Author(s): Aleksi Räsänen, Eerika Albrecht, Mari Annala, Lasse Aro, Anna M. Laine, Liisa Maanavilja, Jyri Mustajoki, Anna-Kaisa Ronkanen, Niko Silvan, Oili Tarvainen & Anne Tolvanen

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Review

After-use of peat extraction sites – A systematic review of biodiversity, climate, hydrological and social impacts

Aleksi Räsänen [a,*], Eerika Albrecht [b,c], Mari Annala [d], Lasse Aro [e], Anna M. Laine [f], Liisa Maanavilja [g], Jyri Mustajoki [h], Anna-Kaisa Ronkanen [d], Niko Silvan [i], Oili Tarvainen [a], Anne Tolvanen [a]

[a] Natural Resources Institute Finland (Luke), Oulu, Finland
[b] University of Eastern Finland, Joensuu, Finland
[c] Finnish Environment Institute (Syke), Joensuu, Finland
[d] Finnish Environment Institute (Syke), Oulu, Finland
[e] Natural Resources Institute Finland (Luke), Turku, Finland
[f] Geological Survey of Finland, Kuopio, Finland
[g] Geological Survey of Finland, Espoo, Finland
[h] Finnish Environment Institute (Syke), Helsinki, Finland
[i] Natural Resources Institute Finland (Luke), Tampere, Finland

HIGHLIGHTS

- Systematic review of 356 articles about peat extraction site after-use
- Vegetation and greenhouse gases of abandoned and restored sites have been in focus.
- Afforestation and cultivation have been also studied to some extent.
- There is a lack of studies comparing impacts of different after-uses.
- There is a need for research upscaling the post-extracted sites to a larger context.

GRAPHICAL ABSTRACT

After-use of peat extraction sites
Systematic review of 356 articles

Studied after-use options	No. articles
Abandonment	72
Restoration	162
Replacement (afforestation, cultivation, wetland)	94 (46, 34, 14)
Other studies	28

Studied impact	% of articles
Biodiversity	62
Climate	33
Hydrology	36
Other Ecosystem Services	17
Socioeconomic	6

Gap in knowledge: no studies have compared the environmental and social impacts of different peat extraction after-uses

ARTICLE INFO

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Cutaway
Cutover
Land use
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ABSTRACT

After drainage for forestry and agriculture, peat extraction is one of the most important causes of peatland degradation. When peat extraction is ceased, multiple after-use options exist, including abandonment, restoration, and replacement (e.g., forestry and agricultural use). However, there is a lack of a global synthesis of after-use research. Through a systematic review of 356 peer-reviewed scientific articles, we address this research gap and examine (1) what after-use options have been studied, (2) what the studied and recognized impacts of the after-use options are, and (3) what one can learn in terms of best practices and research gaps. The research has concentrated on the impacts of restoration ($N = 162$), abandonment ($N = 72$), and replacement ($N = 94$), the latter of which consists of afforestation ($N = 46$), cultivation ($N = 34$) and creation of water bodies ($N = 14$). The studies on abandonment, restoration, and creation of water bodies have focused mostly on analyzing vegetation and greenhouse gas (GHG) fluxes, while the studies assessing afforestation and cultivation sites mostly evaluate the provisioning ecosystem services. The studies show that active restoration measures speed-up vegetation recolonization on bare peat areas, reduce GHG emissions and decrease negative impacts on water systems. The most notable research gap is the lack of studies comparing the environmental and social impacts of the after-use options. Additionally, there is a lack of studies focusing on social impacts and

* Corresponding author at: Natural Resources Institute Finland (Luke), Paavo Havaksen tie 3, 90570 Oulu, Finland.
E-mail address: aleksi.rasanen@luke.fi (A. Räsänen).

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downstream hydrology, as well as long-term monitoring of GHG fluxes. Based on the reviewed studies, a comparison of the impacts of the after-use options is not straightforward. We emphasize a need for comparative empirical research in the extracted sites with a broad socio-ecological and geographical context.

Contents

1. Introduction

Peatlands in natural state are terrestrial wetland ecosystems characterized by waterlogged and anoxic conditions in which organic matter production is larger than its decomposition resulting in accumulation of peat (Yu et al., 2010). Especially during the 20th and 21st centuries, peatlands have been under threat due to anthropogenic pressures (e.g., Ramchunder et al., 2009; Page and Baird, 2016). After drainage for forestry and agriculture, one of the main pressures has been the extraction of peat primarily to horticultural and energy fuel purposes (Joosten and Clarke, 2002; Chapman et al., 2003; Ylönen and Simola, 2012; Albrecht and Ratamäki, 2016). Outside tropical area, ca. 10 % of the loss of peatlands in natural state can be attributed to peat extraction activities; while the corresponding percentages for agriculture, forestry and urbanization have been 50 %, 30 %, and 5 %, respectively (Joosten and Clarke, 2002).

Peat extraction destroys the original peatland ecosystem as the peat is totally or partially removed (Joosten and Clarke, 2002; Chapman et al., 2003). Extraction has also major impacts on climate, hydrology, and biodiversity (e.g., Price et al., 2003; Frolking et al., 2011; Renou-Wilson et al., 2019). In the 2000s, ca. 25,000–30,000 kt of peat have been extracted annually (Fig. 1; USGS, 2023) depending, e.g., on summer weather conditions. For instance, in Finland, the dry summer in 2018 temporarily increased peat extraction. Finland, Ireland, and Germany have been leading countries in peat extraction. Annually, in the 2000s, 50–70 % of the extracted peat has been used for energy production, 20–35 % for horticultural purposes, and 10–25 % for unspecified purposes (USGS, 2023).

Typically, peat extraction for horticulture has required large areas, since only the uppermost *Sphagnum* peat layer is utilized. Instead, in energy peat extraction, a thick peat layer has been extracted while the residual peat layer has been shallow (Wilson et al., 2015). Therefore, in countries such as in Canada, where peat has been extracted almost solely to horticultural purposes (Chapman et al., 2003), the relative areal cover of peat extraction sites can be considerable. In some other countries, such as in Finland and Sweden, mostly energy peat has been extracted (Ylönen and Simola, 2012, Albrecht and Ratamäki, 2016). Overall, there are several types of peat extraction practices and different terms have been used globally (Fig. 2).

Following peat extraction, different measures are conducted depending on the target of the after-use. First, the former extraction sites may be abandoned by relying on spontaneous successional processes (e.g., Lavoie et al., 2003; Prach et al., 2011). Abandonment is not legally currently allowed in most of the countries and existing the abandoned sites are mainly remnants from the past, e.g., from the Soviet era in Eastern Europe (Karofeld et al., 2017). Second, active restoration measures including soil amendment, nutrient addition, hydrological manipulation, and revegetation can be conducted to assist and boost the recovery (e.g., Price, 1997; Tuittila et al., 1999; Nugent et al., 2021). A third option is to replace the extracted ecosystem with alternative land-use, such as commercial forestry (e.g., Hytönen and Kaunisto, 1999; Aro et al., 2020), cultivation of

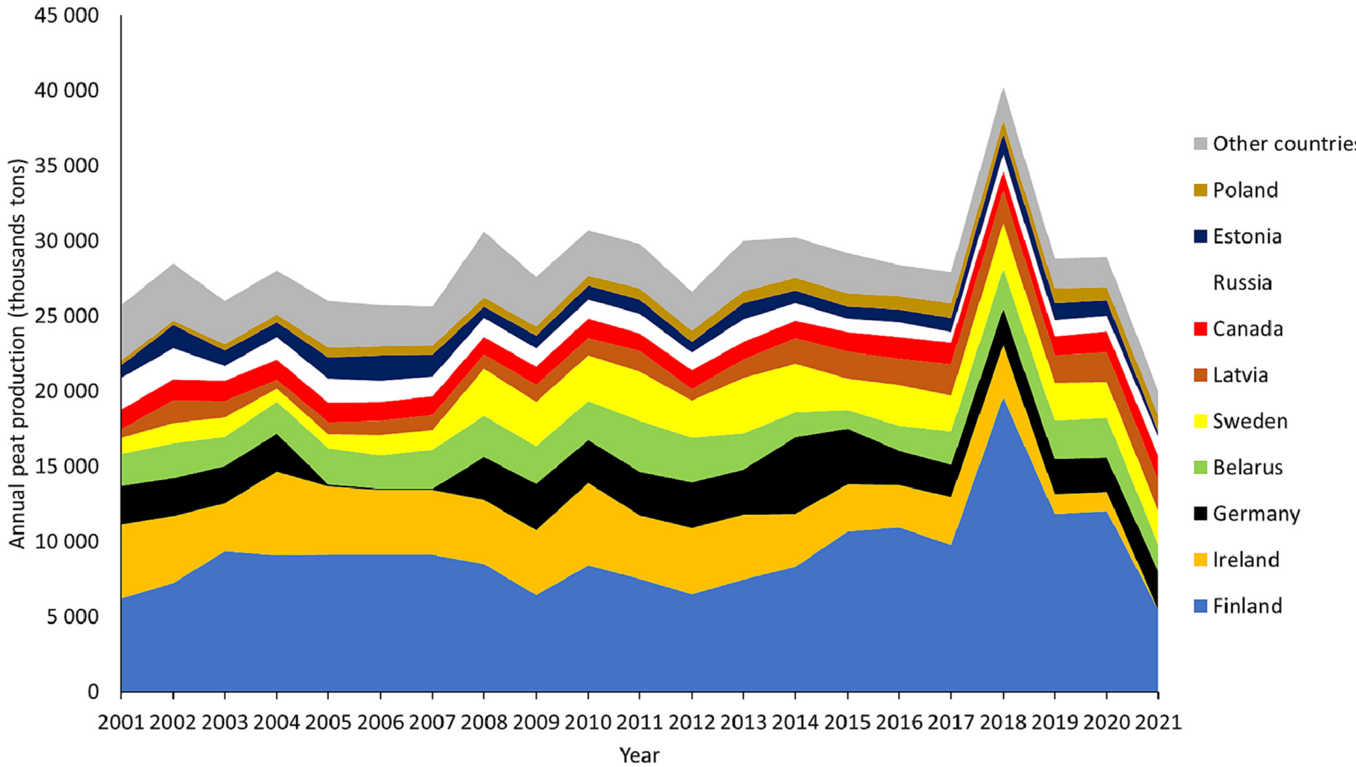

Fig. 1. The amount of peat extracted each year in the top ten and other countries extracting peat. The countries are in descending order, so that the countries with largest amount of extracted peat during the period are in the bottom. There are some uncertainties in the numbers, e.g., for Germany in 2005–2007, only horticultural peat extraction is reported. Data source: USGS (2023).

crop plants (e.g., Salonen, 1989; Espenberg et al., 2016), or creation of water bodies which can create habitats for different wetland species (e.g., Kozlov et al., 2016).

There are differences between countries concerning the policy instruments and legislation guiding the after-use of peat extraction sites. For example, in Finland, an environmental permit must be applied for peat extraction (Environmental Protection Act 527/2014). According to the permit conditions, some after-use management, such as ash spreading or raising the water table level (WTL), must be conducted to initiate the revegetation or creation of water bodies (Ministry of the Environment, 2015) before returning the extraction site to the landowner who decides on the after-use. Similar requirements are also in some other European countries, e.g., Sweden and Estonia. The chosen after-use is dependent on the landowner preferences; in Finland, a majority of the peat extraction sites are privately-owned, while for example, in the Baltic states, the state owns a significant proportion of the areas. Preferred after-use options in private lands in many European countries have included afforestation, cultivation, and creation of water bodies (Laasasenaho et al., 2022). Instead, in Canada, the preferred option is active restoration with transplantation of peatland vegetation (i.e., moss-layer-transfer-technique (MLTT);

Common terms	Extraction methods	Leading countries or regions
Peat extraction = a generally accepted and recently used term, refers to stepwise peat removal from the peat extraction or extracted peatland area.	Milling peat extraction method = a method where the shallow peat layer is milled at a time, used for both energy and horticultural peat.	Baltic countries (Estonia, Latvia, Lithuania), mostly horticultural peat extraction by milling, sod peat and block peat methods.
Peat mining = a dated term for the peat extraction, an analog to the mining of minerals, e.g., iron mining.	Sod peat extraction method = a method where small pieces of peat are extracted at a time, used for horticultural and energy peat.	Canada, horticultural peat extraction by the milling method only.
Peat production = a dated term for the peat extraction, a misleading analog to the “production”, e.g., biomass production.	Block peat extraction method = a method where rather large pieces of peat are extracted at a time manually or mechanically, used for horticultural and energy peat.	Finland, both energy and horticultural peat extraction by milling and sod peat methods.
Cutaway peatland = a peatland, where usually the whole usable peat layer has been removed.		Ireland, both energy and horticultural peat extraction by milling and sod peat methods, also conventional manual block peat method is still in use. Industrial energy peat extraction has ceased.
Cutover peatland = a peatland, where the white, horticultural peat layer or the uppermost Sphagnum moss layer has been removed.		Sweden, both energy and horticultural peat extraction by milling and sod peat methods.

Fig. 2. A summary of the constitutive terms and methods and main peat extracting regions (in alphabetical order). The summary is assembled by utilizing expert knowledge. Similar information can be found also e.g., in International Peatland Society (2023).

Rochefort et al., 2003). This is supported by the Responsibly Managed Peatlands certificate (SCS Global Services, 2023). In Europe, a corresponding certificate supporting restoration is called Responsibly Produced Peat (Foundation Responsibly Produced Peat, 2023).

The after-use of peat extraction sites has been generally studied, and there are also review and overview articles on after-use options covering many geographic areas (e.g., Andersen et al., 2017; Chimner et al., 2017; Karofeld et al., 2017). However, there has been no synthesizing research on the environmental and social impacts of the different after-use options. Therefore, a global synthesis is still needed to identify research needs that help to guide the planning and management of after-use so that biodiversity, ecosystem services and public acceptance are taken into consideration.

We address this research gap by a systematic review. We ask the following research questions: (1) Which after-use options of peat extraction sites have been studied most widely? (2) What are the studied and recognized impacts of the after-use options? (3) What are the best practices and research gaps based on the previous studies?

2. Materials and methods

We followed a systematic review protocol (Mengist et al., 2020) by searching and analyzing with a clear methodology. We searched the Web-of-Science database for keywords (Fig. 3) in the abstract, title, and keywords of the database articles on March 30, 2022. We searched only peer-reviewed journal articles written in English. The search resulted in total of 624 articles published between years 1975 and 2022. We excluded the articles that focused on peat production and not on after-use, were based on a laboratory test, or considered oil sand mining or threat of peat extraction to other land-use. After exclusions, we reached 338 articles to review, which included sixteen review articles. Recognizing the limitations of this search method (e.g., that all studies are not linked to the selected database), we also looked for articles that were cited in the articles included in the database search and added 18 articles to the review. The final number of articles was 356.

We categorized the articles into three major after-use categories by applying the restoration ecology framework introduced by Bradshaw (1996) and redefined in later papers (e.g., Gann et al., 2019). The categories were:

1) **Abandonment** of the site with no active measures, reliant on spontaneous revegetation.
2) **Restoration** by active measures such as blocking ditches and active revegetation to bring-back the peatland ecosystem structure and functioning. This category included rehabilitation measures targeted for partial recovery since differentiation between rehabilitation and restoration measures was not straightforward and the objective of the measures was not always described in the articles.
3) **Replacement** or reclamation of the peat extraction site with an alternative land use or ecosystem different from the original peatland ecosystem. Main replacement categories included afforestation, cultivation (including paludiculture) of agricultural products, and creation of water bodies.

In some articles, multiple after-use options were studied; for instance, numerous restoration studies used abandoned areas as control sites. Therefore, the categorization was conducted based on the primary after-use option. Additionally, the categories were sometimes overlapping, and some after-use measures were a mix of different categories (e.g., creation of water bodies and restoration can have similar aims and measures). A set of the articles that did not have a clear primary after-use option were lumped into a fourth category: **other studies**.

We constructed a spreadsheet table in Microsoft Excel (simplified version in Table S1) in which we filled general information and analyzed the content of the articles. The table included information about the study area (e.g., peatland type and size) and country, study setup (e.g., monitoring time, conducted measurements in the field and laboratory), after-use category, key results, and whether different impacts were studied. The impact categories consisted of the following main categories:

1) **Biodiversity** included plants and vegetation, animals (insects, mammals, birds), and other living organisms, including terrestrial, soil and aquatic organisms.
2) **Climate** included the main GHG fluxes (CO_2, CH_4, N_2O) and sequestration of carbon.
3) **Hydrology** included water quality (suspended solids, nutrients, organic carbon, pH, electrical conductivity, metals) and quantity (i.e., WTL, runoff, soil moisture) conducted on the former peat extraction site and downstream impacts on surface water hydrology.
4) **Other ecosystem services** (ESs) included berries, game, timber production, bioenergy, recreation, amenity, and other production and cultural services.
5) **Socioeconomics** included acceptability, establishment and production costs, yield, logistics, employment, financial support and permits.

We conducted a quantitative content analysis of the articles primarily to calculate the number of articles (1) published each year (result Section 3.1), (2) conducted in different countries (Section 3.1), (3) studying each after-use (Section 3.1), and (4) assessing different impacts of the after-uses

Search term 1		Search term 2
"peat extract*" OR "extracted peat*" OR "extracted bog*" OR "extracted fen*" OR	AND	after-use OR
"peat min*" OR "mined peat*" OR "mined bog*" OR "mined fen*" OR		landuse OR land-use OR
"peat harvest*" OR "harvested peat*" OR "harvested bog*" OR "harvested fen*" OR		"land manag*"OR
"peat excavat*" OR "excavated peat*" OR "excavated bog*" OR "excavated fen*" OR		restor* OR
"peat mill*" OR "milled peat*" OR "milled bog*" OR "milled fen*" OR		recover* OR
peat production OR		revegetat* OR
(cutaway OR cutover OR cut-over OR cut-away) AND peat* OR		afforest* OR
"cutaway bog*" OR "cutover bog*" OR "cut-over bog*" OR "cut-away bog*" OR		cultiv* OR
"cutaway fen*" OR "cutover fen*" OR "cut-over fen*" OR "cut-away fen*"		rewet*

Fig. 3. Specific keywords used in the literature search. The final article set consisted of articles that had at least one search term from both boxes.

(Sections 3.1–3.5). Furthermore, we utilized a qualitative content analysis (Cresswell, 2014) to examine what kind of studies were included in the review and how the different impacts were studied (Sections 3.2–3.5).

3. Results

3.1. General patterns

Of the reviewed 356 articles, 90 % were published in 21st century. There was a sharp rise in the published articles in the early 2000s after which there has been a notable fluctuation in the number of articles published each year (Fig. 4). This was seen also in the articles in each main category (i.e., abandonment, restoration, replacement, and other studies). In total, 38 % of the studies included study areas from Canada, while other main countries were Finland (16 % of studies), Estonia (11 %), and Ireland (8 %) (Table 1). Most of the studies conducted in Canada concentrated on restoration and abandonment, while replacement studies were more common in European countries. The most studied impact categories were biodiversity, climate, and hydrology, while studies analyzing other ecosystem services, and socioeconomic aspects were relatively rare (Fig. 5).

3.2. Abandonment

Of the 135 papers on abandoned peat extraction sites, 72 targeted primarily abandonment (Fig. 4), while in the rest, abandoned areas were used as comparison sites for restoration (61), afforestation (one article), or cultivation (one article). Biodiversity was the main focus in 91 (54 primary) articles, while the main focus in the rest of the articles was either GHG fluxes (25 in total, 12 primary), hydrology (18 in total, six primary), or cultivation (one article; Tarvainen et al., 2022). Few studies examined impacts categorized into "Other ecosystem services" and "Socioeconomics" (Fig. 5). Furthermore, abandonment was included as an after-use option in some other category studies, but synthesis from those articles is in Section 3.5. We included two review or summary articles (Lavoie et al., 2003; Prach et al., 2011) into the abandonment category.

Abandonment of the site was showed to be an ecologically relevant option (Prach et al., 2013). Nevertheless, without any intervention, it may lead to an ecosystem that largely differs from a peatland in natural state, the outcome being heavily reliant on the WTL of the area and moisture condition (Graf et al., 2008; González et al., 2013; Konvalinková and Prach, 2014).

3.2.1. Impacts on biodiversity

Of the 72 articles that focused primarily on abandonment, 63 analyzed biodiversity impacts. Majority of the papers dealing with biodiversity (108 of all articles dealing with abandonment, 59 of primarily targeting abandonment) considered vegetation, such as historical plant species composition, spontaneous revegetation, and the relation of vegetation to ecosystem functioning. Other taxa were studied in 20 articles (10 primary) and included invertebrates such as beetles and butterflies, birds, snakes,

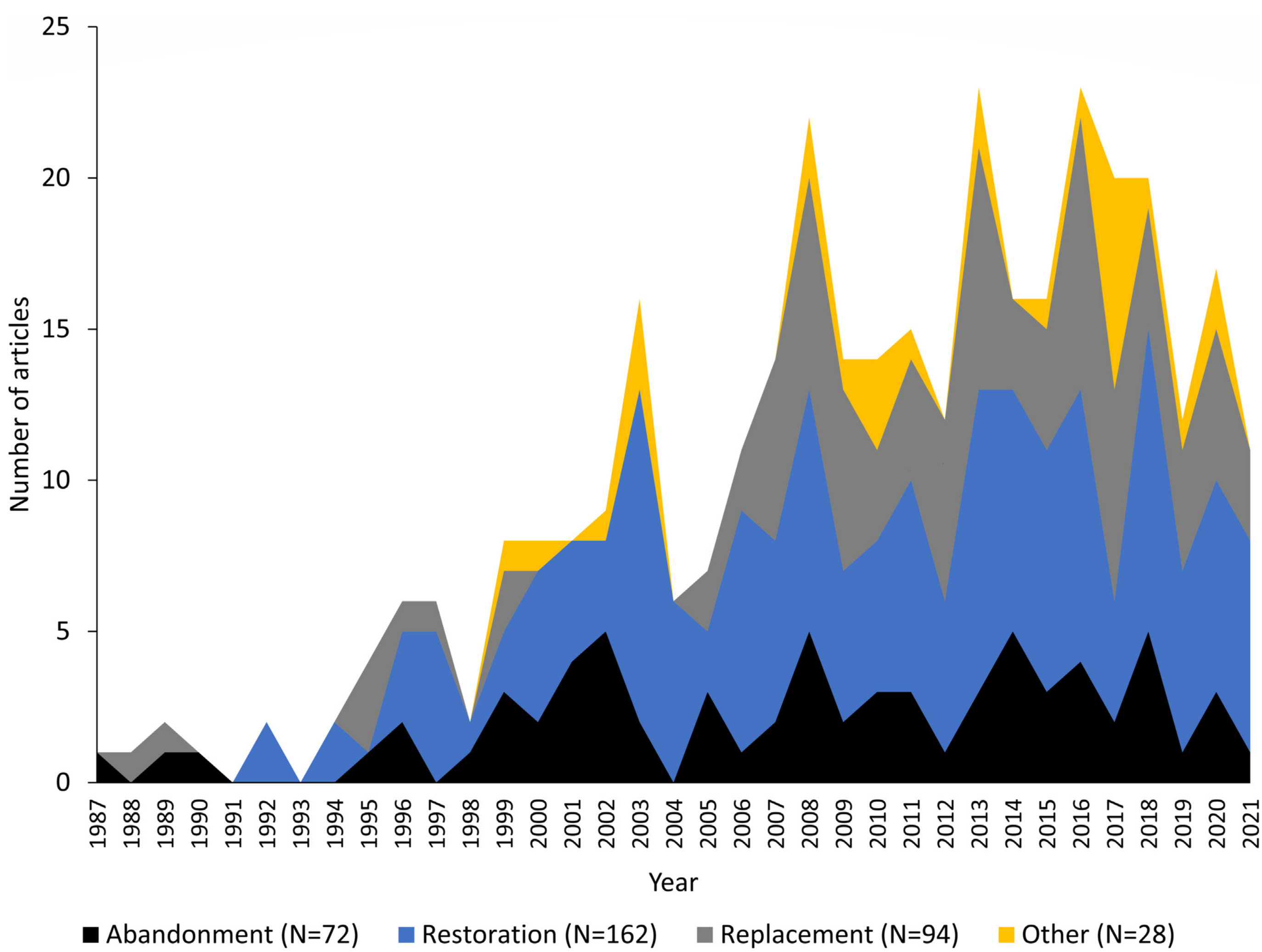

Fig. 4. Number of articles published each year per each primary category of after-use options of peat extraction sites. Note that the literature search was conducted in March 2022. The articles published in 2022 ($N = 7$) are not shown in the area chart but included in the number of articles in the figure legend.

Table 1
Number of studies for peat after-use options of peat extraction sites conducted in each country. One article can include results from multiple countries or after-use options.

Country	Abandonment	Restoration	Replacement			General studies	In total
			Afforestation	Cultivation	Water body		
Canada	63	96	6	6	1	4	134
Finland	14	13	20	16	0	5	59
Estonia	9	14	5	10	0	6	40
Ireland	3	9	6	0	5	6	28
Germany	0	11	0	5	1	3	19
Czech Republic	8	1	2	0	0	0	11
United Kingdom	5	4	0	1	0	2	11
Switzerland	8	1	0	1	0	1	10
Japan	7	3	0	0	0	0	8
New Zealand	5	5	0	0	0	1	8
Sweden	1	0	2	0	4	1	8
Latvia	2	1	3	0	0	1	7
Poland	5	2	1	0	0	0	6
Belarus	1	2	1	2	1	0	5
Netherlands	0	2	0	0	2	1	5
Russia	1	0	0	0	0	3	4
France	2	1	0	0	0	0	3
USA	2	1	0	0	0	1	3
Lithuania	1	1	0	0	0	1	2
Australia	0	0	0	0	0	1	1
Malaysia	0	0	0	0	0	1	1
Papua New Guinea	0	0	0	0	0	1	1
Slovakia	1	0	0	0	0	0	1

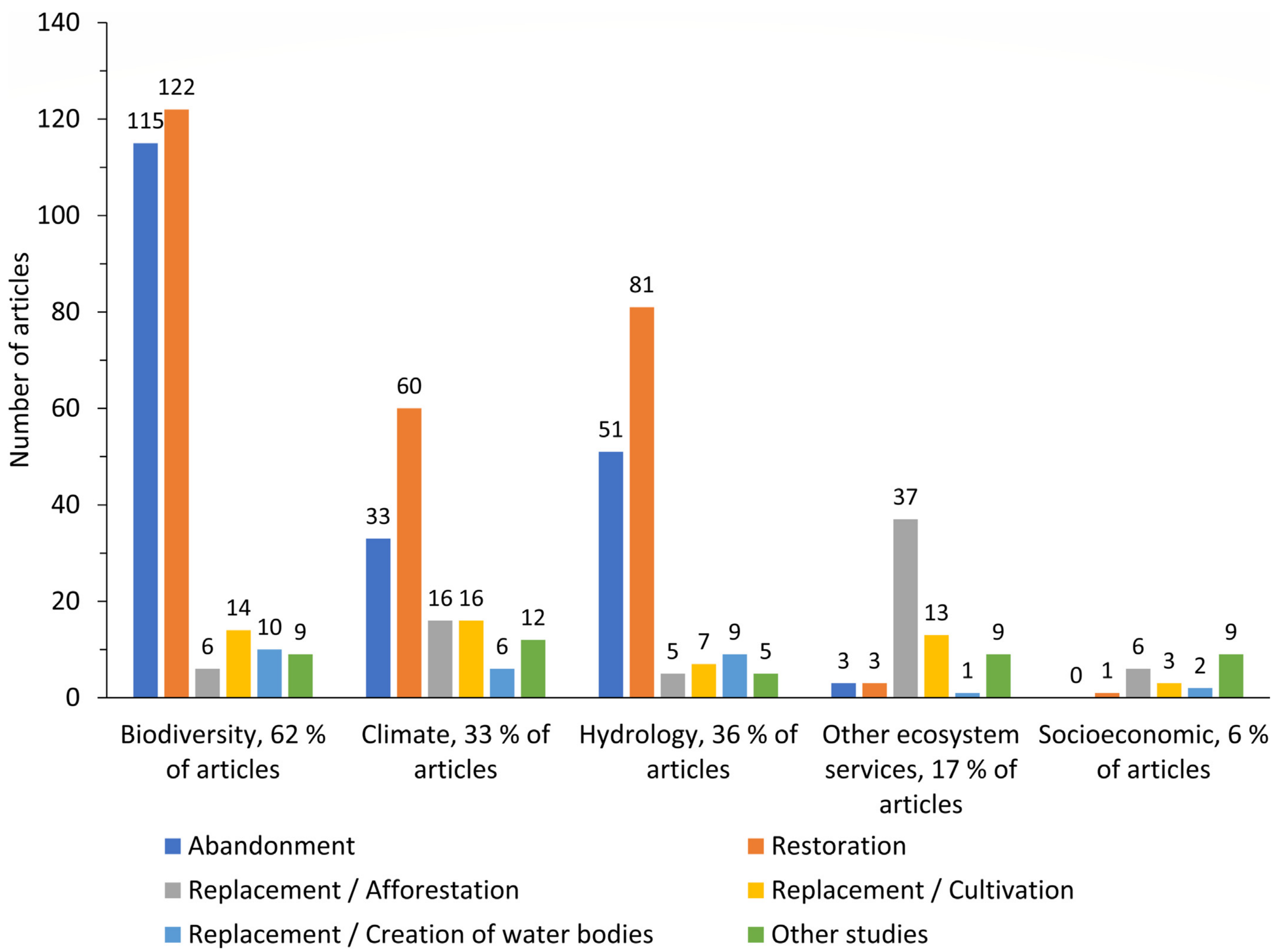

Fig. 5. The number of articles analyzing different impact categories per each after-use category. Additionally, the proportion of articles analyzing each impact is shown. One article can include results for multiple after-uses or impacts.

fungi, and soil organisms. In most papers, biodiversity was inventoried once, or the studies were short term with a maximum of six years. However, the time since the abandonment varied from one to 100 years (Konvalinkova and Prach, 2010; Prach et al., 2013), providing a possibility to evaluate revegetation along a chronosequence. A few studies stated that the lessons learned from inventories of spontaneously revegetated abandoned peat extraction sites can be used in planning restoration objectives (Mahmood and Strack, 2011; Bérubé et al., 2017; Liira et al., 2019).

Spontaneous revegetation was determined by two main factors: residual peat thickness and WTL. Similarly, the responses of other organism groups were driven by WTL. Furthermore, abiotic factors such as topographical features affecting microclimatic conditions (e.g., Konvalinkova and Prach, 2010) and the upper layer peat properties (e.g., Salonen, 1987) affected seed germination and seedling growth. The viable propagule bank of the peat layers after extraction is typically absent or extremely limited; thus, the spontaneously spreading plant species have a great role in revegetation, as they provide litter that either promote (seed trap) or hinder (control of dormancy) the seed bank formation (Egawa et al., 2009). The distance to plant seed/bryophyte sources impacted the spreading of the plant species (e.g., Poulin et al., 1999). Furthermore, tussock-forming species such as *Eriophorum vaginatum* facilitated other plant colonisers (Tuittila et al., 2000; Koyama and Tsuyuzaki, 2010). However, *Sphagnum* and *Polytrichum* were reported to be the key taxa that facilitate the returning to a functional peatland ecosystem (e.g., Lavoie and Rochefort, 1996).

3.2.2. Impacts on climate

Of the studies targeting primarily abandonment, 16 studied climate impacts. All studies measured short term impacts with a maximum of three growing seasons but the time since the abandonment varied from one to 60 years. The studies focused on different gases so that CO_2 emissions, and sometimes also uptake, were measured by 23 papers (of which 12 targeted primarily abandonment), CH_4 emissions by 14 papers (six primary), while N_2O measurement results were found only from three studies (two primary). Based on these studies, the abandonment may result in diverging successional trajectories depending on extraction method, moisture conditions and prevailing climatic conditions (e.g. Yli-Petäys et al., 2007; Rankin et al., 2018). The trajectory of GHG development depended mostly on moisture conditions and vegetation cover. In couple of studies with wet site conditions and nearly full *Sphagnum* moss cover, sites abandoned some four to five decades ago had turned into CO_2 sinks (Bortoluzzi et al., 2006; Yli-Petäys et al., 2007; Samaritani et al., 2011), otherwise abandoned sites were reported as carbon sources during the growing season.

3.2.3. Impacts on hydrology

Hydrology-related data was collected in 27 articles targeting primarily abandonment. Abandonment generally happened five to 60 years before sampling. Nearly all studies were conducted in originally bogs and only three studies were done at fens. None of the studies contained analysis for suspended solids load from the area but pH was measured most often (ten articles). Nutrient concentrations were measured in eight studies but only one study contained metal or organic carbon concentrations. The most measured hydrological parameter was WTL as prerequisite for *Sphagnum* recovery or as an environmental parameter for GHG emissions and carbon sequestration. Although WTL and soil moisture were often seen to be higher in abandoned sites than during active peat extraction, those differed from the natural or restored condition (e.g., Andersen et al., 2010; Bieniada and Strack, 2021) associated to higher evaporation and existing of ditch network. The most often reported challenge was too long-lasting drainage of the area (Price and Whitehead, 2001; Van Seters and Price, 2002; Girard et al., 2002).

Generally, recovery of hydrology in abandoned sites depended on the time and the intensity of the disturbance. Residual peat thickness and site-specific peat properties (such as peat type, porosity, bulk density, hydraulic conductivity, and ash content) was found to be indicators for water-holding capacity characteristics of abandoned sites and the key importance on revegetation of peatland flora (Shantz and Price, 2006; Triisberg et al., 2014; Zając et al., 2018). For example, on an abandoned site of over 40 years old, it was found that the regenerated *Sphagnum* layer had generated to the point where it could regulate soil moisture in the same way as peatlands in natural state (Taylor and Price, 2015). Based on the few studies including water and/or peat chemistry data, pH and nutrients were found to be highly comparable to peatlands in natural state or counterparts especially during growing seasons (Andersen et al., 2010; Rankin et al., 2018).

3.3. Restoration

Restoration was included as a primary after-use option in 162 articles, while it was considered also in some other category after-use studies (Section 3.5). Biodiversity was the primary focus in 74 of the restoration articles, while 51 focused primarily on GHG fluxes and 37 on hydrological aspects. Other aspects were little studied (Fig. 5). There was one review article (Price and Whitehead, 2001) that we included in the restoration category.

The studies focused roughly on two different types of restoration methods. Most of the Canadian studies concentrated on impacts of the MLTT (Rochefort et al., 2003), in which hydrology is improved by filling in the drainage ditches and shaping the peat surface after which *Sphagnum* moss material is spread to the surface and protected with mulch layer. Most of the European-based studies were rewetted sites with spontaneous revegetation but some Estonian studies analyzed the MLTT (Karofeld et al., 2016; Purre et al., 2020). Twenty-four studies were conducted at the Bois-des-Bel peatland in Quebec, Canada. The first study from Bois-del-Bel was published in 2001 (Petrone et al., 2001) and the latest one in 2021 (Nugent et al., 2021).

3.3.1. Impacts on biodiversity

Ninety-five articles included either abandoned or natural peatland areas as comparisons when analyzing restoration success. Moreover, 113 articles analyzed terrestrial vascular plants and bryophytes, in particular *Sphagnum*, while other taxa or biodiversity aspects were less covered. Insects were surveyed in 11 articles, mammals and birds each in one article, aquatic flora in four and fauna in five articles, soil microbiota in nine articles, and fungi and paleoecology each in one article. The goal in the studies was generally on the re-establishment success of target peatland plant species and communities (e.g., Pouliot et al., 2012; Poulin et al., 2013) and not on species richness or diversity metrics.

The recovery was found to be faster and more successful for common plant species (Poulin et al., 2013; Bourgeois et al., 2018) and invertebrates (Watts et al., 2008; Krieger et al., 2019) than for overall ecological community composition (Pouliot et al., 2012; Taillefer and Wheeler, 2012) or soil organisms (Andersen et al., 2006, 2013). However, there was a large variation in the studies in how many years had passed since the restoration (0–30 years), and in the peatland type and target taxa. Furthermore, multiple different restoration measures were tested. These included, for example, direct transfer of intact peatland vegetation and peat sods, transplantations or introductions of donor and seedling materials either mechanically or manually, surface profiling and modifications, different ditch blocking techniques and hydrological manipulation, fertilization, and combinations of these (e.g., Price, 1997, Watts et al., 2008, Nishimura and Tsuyuzaki, 2015, Rochefort et al., 2016).

3.3.2. Impacts on climate

Of the restoration articles studying climate impacts, studies targeting CO_2 exchange (both uptake and emissions) were most common (45 articles), followed by CH_4 (32 articles). Only eleven studies measured N_2O and in nine studies all three gas species were measured concurrently. Measurements were made from the time of restoration until >30 years, with an average of eight years (median four years). Therefore, large share of the studies reported the initial impacts of the rising WTL and early stages of revegetation. In addition, the measurement period was typically rather short, with 20 of the studies reporting measurements conducted over one growing season or a year, while only eight studies followed gas exchange for at least four years.

Common feature to many of the studies was that restoration decreased soil CO_2 emission and increased CH_4 emissions compared to the peat extraction site. Rate of gas exchange was commonly explained by the WTL and vegetation properties. The higher the WTL and the more abundant the vascular plant cover, the higher were the CH_4 emissions (e.g., Wilson et al., 2013; Strack et al., 2016). The same conditions typically also increased the net CO_2 uptake (e.g., Wilson et al., 2013, Strack et al., 2016). In some of the long-term studies, with a decade or more since restoration activities, the gas exchange had started to resemble that of peatland in natural state (e.g., Soini et al., 2010; Strack and Zuback, 2013). Others reported higher GHG balance (i.e., more warming) and higher sensitivity to climate anomalies compared to intact peatland after a decade from the restoration (e.g., Wilson et al., 2016). Lucchese et al. (2010) concluded that the development of a thick accumulated organic matter layer able to offset WTL fluctuations was a necessity for the ability of a peatland to accumulate carbon in a long-term, likely taking more than a decade. In addition, the reintroduction of *Sphagnum* was seen as an elementary process to control gas exchange, with a potential to decrease CH_4 emissions (e.g., Kivimäki et al., 2008; Putkinen et al., 2018).

3.3.3. Impacts on hydrology

Recovery of peatland hydrology was reported to be one of the most critical elements to support restoration of a peatland ecosystem. Restoration actions had been conducted from zero to >30 years (e.g., Glatzel et al., 2006) prior to the studies. Follow-up times varied from zero to eleven years and were often one to four years. The reference sites were typically either natural or unrestored sites. Few studies considered before-after-control-impact comparison and 19 studies did not have any reference area. The studies focused mostly on how restoration influenced different hydrological aspects such as runoff, evapotranspiration, and water storage capacity at the peatland area itself. Almost all the studies included a field survey, and over half of them had laboratory analyses. The most often measured hydrological variables were pH, electrical conductivity, and WTL in the studied areas. A few studies contained data for runoff processes and water balance component, such as evapotranspiration, aiming to evaluate the impact of restoration on surface water quantity (e.g., Ketcheson and Price, 2011).

WTL was reported to be successfully recovered by active restoration (rewetting by ditch blocking, dam construction etc.) (e.g., McCarter and Price, 2013; Montemayor et al., 2015). However, WTL fluctuation and moisture dynamic of peat layer were found to be difficult to maintain in restored peat extraction areas (Glatzel et al., 2006; Howie and Hebda, 2018). Impact of the restoration on evapotranspiration diverged as in some studies evapotranspiration was found to increase (Ketcheson and Price, 2011) but in others no changes were detected (McCarter and Price, 2013). Moreover, higher variation in WTL was associated with higher nutrient (Wind-Mulder and Vitt, 2000; Andersen et al., 2010) and carbon (Glatzel et al., 2006; Strack et al., 2011) level leaching from the restored areas compared to their natural counterparts. According to Andersen et al. (2010), the loads were lower from the restored sites than from the abandoned areas. Generally, the disturbance of a peatland by drainage and peat extraction were documented to increase organic matter decomposition, compression of the peat (Kennedy and Price, 2005), loss of capillarity (e.g., Price et al., 2002), and decrease in hydrological connectivity which takes time to recover. McCarter and Price (2015) showed that despite of 15 cm thick *Sphagnum* layer observed after 10 years of restoration, the soil moisture characteristics of the restored areas still differed remarkably from the natural area, indicating a long-lasting recovery process after the restoration. To minimize these negative impacts, restoration actions should be conducted as soon as possible after the peat extraction (Price, 1997; Kennedy and Price, 2004).

3.4. Replacement

There were three main categories in the replacement articles: afforestation (46 articles), cultivation (34 articles) and creation of water bodies (14 articles). Additionally, cultivation of *Sphagnum* was a secondary focus in six restoration or abandonment articles, while cultivation of grass was included in one afforestation study. When compared to the abandonment and restoration studies, the replacement studies focused more on provisioning ecosystem services, in particular growing of plants for different purposes, and to a limited extent on social aspects (Fig. 5). Nevertheless, also biodiversity, GHGs, and hydrology were considered in many studies.

3.4.1. Afforestation

Main target of the afforestation studies was timber production (ten articles), production of energy biomass, typically according to principles of short-rotation forestry (16 articles) or re-establishment forest ground vegetation (e.g., on sites difficult to rewet; two articles). Afforestation was also studied as an option to recycle waste material as fertilizers (three articles). In addition, some papers focused on the effect of afforestation (including spontaneously born stands) on carbon sequestration (four articles), soil GHG emissions (three articles), environmental load (three articles), and plant ecology and diversity (five articles). In the study sites of afforestation, average peat thickness varied from 0.05 to 3.0 m, and deep peat layers dominated the sites. Nutrient status of the residual peat layer was presented to some extent in most of the papers (33 articles). Properties of the mineral sub-soil beneath the residual peat layer were shortly described in eleven studies. The most common afforestation method was planting (32 articles), following sowing and coppicing (four articles each). Almost a third of the studies (13 articles) were based on spontaneously established tree stands. Different planting materials, densities, and planting or seeding times were included in nine papers.

Shortage of phosphorus and potassium in the residual peat soil in relation to the uptake of them by trees was found in 29 studies; therefore, the use of commercial fertilizers (e.g., Hytönen et al., 1995; Caisse et al., 2008; Aro et al., 2020) or waste material, such as wood or peat ash (e.g., Lumme, 1988; Zuševica et al., 2022), or composted sewage sludge (Järvis et al., 2017), was proven to be a necessary measure to ensure satisfactory seedling stand establishment and growth of trees. Moreover, even nitrogen fertilization was needed for coniferous tree growth in eastern Canada and Ireland (e.g., Renou-Wilson and Farrell, 2007a; Caisse et al., 2008). Furthermore, re-establishing of ground vegetation benefited from fertilization (e.g., Huotari et al., 2009; Zuševica et al., 2022). However, in certain conditions phosphorus and potassium fertilization may increase phosphorus leaching from the site (e.g., if peat has a low capacity to bind phosphorus; Renou-Wilson and Farrell, 2007b). Fertilization can also encourage weed colonization and thus inhibit survival and growth of tree seedlings (Järvis et al., 2017) or promote colonization of unwanted tree species (Bravo et al., 2020). In general, 18 studies focused on initial survival rate and growth of tree seedlings during quite a short period (five years in maximum) after seedling stand establishment. However, some Finnish and Irish studies focused on more than ten-year-old stands (e.g., Hytönen and Kaunisto, 1999; Renou-Wilson and Farrell, 2007a; Aro et al., 2020). A few studies indicated that growing of tree species can be profitable, including short-rotation biomass production of downy birch (*Betula pubescens*) (Jylhä et al., 2015), short-rotation coppiced willow (*Salix* spp.) for bioenergy (Rodzkin et al., 2018), and Scots pine (*Pinus sylvestris*) for timber (Aro et al., 2020).

3.4.2. Cultivation

Majority of the cultivation studies (18 articles) considered reed canary grass (RCG) cultivation. The RCG studies focused mainly on the GHG effects of the cultivation, but also, e.g., the energy potential, microbial community, and evapotranspiration. Other studied cultivation options were *Sphagnum* farming (six articles), blueberry cultivation (five articles), cloudberry cultivation (one article), cereal production (one article), sod production (one article), reindeer forage plant introduction (one article) and combined nature conservation and biomass production (one article). Almost all the studies, regardless of the topic, were short-term with a maximum of five years monitored, but two *Sphagnum* farming-studies considered situation ten (Gaudig et al., 2014) and 15 years (Gaudig et al., 2017) after the initiation of the new land-use operation. The time since the peat extraction had ceased was mainly under ten years but one Estonian study (Tasa et al., 2015) considered situation 23 years after the abandonment. In all but one study, perspective was biological: considering environmental effects, yield, or some other biological factors. The only exception was Wichmann et al. (2017) who considered the economy of *Sphagnum* farming extensively.

General feature in many of the studies was that cultivation, regardless of the cultivated species, decreased the GHG emissions compared to peat extraction or abandoned sites, but only 16 cultivation articles studied climate impacts with five studies analyzing all three main GHGs. Especially, RCG fields were regarded as sinks of atmospheric carbon, mainly because of a carbon sequestration potential of RCG, but had also decreased CH_4 emissions compared to the peat extraction or abandoned sites (Hyvönen et al., 2009). Otherwise, the rate of GHG emissions on the cultivations was generally well explained by the WTL and vegetation properties (Järveoja et al., 2016). On the one hand, some *Sphagnum* farming sites were proven to be rather large sources of CH_4, and the higher the WTL was the higher also the CH_4 emissions were (Waddington and Day, 2007). On the other hand, soil respiration rates on the *Sphagnum* farming sites were clearly lower than on the peat extraction or abandoned sites (Strack et al., 2014, 2016).

3.4.3. Creation of water bodies

The primary targets of the studies focusing on creation of water bodies were to analyze GHG fluxes (five articles), biodiversity (six articles) and hydrology (two articles) while studies on other impacts were missing. The GHG studies looked at CO_2 (three articles), CH_4 (five articles) and N_2O (three articles) fluxes, while assessed biodiversity aspects included terrestrial and aquatic vegetation (eight articles) and plankton (three articles). Studied hydrological aspects included measurements of WTL (six articles) and water chemistry analysis (eight articles), and one study (Lundin et al., 2017) analyzed outflow of elements into downstream waters. The measurement period was typically under five years but extended up to 15 in a couple of studies (Kozlov et al., 2016; Lundin et al., 2017).

The studies focusing on GHG fluxes indicated that even though the creation of shallow lakes of peat extraction sites caused CH_4 emissions to the atmosphere, it had potential to reduce GHG fluxes due to carbon sequestration (e.g., Minke et al., 2016, Jordan et al., 2020). Hydro-chemical stabilization of the water bodies may be fast or take multiple years (even over a decade), depending on the site and soil properties beneath the created water body (e.g., Lally et al., 2012; Lundin et al., 2017). Moreover, some studies indicated that created water bodies were vulnerable to phytoplankton and algal blooms (e.g., Higgins et al., 2006; Higgins and Colleran, 2006). It was also found that rewetting and inundation can promote plant colonization for the former cut-over areas (Kozlov et al., 2016).

3.5. Other studies

The articles in the other studies category were divided into two subcategories: 20 articles considered general aspects of peatland after-use and eight articles were about socio-economic impacts of the after-use. The socio-economic studies were included in this category since they targeted multiple after-use options.

In the general aspects subcategory, the studies were conducted all over the globe but focused mostly on European countries. There were twelve review or overview articles, with different foci. Some studies were general reviews, summaries, or opinion pieces about peatlands, their management (e.g., Whinam et al., 2003; Minayeva et al., 2017), restoration (e.g., Vasander et al., 2003; Chimner et al., 2017; Andersen et al., 2017), and ecosystem services (Kimmel and Mander, 2010) but without a particular focus on after-use of peat extraction sites. Only one review article focused explicitly on the after-use of peat extraction sites but solely in Baltic countries (Karofeld et al., 2017). Among the eight non-review articles, there were five studies applying remote sensing to monitor cut-over peatland after-use or to detect different peatland vegetation and management types, including peat extraction and its after-use (e.g., Knoth et al., 2013; White et al., 2020). The remaining three studies focused on wind erosion in abandoned sites (Campbell et al., 2002), provided guidance for restoration of partly extracted shallow peatlands (Grand-Clement et al., 2015), and assessed wildfire risks and their mitigation in managed northern peatlands (Granath et al., 2016).

All eight socioeconomic studies focused on Europe, with four studies in Ireland, three in Finland, and one in Estonia. The Irish studies utilized semi-structured, focus group interviews and ethnographic research to study deliberative or community-level after-use planning, place-based perceptions, after-use preferences, and environmental values (Collier and Scott, 2008, 2009, 2010). In an opinion piece, Collier (2011) further emphasized the role of social science research to facilitate collaborative after-use planning. In Finland, survey was applied to study landowners' preferences on after-use options (Laasasenaho et al., 2017), and in Estonia, multi-criteria decision analysis framework was developed to select preferable after-use options (Padur et al., 2017). In the remaining two Finnish studies, peat extraction and its after-use were among multiple land use options which utilized choice experiment survey to reveal land use preferences of local stakeholders (Tolvanen et al., 2013), and integrated biophysical-economic modeling to evaluate cost-effective peatland use options (Juutinen et al., 2020).

4. Discussion

4.1. Discussion of main results

According to our systematic review, the studies on abandonment, restoration, and creation of water bodies focus mostly on vegetation and GHG exchange while studies on other environmental impacts and social impacts are scarce. Conversely, the studies about other after-use options, such as afforestation and cultivation, mostly evaluate the provisioning ecosystem services. This difference is understandable since the target of restoration is usually on ecological or environmental benefits while the target in the replacement options is more often on economic returns (Woziwoda and Kopeć, 2014; Juutinen et al., 2020).

Almost all the research has been conducted in Canada, and in Northern and Western Europe (Table 1) which have been geographic hot spots of peat extraction (Fig. 1). In the countries with the most studies, peat extraction has been either regionally or nationally an important economic sector and targets locally a significant proportion of peatlands (e.g., Saarikoski et al., 2019). According to our results, there is a clear division between Canadian and European research strands on after-use options. While Canadian studies focus on natural science research, and on abandoned or restored sites, in Europe, the research field is more diverse and includes research on replacement options and social sciences. We argue that this disparity can be explained by the differences in primary after-uses, methods, and purposes of the peat extraction (Fig. 2), and characteristics of the residual peat between the continents.

There has been no clear rise in the number of the studies published annually after ca. year 2005, possibly because peat extraction has not increased during the recent past (Fig. 1; USGS, 2023). There has neither been clear temporal trend in the number of studies in different main categories. It could have been expected that the number of abandonment studies would have declined, and number of restoration, comparative, or other studies risen during the past decades because studies conducted already in 1990s (e.g., Price, 1997; Tuittila et al., 1999) have showed the benefits of active measures.

Reviewed research shows that active restoration or replacement measures are needed to speed-up vegetation recolonization on bare peat areas, reduce GHG emissions to the atmosphere, and minimize negative impacts on water bodies (e.g., Pouliot et al., 2012; Wilson et al., 2013; Lundin et al., 2017). There are multiple different possibilities for active measures. Raising the WTL, decreasing evaporation by mulch cover, and filling the ditches produce possibilities for suitable habitats of hydrophilic species (Petrone et al., 2001), transplantation of peatland species, e.g., with MLTT helps to restore certain peatland species (González and Rochefort, 2014; Purre et al., 2020), while ash fertilization can be used to facilitate the growth of trees and tall shrubs (Lumme, 1988; Zuševica et al., 2022).

Even though multiple measures aid to revegetate the site and to reduce vertical and lateral emissions, the restoration of original peatland vegetation is not as straightforward. Instead, numerous peatland species have strict habitat requirements, related, e.g., to WTL and its stability and nutrient availability; therefore, manipulation of environmental conditions and species transplantations are often needed (González and Rochefort, 2014; Crowley et al., 2021). There are also risks for unwanted alien species colonization, especially if the environmental conditions are not optimal for the target peatland or forest species (Paradis and Rochefort, 2017; Rankin et al., 2018).

4.2. Gaps in knowledge

There is a lack of studies comparing the environmental and social impacts of after-use options. This is unfortunate because there is a societal need to steer environmentally friendly and socially just development in the after-use of peat extraction sites (Collier, 2011; Tolvanen et al., 2013; Padur et al., 2017). The role of comparative research seems to be left for a limited number of social science or general studies that would, however, benefit from clear empirical evidence of after-use impacts. We consider that when the comparison is made solely based on landowner preferences (Laasasenaho et al., 2017, 2022) and limited knowledge of peatland use impacts, it falls short from a valid multi-objective study. However, we acknowledge that the set-up of comparative empirical studies is demanding because of the need for a long-term monitoring and a large area of similar sites.

It is obvious that the residual peat thickness, chemical and physical properties of the residual peat, and geological and environmental site conditions influence the types of after-use suitable for the area (Renou et al., 2006; Triisberg et al., 2014; Padur et al., 2017) but there is relatively little research on this. There is also rather limited knowledge on restoring nutrient-rich shallow peat sites aiming to fen communities, while the restoration knowledge on nutrient-poor conditions aiming for bog communities is better (e.g., MLTT).

4.2.1. Impacts on biodiversity

Most of the reviewed biodiversity studies have considered revegetation in the abandoned or restored peat extraction sites or how revegetation is related to other aspects such as changes in hydrology or GHG fluxes. Few studies have reported impacts of afforestation or cultivation on terrestrial biodiversity. There is also a need for further studies on impacts of different measures on various taxonomic groups, such as mammals, birds, reptiles, amphibians, invertebrates, fungi, and soil microbiota. Furthermore, aquatic ecological research has strongly focused on the effects of restoration measures on bog pool diversity: there is very little knowledge of aquatic responses on constructed water bodies and abandoned sites, and no studies on other after-use options. Bog pool physico-chemical characteristics and nutrient status play a major role in determining the restoration success of aquatic plant and invertebrate communities. For example, high nutrient status and drainage from surrounding sites hinders the formation of natural-like communities (Krieger et al., 2019; Cooper et al., 2005) and may lead to a development of severe phytoplankton blooms (Higgins et al., 2006).

4.2.2. Impacts on climate

The reviewed GHG studies have mostly been conducted within a rather limited study period. With only one measurement year, it is not possible to evaluate the interannual variation in flux rates caused by changing weather conditions (e.g., Rinne et al., 2018). An exceptionally dry year may lead to high CO_2 emissions and low CH_4 emissions, as is the case in the study by Strack and Zuback (2013). Succession after restoration is a long process and therefore GHG's likely change along the process. Among after-use types, GHG emissions in relation to restoration have been studied the most; yet even there is a lack of long-term studies. Secondly, restoration methods vary, especially between Canada (MLTT) and Europe (rewetting), which lead to different types of vegetation communities and consequently different GHG exchange rates. Comparison of the climate impacts of different restoration methods would be interesting, yet there are still quite a few studies carried out outside Canada.

4.2.3. Impacts on hydrology

The lack of studies assessing restoration effects on surface water quality, amount and diversity at larger scale is conspicuous. This is an essential shortcoming for the objectives of the Water Framework Directive of the European Union that needs further attention. Typically, each case is unique and site-specific characteristics strongly control large scale impacts which challenge upscaling impact assessment and transformation of results to new restoration cases (Whitfield et al., 2009; Holden et al., 2017; Monteverde et al., 2022). Water and peat chemistry changes are complicated and require a long time (Andersen et al., 2010). Especially, development of diplotelmic peatland structure (acrotelm-catotelm) has been seen to be the key in proper hydrological recovery (Cagampan and Waddington, 2008). However, very few studies have focused how this unique peatland structure controls horizontal and vertical emissions as well as local scale hydrology. Since most of the studies have contained only one or two years of data, long term changes and hydrological responses have not been able to observe.

4.2.4. Replacement studies

Most available afforestation studies focus on tree growth and carbon sequestration, while the potential soil GHG emissions have been studied only in a handful of papers and study sites. Based on these publications, it is impossible to draw conclusions on how the carbon balance of afforested sites develops in time and in different types of sites (varying peat depth, climate, nutrient status). Carbon balance and GHG's of forestry drained peatlands have received more scientific attention, and even within one country such as Finland show huge variation between habitats and tree stands (e.g., Ojanen et al., 2013; Ojanen and Minkkinen, 2019). Consequently, it is unrealistic to expect all afforested sites to follow one path and carbon balance trajectory. Similarly, short-term cultivation studies in various growth conditions have given somewhat conflicting results about climate impacts. Overall, only fragmented knowledge on the climate and biodiversity impacts of cultivation is available.

Some after-use options such as paludiculture (i.e., wet agriculture), and solar and wind power have not been explicitly researched. Paludiculture has been considered a possible solution to keep peatlands under productive use and simultaneously reduce GHG emissions (Joosten et al., 2016; Lahtinen et al., 2022). Of the cultivation studies, only *Sphagnum* farming can be regarded as paludiculture, while the other analyzed cultivation options are more or less “dry land” cultivation with the intensive drainage of cultivation area. Renewable energy production, on the one hand, might not enable restoration of the peat extraction areas for which there are targets in national and international policies (e.g., Cortina-Segarra et al., 2021). On the other hand, former peat extraction sites could be considered as “renewables go-to-areas” (c.f. Joint Research Centre, 2023) as they are already heavily converted sites.

4.2.5. Social science studies

There has also been a lack of social science studies examining the local preferences, perceptions, and acceptability as well as management and governance of after-use. There is still room especially for empirical social scientific analysis to get both deeper understanding of local contexts and wider knowledge of stakeholder opinions. More research is also needed on policy acceptance of the land use policies on the after-use of peat extraction sites. Land use policies might create new costs or burden to the landowners, which is why aspects of social justice (Miller, 1999) and just transition (McCauley and Heffron, 2018) should be studied further.

4.3. Decline of energy peat extraction – impacts for after-use

Fuel peat extraction in Europe has declined largely during the past couple of years (Fig. 1). The main reason has been the EU emission trade mechanism affecting the price of peat fuel due to the high CO_2 emission from peat combustion (Holmgren et al., 2008; Ojanen et al., 2020). EU emission trade mechanism has accelerated to phase out peat combustion particularly in large energy stations and consequently also peat extraction in member states such as Ireland and Finland. However, in countries where peat has been produced mainly for horticulture, the decline in the use of peat has not been as notable.

In countries like Finland, energy peat extraction has typically resulted in sites with a shallow residual peat layer, <40 cm (Holmgren et al., 2008). Now, peat extraction sites are likely to be transferred to other land uses earlier, as the quality of deeper peat for other uses such as growing media is not as good as the quality of topmost peat (Wilson et al., 2015). However, there are country-specific variations; for instance, in Germany and Lithuania, licensing new peat extraction sites has been almost stopped and probably all usable peat in old sites will be extracted. Nevertheless, a thick residual peat layer impacts the site conditions, which affects the possibility to utilize different after-use options, and the environmental impacts of after-use (Triisberg et al., 2014, Padur et al., 2017). Afforestation, for example, is a preferred after-use among landowners in Finland (Ronkainen et al., 2022); however, on thick peat, successful and productive afforestation would likely require costly repeated fertilization and ongoing drainage (Aro and Kaunisto, 2003). In addition, decomposition of peat and soil CO_2 emissions will continue and be long-lasting.

In Canada, extracted sites are mainly extracted for horticultural peat only and are commonly transferred to other land uses having thick residual peat. A common after-use for peat extraction sites in Canada is restoration with MLTT (Quinty et al., 2020a, b, c, d), which has been developed over the years and is shown to produce good results (González and Rochefort, 2014; Nugent et al., 2021). At sites where rewetting is probably not useful, or to better mimic the original, often partly treed peatland landscape, tree planting is also used as an after-use type (Bussières et al., 2008, Bravo et al., 2018, Quinty et al., 2020a).

While learning from the experiences from different areas of the world and from the past, care should be taken to understand the impacts of differing extracting practices and different climate which cause differing sites conditions. Block cutting, which has been common in the past, produces microhabitat variation, which in turn makes the starting point for rewetting and restoration very different from the peat milling techniques that leave the field surface more even (Karofeld et al., 2017). A climate with hot summers poses a need for a protective mulch cover for the colonizing *Sphagnum* mosses, which in cooler climate might not be necessary (Corson and Campbell, 2013). We argue that to manage the site with thick residual peat in a way that is both good for climate and economically sustainable, the landowner needs consultation services and economic incentives. This is a challenge for governments and consultation organizations in the countries where active restoration of extracted sites with thick peat is a new task. Therefore, there are emerging challenges for evidence-based sustainable management of after-use of peat extraction sites which calls for support from scientific knowledge.

5. Conclusion

We have conducted a systematic literature review on the after-use of peat extraction sites. Our results show that the research has mostly concentrated on GHG fluxes and vegetation succession on restored and abandoned peat extraction sites, and evaluating the possibility to produce biomass, timber, and agricultural products.

Some practical implications and good practices can be drawn from our review. Active restoration or rewetting measures such as ditch blocking and other hydrological measures speed-up vegetation recolonization on bare peat areas, reduce GHG emissions to the atmosphere and minimize negative impacts on water bodies. To bring back the original peatland ecosystem structure and functioning, more sophisticated techniques such as MLTT or acrotelm transplanting are often necessary. However, former peat extraction sites have often a mosaicked structure and not all areas rewet easily. For drier areas or originally treed sites, initialization of revegetation e.g., through fertilization can be recommended.

We have encountered multiple research gaps of which the most notable is the lack of research comparing the social and environmental impacts of the different after-use options. To address the recognized research gaps, we argue that there is a clear need for empirical research comparing the after-use options and research approaches that situate the extracted sites on a wider socio-ecological and geographic context. Research should also include long-term monitoring considering especially ecological and environmental impacts of the after-use options. Even though the peat extraction sites are typically marginal patches within broader landscapes, they can be key sites for biogeochemical flows of carbon and nutrients and might be key sites to restore peatland flora and fauna. Therefore, catchment-based hydrological approaches quantifying after-use options' nutrient and suspended solid loads could be integrated with ecosystem-atmosphere carbon and nitrogen flux analyses and spatial biodiversity models. Simultaneously, there are multiple global-to-local-scale societal drivers of change affecting land use and management. Therefore, the research approaches should be set into a nexus-thinking that simultaneously considers the societal needs e.g., for clean energy and water, local landowner and land-user preferences and environmental impacts of the different after-use options.

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CRediT authorship contribution statement

Aleksi Räsänen: Conceptualization, Methodology, Investigation, Writing – original draft, Visualization. **Eerika Albrecht:** Investigation, Writing – original draft. **Mari Annala:** Investigation, Writing – original draft. **Lasse Aro:** Investigation, Writing – original draft. **Anna M. Laine:** Investigation, Writing – original draft. **Liisa Maanavilja:** Investigation, Writing – original draft. **Jyri Mustajoki:** Investigation, Writing – original draft. **Anna-Kaisa Ronkanen:** Investigation, Writing – original draft. **Niko Silvan:** Investigation, Writing – original draft. **Oili Tarvainen:** Conceptualization, Methodology, Investigation, Writing – original draft. **Anne Tolvanen:** Investigation, Writing – original draft.

Data availability

Research data (i.e. the reviewed articles) are listed and described in the Supplementary Material.

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.

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