storage (~€1.7 million/yr) and carbon sequestration (~€172 million/yr, based on CO_2 from soil and wood), we estimated that the rewetting of peatland forests would exceed the loss of wood production. Thus, there is an opportunity to rewet drained peatland forests towards meeting social, economic, and environmental targets.

4.1.2. *Drainage maintenance vs. rewetting cost*

To continue with business-as-usual wood production in peatland forest requires the maintenance of the drainage networks, whereas the rewetting of peatland forests requires the blocking of drainage ditches. Our results indicate that the maintenance of drainage is 10 times cheaper (~€1.7 million/yr) compared to costs of dam constructions for rewetting (~€17 million/yr). However, the overall benefit of rewetting drained peatland forests still exceeds the current situation. We thus argue that the rewetting and restoration of peatlands should be viewed as a long-term investment, where the first decade involving costs for rewetting would be followed by decades of future earnings.

4.1.3. *Sensitivity analysis*

Economic value chains are dynamic, and not all benefits of forest ecosystems can be measured using monetary valuations. The price of raw sawlogs and pulpwood has remained stable the past 20 years with small increases matching the Consumer Price Index (State Forest Service, 2021b; The World Bank, 2022). Calculated monetary values of water storage in Central Europe, including Lithuania, has also remained relatively stable over the last decade, despite changes of other macroeconomic indicators (Grygoruk et al., 2013; Stachowicz et al., 2022). In contrast, costs of maintaining forest drainage system and forest management have soared.

Even if estimating economic values of ecosystem services is widespread (de Groot et al., 2012), it remains to develop policy instruments and business models for landowners that pay for the full range of ecosystem services (Simoncini et al., 2019). Given the importance of mitigating climate change, there are indications that the value of non-wood product ecosystem services will increase and mechanisms for payment will develop (Gómez-Baggethun et al., 2010; Redford and Adams, 2009). However, the estimations of carbon prices are volatile and need to be considered (Richstein et al., 2015).

This kind of exploratory study is sensitive to several uncertainties and assumptions. For example, the analysis of peatland forest data showed mismatches among the five approaches applied to estimate peatland forest area and the area of drained peatland forests. This suggests that different actors and stakeholders might reach different conclusions regarding costs and benefits of different alternatives. This study suggests that the harmonizing of available data on soils, forests and water cadaster is needed. Another potential uncertainty is the length of the drainage system affecting Lithuania's peatland forests. Our estimate of 13 626 km is similar to the findings of ~15 000 km reported by Ruseckas and Urbaitis (2013). The slight difference we assume is due to the different methods used to identify and measure the drainage systems, however, there are no other spatial databases that identify the forest drainage network.

4.1.4. *Other ecosystems services*

This study focused on only seven economic indicators (drainage and rewetting costs and three ecosystem services (wood, water, and 3 carbon indicators)) provided by three peatland forest states (natural, current, and rewetted). Our results indicate that the draining of peatland forests has increased wood production, but also diminished the ecosystems service benefits of both water and carbon. However, on the one hand, there are many other ecosystems services that were not considered in this study that would further exacerbate the disservices of draining peatland forests. These include ecosystems services of non-wood products such as, nutrient filtration, water filtration, reduced GHG emissions and the maintenance of wetland biodiversity. On the other hand, the benefits of draining peatland for wood production, peat extraction or other land uses are generally less.

Considering the interactions between hydrological, soil and ecological processes in forests, we propose that water retention and carbon storage in peatland forests should be considered as "umbrella" ecosystem services (sensu Turpie et al., 2008). Storing water in forests enhances biodiversity, fosters buffering capacities, water filtration and nutrient capture, especially for forests located downstream from agricultural land (Walton et al., 2020), as well as site specific features (Strzęciwilk et al., 2023). While sustained yield wood production is well studied and practiced (Angelstam et al., 2022), the valuation of ecosystems services such as water retention, carbon sequestration and emissions are less developed (Camia et al., 2020; Grassi et al., 2021). This is because environmental benefits are difficult to account for as they consist of various nonmarket outcomes, such as human well-being and biodiversity, which are mediated by environmental conditions (Hsiang et al., 2019).

In parallel with the European Union's agro-environmental schemes, it is feasible to develop similar schemes for forest management. Although the agro-environmental schemes, at the beginning, seemed an unfeasible tool in directing European agriculture towards more sustainable paths, revision of their efficiency proved that they are effective for conserving nature on farmland (Batáry et al., 2015). This is despite being expensive and requiring carefully designed and targeted approaches. In the case of forests, schemes aimed at subsidizing environmental functions may be even cheaper and easier to implement. The ownership of European forests is highly variable, ranging from small non-industrial ownership to state and forest industry (Pulla et al., 2013). Within larger blocks of public ownership, it should be easier to design and execute schemes that would promote the storing water and fostering carbon sequestration. Implementation of such schemes may convince stakeholders to focus their management initiatives on ecosystem services not related to wood production. However, restoration of aquatic and wetland environments remains a "hobby" type activity (Szałkiewicz et al., 2018), and strategic spatial planning is needed to help prioritize the conservation and restoration of peatlands (Manton et al., 2021).

Paludiculture is one possibility for the productive use of wet peatlands, which promotes land use alternatives that reduces GHG gas emissions and increases water storage (Tan et al., 2021; Ziegler et al., 2021). This creates opportunities for rewetting that can also be accompanied by productive uses which offers innovative sustainability for land managers and owners. For instance, income from berry and mushroom picking is important for rural livelihoods in many European regions (Turtiainen and Nuutinen, 2012). It is estimated that collecting berries and mushrooms in Lithuania delivered a benefit of €18/ha in 2020 (State Forest Service, 2021b). As peatlands are where cranberries (*Vaccinium oxycoccos*) grow, rewetting of drained peatland forests may also increase this benefit. This implies that the benefits and values of natural and rewetted forest peatland would be much greater than reported in this study.

4.2. Lithuanian perspective into peatlands

At a regional scale, the three Baltic States rank among the EU's Top 10 of GHG emitters from drained peatlands (Latvia 5th, Estonia 8th, and Lithuania 9th (Wetlands International, 2015). With 70% of Lithuania's peatlands being drained, peatland restoration has become an important topic for water storage, CO_2 sequestration, biodiversity conservation and human well-being as well as an avenue towards mitigating climate change (Valatka et al., 2018). While Lithuania's peatland forests were in focus in this case study, Lithuania's agricultural peatlands are also important and heavily exposed to drainage for improved crop production (Manton et al., 2021). Of Lithuania's total peatland area, 46% is forest land and 54% is agricultural land, of which 50% and 90% are drained, respectively.

This emphasizes that peatland restoration is needed. The high proportion of degraded peatland ecosystems in Lithuania has stimulated restoration efforts through rewetting with ~10 000 ha completed (88% peatland forests and 12% agricultural peatlands (Pers.com L. Jarašius 30th Jan 2023)). However, the actual success on the ground of peatland restoration is largely unknown due to a lack of systematic monitoring and assessment (Manton et al., 2021).

Considering the degradation of Lithuania's peatlands, the Lithuanian Economic Recovery and Resilience Facility (Lithuanian Finance Ministry, 2021) has set a target to restore and rewet 8 000 ha of peatlands on agricultural and forest land, with a financial budget of €16 million. Although this is a step in the right direction, it will restore <2% of Lithuania's total drained peatland area.

4.3. Policy instruments

The valuation of different sets of ecosystem service benefits, and disservices, can be viewed as a tool towards creating, implementing and monitoring policy. To classify policy implementation instruments, a triad of economic (carrot), regulative (stick), and informational (sermon) instruments can be used (Vedung, 1998).

4.3.1. Payments for ecosystems services (Carrot)

The tradition of sustained yield forestry and economic benefits of wood are long established. In contrast, the benefits of water and carbon storage are less tangible given that these ecosystem services are accumulative and remain permanently secured in peatlands. Thus, society cannot feel, touch, or directly use these benefits compared to wood products. This implies both political issues and economic challenges that need to be solved. For instance, how can financial benefits be generated and made available for water and carbon? Climate change has become a new driver, which can help forest managers to explore benefits other than wood harvesting. Non-productive forest land is a good example where other non-wood benefits should be monitored, assessed, and reported.

As a guiding notion, no landowner or user should be economically or socially deprived by maintaining wetlands or rewetting peatlands. This should be addressed by coherent standards for agricultural practices on peatlands and focused agri-environmental and climate schemes (AECSs) that provide incentives for climate-smart water management, carbon sequestration, GHG reduction and paludiculture (Tanneberger et al., 2021; Wichmann, 2018).

Biodiversity banking schemes and carbon emission trading have been proposed as possible solutions where large companies buy carbon rights from landowners to offset their own pollution debt. However, such initiatives and payment schemes may be labeled as green washing, because the GHG emissions or environmental degradation produced by large companies remains at the same level (Dahl, 2010). Thus, there is generally no overall reduction in carbon emissions or ecosystem degradation. Another option for peatland rewetting is to combine it with paludiculture, which can also provide greater incentives and solutions to society, including social (additional employment in rural areas), economy (alternative incomes in agriculture and forestry), and environment (ecosystem services, substitution of fossil resources) (Tan et al., 2021; Tanneberger et al., 2022).

Indeed, agri-environmental and climate schemes are programmed in the EU Common Agricultural Policy (CAP). So far, payments have been provided mainly for biodiversity conservation purposes to private landowners, but payments for peatland rewetting, the raising of water table levels and carbon sequestration, which are instrumental towards mitigating climate change, have not been included (Peters and Unger, 2017; Wichmann, 2018). The implementation of the CAP is considered relatively weak for environment and climate mitigation (Dupraz and Guyomard, 2019). Weighing up the tradeoffs of commercial and industrialized agriculture and forestry on drained peatlands, i.e., increased provisioning services at the expense of regulating services, it is not likely that governments will quickly recognize these land transformations for production as a disservice. This is because strong economic markets already exist, whereas payments for other ecosystem service benefits are relatively new.

4.3.2. Regulation through policy (Stick)

Command-and-control approahes can fulfill an important supplementary function with distinct rules regarding the sustainable use, protection, and rewetting of peatlands (Ekardt et al., 2020). It is only approximately five decades since policy has recognized and developed criteria to halt the negative impacts of land use, land-use change and forestry. There are three levels of regulations of peatland forests: international, regional, and national. Internationally, the Ramsar Convention on Wetlands of International Importance (UNESCO, 1971) and the CBD targets (Convention on Biological Diversity, 2010, 2022) set the standards of conservation and sustainable use of wetlands and their protection. More recently, the Paris Agreement set a target of zero net CO_2 emissions by 2050 (United Nations, 2015). This encourages a complete cessation of peatland drainage and reversal of the effects of existing drainage is required (Tanneberger et al., 2021).

At a regional level, the EU supports this target by approving the European Green Deal (European Commission, 2019) with all EU member states collectively agreeing to reach the zero net CO_2 emissions target. Forest, water, and agricultural policies, such as the EU CAP, contain the main management aspects for peatlands including, their extensive drainage activities. There are multiple options within the CAP, which can direct future use of peatlands which supports agriculture on wet peatlands, but not all proposed instruments are equally suitable for application in peatlands. Nonetheless, deliberate degradation of the long-term carbon storage capacity of peatlands should be penalized and result in payments back to the EU or at least rewetted to help mitigate climate change and safeguard human well-being. For a comprehensive overview of the different policy options for peatlands in the CAP, see Tanneberger et al. (2021).

At the national level, Lithuania's protected area network can be broadly divided into formal and voluntary, where the management objectives and actions vary from strict protection with no intervention to protected areas with management interventions. Analyzing the protected areas of Lithuania's forests, Elbakidze et al. (2016) showed that the voluntary protected forest areas were fragmented and did not complement the strict protected areas. Similarly, Manton et al. (2021), showed that peatland protection in Lithuania Neman river basin did not meet the Convention on Biological Diversity, (2010) 17% protection target, and that the drainage of peatlands is a major issue.

The Forest Stewardship Council (FSC) certification program is also considered another regulator of forestry in Lithuania. However, the regulations for sustainable use of peatland forests are minimal and fall under the umbrella of national and international policies. For instance, the implementation of management activities for regeneration under the FSC indicator 10.1.3 states that "*Surface water is drained down to* 70 cm *deep drainage furrows where otherwise regeneration of the forest* would be impossible*" (Forest Stewardship Council, 2020). This means that it supports the draining of forest for the promotion of wood and does not entirely consider other ecosystems service benefits, such as water and carbon storage.

Lithuanian forest law requires the maintenance of forest drainage systems, and the creation of new forest drainage systems are subject to environment impact assessments (Ministry of the Environment, 1994). Although the drainage system is required to be maintained by law, forest drainage is often not maintained by private forest ownership, which amounts to ca. 40% of Lithuania's total forest area. With small holdings (on average 3.4 ha) most non-industrial private land owners have limited resources to manage their forests (Varnagirytė-Kabašinskienė et al., 2019).

4.3.3. Learning through evaluation (Sermon)

Traditionally, forest management is based on a rich bed of cultural knowledge, norms and social relations which have been developed in specific geographical contexts over long periods of time (Angelstam et al., 2021, 2022). Forest management in Lithuania's post-soviet context has adopted the Scandinavian forest management model, based on even-aged rotation cropping system like in agriculture, based on clear-felling systems focusing on sustained yield wood production. This has led to increased wood harvesting in Lithuania growing from 3 million m^3 in 1990 to 7 million m^3 in 2018 (State Forest Service, 2020).

Although the Fennoscandinavian forest management model is seen as a role model for wood production, it has become evident that many other ecosystem services provided by forest are impaired (Felton et al., 2020). The drainage of peatland forests has led to emissions of dissolved organic carbon and the brownification of rivers, lakes and streams, and the eutrophication of the Baltic Sea (Kritzberg et al., 2020; Nieminen et al., 2021). Recent research in Finland shows that their land use sector has gradually transitioned from being a CO_2 sink to an emissions source (Statistics Finland, 2022). The fastest way to strengthen carbon sinks in Finland is to reduce logging (Siljander et al., 2022). While this measure is considered difficult to implement, the Nature Panel (Lång et al., 2022) recommends rewetting and restoring wetlands and peatlands; fertilize forests for better growth; introduce a permit to clear forest land for arable land; and reintroduce minimum diameter requirements for final felling.

A valuable complement towards sustainable forest management is to transition from a traditional perspective of wood only crop production on peatlands by including other ecosystems services, such as water, GHGs, biodiversity and other values, as well as the risks and vulnerabilities affecting landscape functionality, and monetary values. However, the increased focus on coping with climate change and nature restoration has made forestry a contested topic (e.g., Angelstam et al., 2022; Larsen et al., 2022; Lindahl et al., 2017). For instance, a recent "Scientist letter sent to European Commission, regarding the need for climate smart forest management" with >500 signatures (Irslinger, 2022) argued for less forest conservation and more forestry. In response, another scientific group, with >500 representatives, responded to the European Commission on the need to reduce forest logging for the sake of mitigating climate change and safeguarding biodiversity (van der Spoel, 2023). Thus, we call for careful revision of forest management strategies on peatlands. As an example, Polish forest management policy already restricts wood production on peatlands.

This parallels the proposed concept of closer-to-nature forest management which aims at resilient forest ecosystems (European Commission, 2021). It is forecasted that climate change will involve extreme temperatures and prolonged droughts, strong winds and flooding, which will negatively affect forest landscapes (Messier et al., 2022). Closer-to-nature forest management aims towards improving the conservation values and climate resilience of multi-functional managed forests. According to Larsen et al. (2022), closer-to-nature forest management encompasses all approaches and terminologies under the auspices of sustainable forest management that supports biodiversity, resilience and climate adaptation in forest landscapes. This requires the emulation of natural forest patterns and processes by moving beyond maximized sustained yield forest management (Kuuluvainen et al., 2021).

4.4. Need for multilevel landscape perspective

Managing ecosystem services requires a multilevel landscape perspective from individual peatlands to catchments and relevant levels of governance (Manton et al., 2021; Reed et al., 2017). The highly variable forest ownership distribution in the EU (Pulla et al., 2013) complicates co-ordination of sustainable forest management among neighboring landowners. For example, non-industrial private forest owners have small forest holdings, whereas state and industrial private owners have large forest management units. Thus, targeting drained peatlands owned and managed by the state and industrial private owners should be a rewetting priority because their degradation and emissions footprint is generally larger due to higher management intensity.

Measuring the effect of forest management systems claiming to support multi-functional forest landscapes requires the accounting of all ecosystem services and their benefits and disservices. This includes all types of value creation within and among different value chains, as well as the costs in terms of subsidies and disservices (Angelstam et al., 2022). It is unlikely that all degraded peatlands will be restored as landowners may not be willing to change practices, or that some peatlands may be too degraded to restore. Thus, the development of methodology and tools are needed to facilitate the accounting of all ecosystem services, and to cope with conflicting views among actors and stakeholders.

5. Conclusions

Managing for a diversity of ecosystem services is a balancing act. Therefore, to support policy about multi-functional forest landscapes, the valuation of different sets of ecosystem service benefits and disservices must be assessed and used as a tool towards creating, implementing and monitoring policies on sustainable forest management. In this case study, we found that the traditional focus of wood only forest management overlooks a whole suite of important ecosystems services that can help mitigate the negative effects of climate change for a broad range of stakeholders and societies. Using seven economic indicators *viz.* drainage maintenance, rewetting, water retention, wood production, and three types of carbon sequestration, we estimated that the draining of peatland forests have lost ~€307 million annually. Rewetting of drained peatland forests is one key measure to reduce this loss, and could transform these current losses into a benefit of ~€37 million. However, this requires two lines of action; first, the development of relevant indicators, valuation tools, economic payment schemes or subsides. Second, decision support systems about entire landscapes that involve informed evidence-based dialog and learning among a range of actors and stakeholders.

Author contributions

Evaldas Makrickas: Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Writing – original draft; **Michael Manton**: Conceptualization, Methodology, Resources, Supervision, Formal analysis, Visualization, Funding acquisition, Writing – original draft, Writing – review & editing, **Mateusz Grygoruk**: Conceptualization, Methodology, Formal analysis, Validation, Writing – review & editing; **Per Angelstam**: Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgements

This research was carried in the framework of the European Union's Horizon Europe programme WET HORIZONS, grant agreement no. 101056848. Data used in the study originated from the project DESIRE (Development of sustainable (adaptive) peatland management by restoration and paludiculture for nutrient retention and other ecosystem services in the Neman River catchment) Index number R3071, project number #R091 implemented in the framework of the Interreg Baltic Sea Region Program, co-funded by the European Regional Development Fund and within the framework of an international project cofounded by the Ministry of Science and Higher Education program entitled "PMW" in 2019–2021; contract no. 5071-INTERREG BSR-19-2020-2.

We would like to thank Andreas Haberl, Jan Peters and Wendelin Wichtmann for constructive critique of an earlier version of the manuscript.

References

Ahti, T., Hämet-Ahti, L., Jalas, J., 1968. Vegetation Zones and Their Sections in Northwestern Europe. Annales Botanici Fennici, JSTOR, pp. 169–211.

Andersen, R., Farrell, C., Graf, M., Muller, F., Calvar, E., Frankard, P., Caporn, S., Anderson, P., 2017. An overview of the progress and challenges of peatland restoration in Western Europe. Restor. Ecol. 25, 271–282. https://doi.org/10.1111/rec.12415.

Angelstam, P., Albulescu, A.-C., Andrianambinina, O.D.F., Aszalós, R., Borovichev, E., Cardona, W.C., Dobrynin, D., Fedoriak, M., Firm, D., Hunter, M.L., de Jong, W., Lindenmayer, D., Manton, M., Monge, J.J., Mezei, P., Michailova, G., Brenes, C.L.M., Pastur, G.M., Petrova, O.V., Petrov, V., Pokorny, B., Rafanoharana, S.C., Rosas, Y.M., Seymour, B.R., Waeber, P.O., Wilmé, L., Yamelynets, T., Zlatanov, T., 2021. Frontiers of protected areas versus forest exploitation: assessing habitat network functionality in 16 case study regions globally. Ambio 50, 2286–2310. https://doi.org/10.1007/s13280-021-01628-5.

Angelstam, P., Asplund, B., Bastian, O., Engelmark, O., Fedoriak, M., Grunewald, K., Ibisch, P.L., Lindvall, P., Manton, M., Nilsson, M., Nilsson, S.B., Roberntz, P., Shkaruba, A., Skoog, P., Soloviy, I., Svoboda, M., Teplyakov, V., Tivell, A., Westholm, E., Zhuk, A., Öster, L., 2022. Tradition as asset or burden for transitions from forests as cropping systems to multifunctional forest landscapes: Sweden as a case study. For. Ecol. Manag. 505, 119895 https://doi.org/10.1016/j.foreco.2021.119895.

Angelstam, P., Elbakidze, M., Lawrence, A., Manton, M., Melecis, V., Perera, A.H., 2018. Barriers and bridges for landscape stewardship and knowledge production to sustain functional green infrastructures. In: Perera, A.H., Peterson, U., Pastur, G.M., Iverson, L.R. (Eds.), Ecosystem Services from Forest Landscapes. Springer International Publishing, Cham, pp. 127–167.

Batáry, P., Dicks, L.V., Kleijn, D., Sutherland, W.J., 2015. The role of agri-environment schemes in conservation and environmental management. Conserv. Biol. 29, 1006–1016. https://doi.org/10.1111/cobi.12536.

Bibri, S.E., 2021. Data-Driven Smart Eco-Cities of the Future: an Empirically Informed Integrated Model for Strategic Sustainable Urban Development. World Futures, pp. 1–44. https://doi.org/10.1080/02604027.2021.1969877.

Brukas, V., 2015. New World, old ideas—a narrative of the Lithuanian forestry transition. J. Environ. Pol. Plann. 17, 495–515. https://doi.org/10.1080/1523908X.2014.993023.

Camia, A., Giuntoli, J., Jonsson, K., Robert, N., Cazzaniga, N., Jasinevičius, G., Avitabile, V., Grassi, G., Barredo Cano, J.I., Mubareka, S., 2020. The Use of Woody Biomass for Energy Production in the EU, EUR 30548 EN. Publications Office of the European Union, Luxembourg.

Convention on Biological Diversity, 2010. The Strategic Plan for Biodiversity 2011-2020 and the Aichi Biodiversity Targets. Convention on Biological Diversity, Nagoya, Japan.

Convention on Biological Diversity, 2022. Kunming-Montreal Global Biodiversity Framework. Conference of the Parties to the Convention on Biological Diversity CBD, Motreal, Canada, p. 14.

Couwenberg, J., Thiele, A., Tanneberger, F., Augustin, J., Bärisch, S., Dubovik, D., Liashchynskaya, N., Michaelis, D., Minke, M., Skuratovich, A., Joosten, H., 2011. Assessing greenhouse gas emissions from peatlands using vegetation as a proxy. Hydrobiologia 674, 67–89. https://doi.org/10.1007/s10750-011-0729-x.

Dahl, R., 2010. Green washing. Environ. Health Perspect. 118, A246–A252. https://doi.org/10.1289/ehp.118-a246.

de Groot, R., Brander, L., van der Ploeg, S., Costanza, R., Bernard, F., Braat, L., Christie, M., Crossman, N., Ghermandi, A., Hein, L., Hussain, S., Kumar, P., McVittie, A., Portela, R., Rodriguez, L.C., ten Brink, P., van Beukering, P., 2012. Global estimates of the value of ecosystems and their services in monetary units. Ecosyst. Serv. 1, 50–61. https://doi.org/10.1016/j.ecoser.2012.07.005.

Dunn, C., Freeman, C., 2011. Peatlands: our greatest source of carbon credits? Carbon Manag. 2, 289–301. https://doi.org/10.4155/cmt.11.23.

Dupraz, P., Guyomard, H., 2019. Environment and climate in the Common agricultural policy. EuroChoices 18, 18–25. https://doi.org/10.1111/1746-692X.12219.

Ekardt, F., Jacobs, B., Stubenrauch, J., Garske, B., 2020. Peatland governance: the problem of depicting in sustainability governance, regulatory law, and economic instruments. Land 9, 83. https://doi.org/10.3390/land9030083.

Elbakidze, M., Ražauskaitė, R., Manton, M., Angelstam, P., Mozgeris, G., Brūmelis, G., Brazaitis, G., Vogt, P., 2016. The role of forest certification for biodiversity conservation: Lithuania as a case study. Eur. J. For. Res. 1–16 https://doi.org/10.1007/s10342-016-0940-4.

Escobar, D., Belyazid, S., Manzoni, S., 2022. Back to the future: restoring northern drained forested peatlands for climate change mitigation. Front. Environ. Sci. 10 https://doi.org/10.3389/fenvs.2022.834371.

European Commission, 2013. Green Infrastructure (GI) — Enhancing Europe's Natural Capital. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. European Commission: Environment, Brussels.

European Commission, 2019. The European Green Deal. COM (2019) 640 final. In: European Commission, Brussels.

European Commission, 2020. EU Biodiversity Strategy for 2030: Bringing Nature Back into Our Lives, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. European Commission, Brussels.

European Commission, 2021. New EU Forest Strategy for 2030, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. European Union, Brussels, p. 28.

FAO, 2020. Peatlands Mapping and Monitoring – Recommendations and Technical Overview. FAO, Rome, Italy, p. 82.

FAO, 2022. Forest Pathways for Green Recovery and Building Inclusive, Resilient and Sustainable Economies, the State of the World's Forests (SOFO). FAO, Rome, Italy, p. 166.

Felton, A., Löfroth, T., Angelstam, P., Gustafsson, L., Hjältén, J., Felton, A.M., Simonsson, P., Dahlberg, A., Lindbladh, M., Svensson, J., Nilsson, U., Lodin, I., Hedwall, P.O., Sténs, A., Lämås, T., Brunet, J., Kalén, C., Kriström, B., Gemmel, P., Ranius, T., 2020. Keeping pace with forestry: multi-scale conservation in a changing production forest matrix. Ambio 49, 1050–1064. https://doi.org/10.1007/s13280-019-01248-0.

Finér, L., Čiuldienė, D., Lībieté, Z., Lode, E., Nieminen, M., Pierzgalski, E., Ring, E., Strand, L., Sikström, U., 2018. WAMBAF–Good Practices for Ditch Network Maintenance to Protect Water Quality in the Baltic Sea Region, Natural Resources and Bioeconomy Studies 25/2018. Luke, Natural Resources Institute Finland, Helsinki, Finland, p. 37.

Forest Stewardship Council, 2020. The FSC National Forest Stewardship Standard of Lithuania. Forest Stewardship Council, Bonn, Germany, p. 74.

Gómez-Baggethun, E., de Groot, R., Lomas, P.L., Montes, C., 2010. The history of ecosystem services in economic theory and practice: from early notions to markets and payment schemes. Ecol. Econ. 69, 1209–1218. https://doi.org/10.1016/j.ecolecon.2009.11.007.

Grassi, G., Fiorese, G., Pilli, R., Jonsson, K., Blujdea, V., Korosuo, A., Vizzarri, M., 2021. Brief on the role of the forest-based bioeconomy in mitigating climate change through carbon storage and material substitution (JRC124374) (Brussels, Luxemburg). In: Sanchez Lopez, J., Jasinevičius, G., Avraamides, M. (Eds.), European Commission.

Grygoruk, M., Mirosław-Świątek, D., Chrzanowska, W., Ignar, S., 2013. How much for water? Economic assessment and mapping of floodplain water storage as a catchment-scale ecosystem service of wetlands. Water 5, 1760–1779. https://doi.org/10.3390/w5041760.

Heath, L.S., Hansen, M., Smith, J.E., Miles, P.D., Smith, B.W., 2008. Investigation into calculating tree biomass and carbon in the FIADB using a biomass expansion factor approach. In: Proceedings of the Forest Inventory and Analysis (FIA) Symposium, pp. 21–23.

Hsiang, S., Oliva, P., Walker, R., 2019. The distribution of environmental damages. Rev. Environ. Econ. Pol. 13, 83–103. https://doi.org/10.1093/reep/rey024.

International Carbon Action Partnership, 2022. ICAP Allowance Price Explorer. ICAP, Berlin, Germany.

IPCC, 2014. Climate Change 2014: Synthesis Report, Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, USA, p. 1435.

Irslinger, R., 2022. Scientist Letter on the need for climate smart forest management. In: European Commission President Ursula von der Leyen. Rottenburg, Germany, p. 35.

Jarašius, L., Etzold, J., Truus, L., Purre, A.-H., Sendžikaitė, J., Strazdiņa, L., Zableckis, N., Pakalne, M., Bociąg, K., Ilomets, M., Herrmann, A., Kirschey, T., Pajula, R., Pawlaczyk, P., Chlost, I., Cieśliński, R., Gos, K., Libauers, K., Sinkevičius, Z., Jurema, L., 2022. Handbook for Assessment of Greenhouse Gas Emissions from Peatlands. Lithuanian Fund for Nature, Vilnius, Lithuania.

Jarašius, L., Lygis, V., Sendžikaitė, J., Pakalnis, R., 2015. Effect of different hydrological restoration measures in Aukštumala raised bog damaged by peat harvesting activities. Balt. For. 21, 192–203.

Jasinevičius, G., 2018. The Role of Wood Products in Climate Change Mitigation: Carbon Accounting Methods and Scenario Analysis in Two European Countries Social Sciences and Business Studies. University of Eastern Finland, Joensuu, Finland, p. 109.

Joosten, H., 2009. The Global Peatland CO2 Picture: Peatland Status and Drainage Related Emissions in All Countries of the World. Wetlands International, Wageningen, p. 35.

Joosten, H., Sirin, A., Couwenberg, J., Laine, J., Smith, P., 2016. The Role of Peatlands in Climate Regulation. Cambridge University Press, Cambridge, UK.

Joosten, H., Tanneberger, F., Moen, A., 2017. Mires and Peatlands of Europe: Status, Distribution and Conservation. Schweizerbart Science Publishers, Stuttgart, Germany.

Kløve, B., Berglund, K., Berglund, Ö., Weldon, S., Maljanen, M., 2017. Future options for cultivated Nordic peat soils: can land management and rewetting control greenhouse gas emissions? Environ. Sci. Pol. 69, 85–93. https://doi.org/10.1016/j.envsci.2016.12.017.

Komulainen, V.-M., Tuittila, E.-S., Vasander, H., Laine, J., 1999. Restoration of drained peatlands in southern Finland: initial effects on vegetation change and CO2 balance. J. Appl. Ecol. 36, 634–648. https://doi.org/10.1046/j.1365-2664.1999.00430.x.

Kritzberg, E.S., Hasselquist, E.M., Škerlep, M., Löfgren, S., Olsson, O., Stadmark, J., Valinia, S., Hansson, L.-A., Laudon, H., 2020. Browning of freshwaters: consequences to ecosystem services, underlying drivers, and potential mitigation measures. Ambio 49, 375–390. https://doi.org/10.1007/s13280-019-01227-5.

Kuuluvainen, T., Angelstam, P., Frelich, L., Jõgiste, K., Koivula, M., Kubota, Y., Lafleur, B., MacDonald, E., 2021. Natural disturbance-based forest management: moving beyond retention and continuous-cover forestry. Front. For. Glob. Change 4, 24. https://doi.org/10.3389/ffgc.2021.629020.

Laine, A.M., Leppälä, M., Tarvainen, O., Päätalo, M.-L., Seppänen, R., Tolvanen, A., 2011. Restoration of managed pine fens: effect on hydrology and vegetation. Appl. Veg. Sci. 14, 340–349. https://doi.org/10.1111/j.1654-109X.2011.01123.x.

Landry, J., Rochefort, L., 2012. The Drainage of Peatlands: Impacts and Rewetting Techniques, Peatland Ecology Research Group. University of Laval, Quebec, Canada, p. 47.

Lång, K., Aro, L., Assmuth, A., Haltia, E., Hellsten, S., Larmola, T., Lempinen, H., Lindfors, L., Lohila, A., Miettinen, A., Minkkinen, K., Nieminen, M., Ollikainen, M., Ojanen, P., Sarkkola, S., Sorvali, J., Seppälä, J., Tolvanen, A., Vainio, A., Wall, A., Vesala, T., 2022. Turvemaiden Käytön Vaihtoehdot Hiilineutraalissa Suomessa (*In Finnish*), Suomen Ilmastopaneelin Raportti2/2022. Finland, Helsinki.

Larsen, J.B., Angelstam, P., Bauhus, J., Carvalho, J.F., Diaci, J., Dobrowolska, D., Gazda, A., Gustafsson, L., Krumm, F., Knoke, T., 2022. Closer-to-Nature Forest Management. From Science to Policy, vol. 12. EFI European Forest Institute.

Lindahl, K.B., Sténs, A., Sandström, C., Johansson, J., Lidskog, R., Ranius, T., Roberge, J.-M., 2017. The Swedish forestry model: more of everything? For. Pol. Econ. 77, 44–55. https://doi.org/10.1016/j.forpol.2015.10.012.

Lithuanian Finance Ministry, 2021. Ekonomikos Gaivinimo Ir Atsparumo Didinimo Planas (In Lithuanian), Naujos Kartos Lietuva. Lithuanian Finance Ministry, Vilnius, Lithuania.

Lõhmus, A., Remm, L., Rannap, R., 2015. Just a ditch in forest? Reconsidering draining in the context of sustainable forest management. Bioscience 65, 1066–1076. https://doi.org/10.1093/biosci/biv136.

Maanavilja, L., Aapala, K., Haapalehto, T., Kotiaho, J.S., Tuittila, E.-S., 2014. Impact of drainage and hydrological restoration on vegetation structure in boreal spruce swamp forests. For. Ecol. Manag. 330, 115–125. https://doi.org/10.1016/j.foreco.2014.07.004.

Maljanen, M., Sigurdsson, B.D., Guðmundsson, J., Óskarsson, H., Huttunen, J.T., Martikainen, P.J., 2010. Greenhouse gas balances of managed peatlands in the Nordic countries – present knowledge and gaps. Biogeosciences 7, 2711–2738. https://doi.org/10.5194/bg-7-2711-2010.

Manton, M., Makrickas, E., Banaszuk, P., Kołos, A., Kamocki, A., Grygoruk, M., Stachowicz, M., Jarašius, L., Zableckis, N., Sendžikaitė, J., Peters, J., Napreenko, M., Wichtmann, W., Angelstam, P., 2021. Assessment and spatial planning for peatland conservation and restoration: europe's trans-border Neman River basin as a case study. Land 10, 174. https://doi.org/10.3390/land10020174.

Manton, M., Ruffner, C., Kibirkštis, G., Brazaitis, G., Marozas, V., Pukienė, R., Makrickiene, E., Angelstam, P., 2022. Fire occurrence in hemi-boreal forests: exploring natural and cultural Scots pine fire regimes using dendrochronology in Lithuania. Land 11, 260.

McCarter, C.P.R., Price, J.S., 2014. Ecohydrology of Sphagnum moss hummocks: mechanisms of capitula water supply and simulated effects of evaporation. Ecohydrology 7, 33–44. https://doi.org/10.1002/eco.1313.

Menberu, M.W., Tahvanainen, T., Marttila, H., Irannezhad, M., Ronkanen, A.-K., Penttinen, J., Kløve, B., 2016. Water-table-dependent hydrological changes following peatland forestry drainage and restoration: analysis of restoration success. Water Resour. Res. 52, 3742–3760. https://doi.org/10.1002/2015WR018578.

Messier, C., Potvin, C., Muys, B., Brancalion, P., Chazdon, R., Seidl, R., Bauhus, J., 2022. Warning: natural and managed forests are losing their capacity to mitigate climate change. For. Chron. 98, 2–8.

Ministry of the Environment, 1994. Lithuania Forest Law. Valstybės žinios, Vilnius, Lithuania.

Mozgeris, G., Kazanavičiūtė, V., Juknelienė, D., 2021. Does aiming for long-term non-decreasing flow of timber secure carbon accumulation: a Lithuanian forestry case. Sustainability 13, 2778. https://doi.org/10.3390/su13052778.

Mustamo, P., Hyvärinen, M., Ronkanen, A.-K., Kløve, B., 2016. Physical properties of peat soils under different land use options. Soil Use Manag. 32, 400–410. https://doi.org/10.1111/sum.12272.

National Land Service, 2017. RELIEF_GRID, Georeferenced Spatial Data Set for the Territory of the Republic of Lithuania, Scale 1:250 000 (GDR250LT). Ministry of Agriculture of the Republic of Lithuania, Vilnius, Lithuania.

National Land Service, 2021. Georeferenced Spatial Data Set for Territory of the Republic of Lithuania: Hydrological Waterways and Drains. GIS-Centras, Spatial Information Portal of Lithuania, Vilnius, Lithuania.

Nieminen, M., Sarkkola, S., Sallantaus, T., Hasselquist, E.M., Laudon, H., 2021. Peatland drainage - a missing link behind increasing TOC concentrations in waters from high latitude forest catchments? Sci. Total Environ. 774, 145150 https://doi.org/10.1016/j.scitotenv.2021.145150.

Nikolakis, W., Innes, J.L., 2020. The Wicked Problem of Forest Policy: A Multidisciplinary Approach to Sustainability in Forest Landscapes. Cambridge University Press.

Nyberg, M., Black, T.A., Ketler, R., Lee, S.-C., Johnson, M., Merkens, M., Nugent, K.A., Knox, S.H., 2022. Impacts of active versus passive Re-wetting on the carbon balance of a previously drained bog. J. Geophys. Res.: Biogeosciences 127, e2022JG006881. https://doi.org/10.1029/2022JG006881.

Pakalne, M., Etzold, J., Ilomets, M., Jarašius, L., Pawlaczyk, P., Bociag, K., Chost, I., Cieśliński, R., Gos, K., Libauers, K., Pajula, R., Purre, A.-H., Sendžikaitė, J., Strazdiņa, L., Truus, L., Zableckis, N., Jurema, L., Kirschey, T., 2021. Best Practice Book for Peatland Restoration and Climate Change Mitigation. University of Latvia, Riga, Latvia.

Parliment of the Republic of Lithuania, 2010. On the approval of regulations for forest fellings: the order of the minister of the environment of the republic of Lithuania No. D1-79 of 27 january 2010. In: Environmental Protection Ministry. Valstybės žinios, Vilnius, Lithuania.

Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., 2003. Biomass Default Tables for Section 3.2 Forest Land Annex 3A.1, Good Practice Guidance for Land Use, Land-Use Change and Forestry. Institute for Global Environmental Strategies, Kanagawa, Japan, p. 593.

Peters, J., Unger, M., 2017. Peatlands in the EU Regulatory Environment. Bundesamt für Naturschutz, Bonn, Germany.

Plakans, A., 2011. A Concise History of the Baltic States. Cambridge University Press.

Povilaitis, A., Lamsodis, R., Bastienė, N., Rudzianskaitė, A., Misevičienė, S., Miseckaitė, O., Gužys, S., Baigys, G., Grybauskienė, V., Balevičius, G., 2015. Agricultural drainage in Lithuania: a review of practices and environmental effects. Acta Agric. Scand. Sect. B Soil Plant Sci 65, 14–29. https://doi.org/10.1080/09064710.2014.971050.

Povilaitis, A., Taminskas, J., Gulbinas, Z., Linkevičienė, R., Pileckas, M., 2011. Lithuanian Wetlands and Their Water Protective Importance. Apyaušris, Vilnius, Lithuania, pp. 1–326.

Price, J., Heathwaite, A., Baird, A., 2003. Hydrological processes in abandoned and restored peatlands: an overview of management approaches. Wetl. Ecol. Manag. 11.

Pulla, P., Schuck, A., Verkerk, P.J., Lasserre, B., Marchetti, M., Green, T., 2013. Mapping the Distribution of Forest Ownership in Europe. European Forest Institute, Joensuu.

Pussinen, A., Karjalainen, T., Kellomäki, S., Mäkipää, R., 1997. Potential contribution of the forest sector to carbon sequestration in Finland. Biomass Bioenergy 13, 377–387. https://doi.org/10.1016/S0961-9534(97)10048-4.

Redford, K.H., Adams, W.M., 2009. Payment for ecosystem services and the challenge of saving nature. Conserv. Biol. 23, 785–787. https://www.jstor.org/stable/29738805.

Reed, M.S., Allen, K., Attlee, A., Dougill, A.J., Evans, K.L., Kenter, J.O., Hoy, J., McNab, D., Stead, S.M., Twyman, C., Scott, A.S., Smyth, M.A., Stringer, L.C., Whittingham, M.J., 2017. A place-based approach to payments for ecosystem services. Global Environ. Change 43, 92–106. https://doi.org/10.1016/j.gloenvcha.2016.12.009.

Richstein, J.C., Chappin, É.J.L., de Vries, L.J., 2015. The market (in-)stability reserve for EU carbon emission trading: why it might fail and how to improve it. Util. Pol. 35, 1–18. https://doi.org/10.1016/j.jup.2015.05.002.

Ruseckas, J., Urbaitis, G., 2013. Sausinimo Tinklų Miškuose Būklės Vertinimo Ir Renatūralizacijos Tyrimų Metodika. Lutute, Vilnius, Lithuania (*in Lithuanian*).

Siljander, R., Cederlöf, M., Skoglund, K., 2022. Climate Annual Report 2022. Ministry of the Environment, Helsinki, Finland.

Simoncini, R., Ring, I., Sandström, C., Albert, C., Kasymov, U., Arlettaz, R., 2019. Constraints and opportunities for mainstreaming biodiversity and ecosystem services in the EU's Common agricultural policy: insights from the IPBES assessment for Europe and central asia. Land Use Pol. 88, 104099 https://doi.org/10.1016/j.landusepol.2019.104099.

Sokka, L., Koponen, K., Keränen, J.T., 2015. Cascading Use of Wood in Finland–with Comparison to Selected EU Countries. Metsäenergian kestävyysselvitys, Project numer.

Stachowicz, M., Manton, M., Abramchuk, M., Banaszuk, P., Jarašius, L., Kamocki, A., Povilaitis, A., Samerkhanova, A., Schäfer, A., Sendžikaitė, J., Wichtmann, W., Zableckis, N., Grygoruk, M., 2022. To store or to drain — to lose or to gain? Rewetting drained peatlands as a measure for increasing water storage in the transboundary Neman River Basin. Sci. Total Environ. 829, 154560 https://doi.org/10.1016/j.scitotenv.2022.154560.

State Forest Service, 2020. Lithuanian Statistical Yearbook of Forestry 2019. Ministry of Environment, State Forest Service, Vilnius, Lithuania.

State Forest Service, 2021a. Lithuanian State Forest Stand Cadastral GIS Database. Ministry of Environment, State Forest Service, Vilnius, Lithuania.

State Forest Service, 2021b. Lithuanian Statistical Yearbook of Forestry 2020. Ministry of Environment, State Forest Service, Vilnius, Lithuania.

Statistics Finland, 2022. Greenhouse Gas Emissions in 2021 Became Revised – the Land Use Sector Was Confirmed a Source of Emissions, Environment and Nature. Statistics Finland, Helsinki, Finland.

Strzęciwilk, K., Stachowicz, M., Grygoruk, M., 2023. Ecosystem services of wetlands – on the nature-based water management solutions that have no technical alternative. Water Management – Gospodarka Wodna. https://doi.org/10.15199/22.2023.1.3.

Szałkiewicz, E., Jusik, S., Grygoruk, M., 2018. Status of and perspectives on river restoration in Europe: 310,000 euros per hectare of restored river. Sustainability 10, 129. https://doi.org/10.3390/su10010129.

Tadesse, T., Teklay, G., Mulatu, D.W., Rannestad, M.M., Meresa, T.M., Woldelibanos, D., 2022. Forest benefits and willingness to pay for sustainable forest management. For. Pol. Econ. 138, 102721 https://doi.org/10.1016/j.forpol.2022.102721.

Tan, Z.D., Lupascu, M., Wijedasa, L.S., 2021. Paludiculture as a sustainable land use alternative for tropical peatlands: a review. Sci. Total Environ. 753, 142111 https://doi.org/10.1016/j.scitotenv.2020.142111.

Tanneberger, F., Appulo, L., Ewert, S., Lakner, S., Ó Brolcháin, N., Peters, J., Wichtmann, W., 2021. The power of nature-based solutions: how peatlands can help us to achieve key EU sustainability objectives. Adv. Sustain. Syst. 5, 2000146 https://doi.org/10.1002/adsu.202000146.

Tanneberger, F., Birr, F., Couwenberg, J., Kaiser, M., Luthardt, V., Nerger, M., Pfister, S., Oppermann, R., Zeitz, J., Beyer, C., van der Linden, S., Wichtmann, W., Närmann, F., 2022. Saving soil carbon, greenhouse gas emissions, biodiversity and the economy: paludiculture as sustainable land use option in German fen peatlands. Reg. Environ. Change 22, 69. https://doi.org/10.1007/s10113-022-01900-8.

Tanneberger, F., Joosten, H., Moen, A., Winham, J., 2017. Mire and peatland conservation in Europe. In: Joosten, H., Tanneberger, F., Moen, A. (Eds.), Mires and Peatlands of Europe. Schweizerbart science publishers, Stuttgart, pp. 178–196.

TEEB, 2010. The Economics of Ecosystems and Biodiversity: Mainstreaming the Economics of Nature: A Synthesis of the Approach. conclusions and recommendations of TEEB, Malta, p. 39.

The World Bank, 2022. Consumer Price Index Lithuania. The World Bank, Washington. DC, USA.

Tolvanen, A., Juutinen, A., Svento, R., 2013. Preferences of local people for the use of peatlands the case of the richest peatland region in Finland. In: Ecology and Society, vol. 18. http://www.jstor.org/stable/26269301.

Turpie, J.K., Marais, C., Blignaut, J.N., 2008. The working for water programme: evolution of a payments for ecosystem services mechanism that addresses both poverty and ecosystem service delivery in South Africa. Ecol. Econ. 65, 788–798. https://doi.org/10.1016/j.ecolecon.2007.12.024.

Turtiainen, M., Nuutinen, T., 2012. Evaluation of information on wild berry and mushroom markets in European countries. Small-scale For. 11, 131–145. https://doi.org/10.1007/s11842-011-9173-z.

UNESCO, 1971. Convention on Wetlands of International Importance Especially as Waterfowl Habitat. Ramsar (Iran) United Nations Treaty series No. 14583. As amended by the Paris Protocol, Dec 3, 1982, and Regina Amendments, United Nations.

United Nations, 2015. Paris Agreement, Report of the Conference of the Parties to the United Nations Framework Convention on Climate Change (21st Session, 2015 (Paris), New York, USA).

Valatka, S., Stoškus, A., Pileckas, M., 2018. Lietuvos Durpynai. Kiek Jų Turime, Ar Racionaliai Naudojame? Gamtos paveldo fondas, Vilnius, Lithuania, p. 92.

van der Spoel, D., 2023. Open letter to EU on forestry. In: European Commission President Ursula von der Leyen, edLetter. Uppsala University, Uppsala, Sweden, p. 27.

Varnagirytė-Kabašinskienė, I., Lukminė, D., Mizaras, S., Beniušienė, L., Armolaitis, K., 2019. Lithuanian forest biomass resources: legal, economic and ecological aspects of their use and potential. Energy Sustain. Soc. 9, 41. https://doi.org/10.1186/s13705-019-0229-9.

Vedung, E., 1998. Policy instruments: typologies and theories. In: Bemelmans-Videc, M. L., Rist, R.E.V. (Eds.), Carrots, Sticks, and Sermons: Policy Instruments and Their Evaluation. Transaction Publishers, New Brunswick, New Jersey, pp. 21–58.

VšĮ Gamtos paveldo fondas, 2018. Lietuvos pelkių ir durpynų GIS duomenų bazės atnaujinimas 2017-2018 (in Lithuanian) (VšĮ Gamtos paveldo fondas, Vilnius, Lithuania). In: VšĮ Gamtos Paveldo Fondas.

Wallage, Z.E., Holden, J., McDonald, A.T., 2006. Drain blocking: an effective treatment for reducing dissolved organic carbon loss and water discolouration in a drained peatland. Sci. Total Environ. 367, 811–821. https://doi.org/10.1016/j.scitotenv.2006.02.010.

Walton, C.R., Zak, D., Audet, J., Petersen, R.J., Lange, J., Oehmke, C., Wichtmann, W., Kreyling, J., Grygoruk, M., Jabłońska, E., Kotowski, W., Wiśniewska, M.M., Ziegler, R., Hoffmann, C.C., 2020. Wetland buffer zones for nitrogen and phosphorus retention: impacts of soil type, hydrology and vegetation. Sci. Total Environ. 727, 138709 https://doi.org/10.1016/j.scitotenv.2020.138709.

Wetlands International, 2015. Briefing Paper: Accelerating Action to Save Peat for Less Heat! Wetlands International, Wageningen, The Netherlands, p. 4.

Wichmann, S., 2018. Economic incentives for climate smart agriculture on peatlands in the EU. Proc. Greifswald Mire Centre 1, 2018.

Yin, R.K., 2014. Case Study Research: Design and Methods. Sage, London, UK.

Ziegler, R., Wichtmann, W., Abel, S., Kemp, R., Simard, M., Joosten, H., 2021. Wet peatland utilisation for climate protection – an international survey of paludiculture innovation. Clean. Eng. Technol. 5, 100305 https://doi.org/10.1016/j.clet.2021.100305.