LCA COMMUNICATION AND LCA FOR ISO LABELS

Life cycle assessment of peat for growing media and evaluation of the suitability of using the Product Environmental Footprint methodology for peat

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Abstract

Purpose Peat extraction rapidly removes carbon from the peatland carbon store and furthermore leads to substantial losses of carbon from the extraction site by stimulating decomposition and erosion. Aim of this study is to evaluate whether the Product Environmental Footprint (PEF) approach is suitable for assessing the environmental impacts of white and black peat used in growing media as well as to provide generic data collected from growing media producers and the scientific literature. It is not the aim of this study to compare different land use options for peatlands.

Method PEF is developed in order to make environmental product declaration claims more reliable, comparable and verifiable across the EU, and to increase consumer confidence in eco-labels and environmental impact information. For PEF-compliant studies all land use activities must be considered. For peat extraction either pristine peatland or previously drained peatland used for forestry or agriculture has to be transformed. Hence, the suitability of land use-related PEF indicators is also investigated.

Results Diesel consumed for peat extraction, electricity used for peat processing and transport are the main contributors to acidification. Fuel production and consumption are the main contributors to human toxicity, with heavy metals to air and freshwater the contributing emissions. Ionising radiation, ozone depletion and resource depletion of minerals and metals are mainly caused by the electricity used. Climate change increased from 26 kg CO_{2eq} per m^3 processed white peat to 51 kg CO_{2eq} per m^3 processed black peat. The use of peat causes substantially higher GHG than the previous life cycle stages combined; white peat causes approximately 183 kg CO_{2eq} per m^3 and black peat 257 kg CO_{2eq} per m^3.

Conclusions Environmental impacts caused by peat are variable and depend on a number of spatial and temporal factors. Although most indicators used for PEF are suitable for assessing peat systems, that does not apply for the land use indicator and is at least questionable for the water use indicator, respectively, its weighting factor. Consequently, it is neither possible to identify the most relevant impact categories based on normalised and weighted results nor to calculate an overall single score for peat containing growing media. Since normalisation and weighting are mandatory steps for PEF conform impact assessment, the current PEF approach is not suitable to assess peat as intermediate product without adaptation of the land use indicator.

Keywords Peatland · Nutrient release · Land use change · Soil quality indicator · Weighting

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1 Introduction

Land provides the principal basis for human livelihoods and well-being including the supply of food, freshwater and multiple other ecosystem services (Shukla et al. 2019). Amongst the most vulnerable ecosystems to degradation are high-carbon-stock wetlands (including peatlands). Peatland ecosystems contain disproportionally more organic carbon than other terrestrial ecosystems (Beaulne et al. 2021). Peatlands cover only 3% of the world's land area and contain

550 gigatons (Gt) of carbon (Joosten et al. 2012; Laine et al. 2009), but also 12–21% of global soil nitrogen (Limpens et al. 2006). Natural peatlands may shift between being carbon and greenhouse gas (GHG) sinks and GHG sources on seasonal and inter-annual time scales and show variability in carbon accumulation rates. Drainage of peatland for various purposes leads to high GHG emissions (Strack and Waddington 2008; Limpens et al. 2008; Murdiyarso et al. 2015; Evans et al. 2019). Drained peatlands are usually considered to be negligible methane sources, but they emit CH_4 under wet weather conditions and from drainage ditches. Whilst ditches cover only a small percentage of the drained area, emissions can be sufficiently high. Drained peatlands emit substantially more CH_4 as undrained ones (Wilson et al. 2016). Drainage causes also N_2O emissions; the total amount depends on the nutrient content of the peat (Salm et al. 2012). Hence nutrient-rich peat causes higher N_2O emissions than nutrient-poor peat

Today there is < 15% of the original wetland area globally than was present 300 years ago (Davidson 2014). Around 65,000 km^2 or 10% of the European peatland area has been lost and 44% of the remaining European peatlands are degraded (Tanneberger et al. 2017). Peat is used for energy generation, horticulture, landscaping and other purposes. Peat extraction rapidly removes carbon from the peatland carbon store and furthermore leads to substantial losses of carbon from the extraction site by stimulating decomposition and erosion

Peat extraction can be sub-divided into four steps: peatland preparation, peat extraction or excavation, peat processing and peatland restoration. Peatland conversion involves the initial drainage of the peatland. Backhoes and bulldozers cut drainage ditches to lower the water table in the peatland (Waddington et al. 2009). The affected area by drainage was assumed to be twice of the extraction area; the area not used for extraction is called surrounding area (Uppenberg et al. 2001; Zetterberg et al. 2004). For horticultural peat two extraction methods are commonly used. For sod peat blocks of peat are excavated and left on the extraction site to dry. For milled peat the upper peat layer is milled before stockpiling in order to enhance drying

Exhausted peatlands cannot return to functional peatland ecosystems because the viable seed bank has been removed during the extraction process. Reducing the GHG emissions from peat soils is a space- and cost-effective climate change mitigation option within the land use and agricultural sectors (Wilson et al. 2015; Ojanen et al. 2010; Barbier and Burgees 2021; Günther et al. 2020). Soil carbon sequestration and avoidable emissions through peatland restoration are both strategies to tackle climate change. However, restoring peatlands is 3.4 times less nitrogen costly and involves a much smaller land area demand than mineral soil carbon sequestration (Leifeld and Menichetti 2018)

In order to return the exhausted peatland to a net carbon sink again, active restoration is needed. The most common restoration method is rewetting. For that drainage ditches are blocked in order to increase the water table. Abandoned peat extraction sites that are not rewetted remain important sources of carbon emissions. Several studies have demonstrated the co-benefits of rewetting degraded peatlands for biodiversity, and improvement of water storage and quality (Martin-Ortega et al. 2014) with beneficial consequences for human well-being (Bonn et al. 2014; Parry et al. 2014)

Emissions from restoration will likely decrease through time; however, Schaller et al. have shown that even after 18 years of rewetting, peatland was still a GHG source (Schaller, Hofer et al. 2022). In order to return to a fully functioning ecosystem, it can take several decades (Lunt et al. 2010; Alm et al. 2007; Strobl et al. 2019) and it might take up to 2000 years to restore the carbon lost due to peat extraction (Clearly et al. 2005)

Peat extraction leads to substantial carbon losses through vegetation removal during site preparation, drainage of the extraction site and its surroundings and the peat collection process (e.g. milling which increases aeration and oxidation of the upper peat layer) (Barthelmes 2018; Waddington et al. 2009; Sarkkola, eds. Sarkkola 2007). When the sod or milled peat is stored in piles the decomposition of peat continues, which can lead to emissions of particulate matter and can cause methane emissions (Silvan et al. 2012); methane emission from stock piles during winter time are substantially higher than in summer (Nykänen et al. 1996). In addition to particulate emissions from piles, the bare dark and lightweight soils of the excavation sites are easily warmed and susceptible to wind and water erosion (Holden et al. 2006; Li et al. 2018; Tuukkanen et al. 2014). The milling process causes also emissions of particulate matter (Tissari et al. 2006)

Organic matter decomposition is a well-known phenomenon in wetlands when the water table is lowered and the oxygen content in the upper soil or peat layer increases (Grant et al. 2012). Increased oxygen availability initiates a cascade of organic matter breakdown that culminates in peat decomposition (Fenner and Freeman 2011). That causes also the release of nutrients (Wind-Mulder et al. 1996; Nieminen 2004; Tuukkanen et al. 2017) and methane emissions from ditches, which can have substantial impact on the overall GHG emissions from drained peatlands (Sundh et al. 2000; Uppenberg et al. 2001; Zetterberg et al. 2004; Parish et al. 2008)

Peat extraction shows adverse effect on biodiversity and water quality in Ireland (MacDonald 2020). Nutrient export from drained peatland has significant impacts on aquatic environments in the northern hemisphere (Laine et al. 2013). It is difficult to predict the change in concentration of certain nitrogen compounds in peat pore water

since different processes of N cycle are functioning simultaneously (Vassiljev et al. 2018, 2019). In many peat land areas in The Netherlands target concentrations for nitrogen (N) and phosphorus (P) in surface water of peatland catchments are exceeded (van Beek et al. 2007); also elevated dissolved organic carbon (DOC) concentration in Scottish peatland catchments affects drinking water quality (Ferretto et al. 2021). Leaching of nitrate was identified at 16 of the 20 United Kingdom Acid Waters Monitoring Network sites during 2005–2006. Headwaters draining eroded South Pennine (UK) peatlands are nitrogen saturated (Daniels et al. 2012). Draining peatland for agriculture in Germany can release 1.000 kg N·ha^{-1}·yr^{-1} from the top layer (upper 30 cm) (Gäth et al. 1997). In Finland concentrations of nutrients and suspended solids were relatively high in catchments containing drained peatland (Koskinen et al. 2017; Marttila et al. 2018). In Estonia the release of nutrients from peat excavation during the drainage construction and drainage is substantially higher than from natural bogs.[1] The release of nutrients from peat excavation areas causes eutrophication in rivers and may have a mortal effect to river's fish stock. Large quantities of nitrogen are released to freshwater bodies, particularly during storm events, subsequently enter coastal estuarine and marine ecosystems with negative consequences (Wang et al. 2016)

Studies of environmental impacts of peat have mainly focused on greenhouse gases (Zetterberg et al. 2004; Hagberg and Holgrem 2008; Kirkinen et al. 2008; Seppälä eta l. 2010; Grönroos et al. 2013). Different studies generate different results depending on the choice of peatland, surrounding area, production methods and the after-extraction alternatives (Höglund and Martinsson 2013; Murphy et al. 2015). Few LCA studies of peat utilisation (Peano and Loenrincik 2012; Eymann et al. 2015; Stucki et al. 2019) take other than GHG emissions into account

Environmental impacts from land use change such as land preparation before peat extraction and restoration after peat extraction are not always considered by studies mentioned above, despite restoration/renaturation is sometimes required by peat extraction permits. Moreover, most LCA studies of peat utilisation do not take nutrient release and particulate matter emissions from peat extraction areas into account. The reasoning for excluding those emissions is mostly not provided

The Product Environmental Footprint (PEF) approach is developed in order to make environmental product declaration claims more reliable, comparable and verifiable across the EU, and to increase consumer confidence in eco-labels and environmental impact information.[2] During the

development and testing of the approach, the approach has been subject of serious critique from the scientific community (Pedersen and Remmen 2022). The PEF method is continuously updated. The latest update of the PEF method was published in 2019 (Zampori and Pant 2019) and used as Annex of the "COMMISSION RECOMMENDATION on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations" (EC 2021)

Several product systems are examined from various industrial sectors and relevant data provided in PEF-compliant format. Peat as intermediate product is not covered so far; moreover product category rules for growing media are under development but not published yet

Aim of this study is to evaluate whether the PEF approach is suitable for assessing the environmental impacts of peat used in growing media as well as to provide generic data collected from growing media producers and the scientific literature. It is not the aim of this study to compare different land use options for peatlands

2 Methodology

In general, the precautionary principle is applied for this study in order not to underestimate environmental impacts. A life cycle approach following the most recent PEF methodology is used considering all emissions associated with the extraction and processing of peat. According to PEF all known emissions shall be considered (Zampori and Pant 2019). For peat extraction either pristine peatland or previously drained peatland used for forestry or agriculture has to be transformed. Whilst peat is extracted the land is occupied and after peat extraction the area is frequently rewetted, i.e. re-transformed. All land use activities from area preparing to area restoration must be taken into account for PEF-compliant studies (Zampori and Pant 2019).

a. Goal and scope

Goal of this study is to provide information on environmental impacts of peat as intermediate product used for the production of growing media. In addition, the suitability of relevant indicators used for PEF impact categories is assessed for peat as an intermediate product.

In the PEF method, it is required that the functional unit (FU) be defined based on the four elements "what," "how much," "how well," and "how long." Since peat is quantitatively the most important but not the only ingredient in growing media, the latter two questions are not considered here. The FU is 1-m^3 processed white or black peat ready to be used as growing media ingredient. The reference flow equals the FU. The use of growing media is not subject of

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this study, although GHG emissions from peat are calculated according to PAS2050-1 (BSI 2012) and discussed.

Different growing media applications require different peat fractions/qualities. The peat fractions/qualities are producer dependent and related data is protected by confidentiality agreements. For sake of simplicity, an average energy consumption for processing 1-m³ harvested, processed and stored black and, respectively, white peat is used here.

The system boundary includes peatland preparation and restoration, peat extraction, storage, and processing and is shown in Fig. 1; the system boundary is in agreement with Grönoos (Grönroos et al. 2013). It corresponds to a cradle-to-gate analysis. Hence, neither the production of growing media nor its utilisation is part of this analysis apart from GHG emissions from peat, which are separately reported.

Peatland drainage and re-wetting may occur in many different ways over different timescales and their effect cannot simply be attributed to lowering and raising the water table. The variability of peat extraction systems is high (Grönroos et al. 2013). Relevant parameters/assumptions determining emissions particularly of peat extraction are area demand, extraction yield, emission factors for extraction and renaturation/restoration, peat density and moisture, etc. The annual peat yield can vary by a factor of 4 depending on weather conditions, diesel consumption by a factor of 3, the surrounding area by a factor of 2 and also drainage efficiency (Uppenberg et al. 2001, Hagberg and Holgrem 2008). Particulate matter emissions occur from peatland erosion, peat storage and applied extraction technique. For the latter measurements are available (Tissari et al. 2006) and already used in LCA (Eymann et al. 2015), particulate matter emissions from erosion are highly variable and not considered here. Leaching from drained peatland causes various emissions, such as nutrients, dissolved carbon and suspended solids. In a nutshell, emissions from land use, from peat extraction, from storage and peat processing depend on a number of factors and modelling assumptions. Therefore, it is paramount to describe the data limitation and modelling assumptions, if transparency as well as reliable, reproducible and verifiable results are the final aim.

b. Important assumptions and limitations

– GHG emissions during drainage and area preparation are assumed to be equal as during peat extraction, whilst nutrient emissions are approximately three times higher during drainage than during the extraction.[3] The drainage period can vary between 2 and 5 years (Uppenberg et al. 2001; Hagberg and Holgrem 2008).

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[3] https://iwlearn.net/resolveuid/c4566dea8a4af31111af7ec4feea599f

– Land previously used for forestry or agricultural is considered to be burden free, because emissions from drainage are allocated to the previous use (Stichnothe 2021).

– Every ha used for peat extraction causes another ha of "surrounding" area, which has also been drained.

– GHG emissions from land use and land occupation are calculated based on emission factors (EFs) as shown in the Annex. For this study peat extraction in temperate climate is assumed.

– The fossil carbon in peat containing products applied at cultivation in open fields or glasshouses is assumed to be completely oxidised in line with PAS2050-1 and ISO14067 (BSI 2012; ISO 2018).

– Leaching emissions such as nutrients, suspended solids and dissolved organic carbon are taken from Kløve (2001). Nutrient leaching during the restoration period is not known. Therefore, it is assumed that the nutrient emissions correspond with DOC emissions; hence the ratio of DOC leaching during peat extraction and DOC leaching during rewetting is used to calculate nutrient leaching from rewetting.

– Particulate matter (PM) emissions and particle distribution from harvesting are taken from Tissari et al. (2006). PM emissions from wind erosion of the drained area and the stockpiles are not considered.

– Diesel consumption for sod- und milled-peat extraction, on-site transport and processing from German growing media producers is based on an annual average from different sites. It results in approximately 770 l·ha⁻¹·a⁻¹ for black peat, which is broadly in line with Pakere, who reports 7.67 kWh per m³ peat (Pakere and Blumberga 2017).

– The time period for drainage is 3.5 years, for area preparation of previously used peatland 1 year, for peat extraction 20 years and for restoration 20 years. Area-based emissions are calculated and then recalculated on a per m³ basis using the annual average extraction yield. For the drainage period that means emissions per ha and year during drainage multiplied by the drainage period (3.5 years) and divided by the extraction period (15 years), → emissions per ha divided by the annual yield that results in emissions from drainage per m³.

– Emissions from peat storage at the extraction site and at the growing media producer's site are not exactly known. Solbikova reports that 5% of peat-carbon is decomposed per year (Stolbikova and Chertkova 2021), which in agreement with Clearly et al. (2005). The storage period during stockpiling can vary from weeks to years and the onsite storage lasts frequently several months. For this analysis, it is assumed that 95% of decomposed peat-C is emitted as CO_2 and 5% as CH_4. The storage period for stockpiling peat is assumed to be 1 year and on-site storage of processed peat 3 months.

Table 1 Relevant data for peat extraction and processing for horticultural purpose peat extraction

Life cycle stage	This study	Min	Max	Literature
Draining period (pristine peatland) (year)	3.5	2	5	Uppenberg et al. (2001)
Land preparation (previously used peatland) (year)	1	0.25	1	Anonymous
Peat extraction (year)	20	6	25	Peatland report (Uppenberg et al. 2001; Sarkkola 2007)
Peatland restoration (year)	20	0	45	Hagberg and Holgrem (2008)
Diesel white peat ($l \cdot ha^{-1}$)	284	160	410	Anonymous
Yield white peat ($m^3 \cdot ha^{-1}$)	570	550	590	Anonymous
Density$_{dry}$ white peat ($kg \cdot m^{-3}$)	95	90	100	Anonymous
C-content (%)	50	45	55	Estimated based on Chambers et al. (2010) and Moore et al. (2018)
Diesel black peat ($l \cdot ha^{-1}$)	770	510	1000	Anonymous
Yield black peat ($m^3 \cdot ha^{-1}$)	900	750	1200	Anonymous
Density$_{dry}$ black peat ($kg \cdot m^{-3}$)	165	160	169	Anonymous
C-content black peat (%)	70	65	78	Estimated based on IPCC (2006) and Chambers et al. (2010)

– Depending on the occurrence of weed seeds peat sometimes has to be sanitised by steaming before it can be used for growing media (Grießer 2016). Sanitation requires fossil resources, but it is not considered in this study.

– The choice of post-harvest treatment depends on many factors. Here, only rewetting is assumed to be used as post-extraction treatment. Peatland restoration emissions were assumed to be constant over the restoration period, although that is a simplification. The diesel consumption for blocking ditches, etc. is not specified; it was not separately reported by peat producers but included in the figures for peat extraction.

– A transport distance of 20 km in rural areas with a truck 5t of payload capacity is assumed. This is a rather arbitrary choice but can easily be adapted when data on transport means and distances are available.

– For peat long-distance transport, the route from the Baltic to Germany is assumed, which is 3.200-km ocean transport in bulk carrier and 200-km road transport by lorry.

Relevant parameters used in this study are shown in Table 1 and Table 2 together with minimum and maximum values from scientific literature.

2.1 Life Cycle Inventory

An extended literature search is conducted in order to gain relevant data that is complemented by a survey amongst German growing media producers. The latter data is provided on basis of confidential agreement and for this study averaged and anonymised. In general, data selection is based on the hierarchy outlined in the FAO (2016). The life cycle assessment is carried out in Gabi version 10.6.0.110 with background data from the ILCD-database, ecoinvent 3.8[4] (cut-off, capital goods excluded) and GABI in that order. European average datasets (EU-28) of ILCD are used whenever possible.

2.1.1 Modelling emissions from land transformation and occupation, or peat extraction, respectively

Pristine peatland must be drained and the top layer removed, whilst for land previously used for forestry or agriculture just the top layer have to be removed. The material is frequently used to refill exhausted peat extraction areas and/or to block ditches for rewetting.

Emissions from land transformation are calculated using area-based emissions from peat. Area-based GHG EFs are taken from the latest IPCC Guidelines for National GHG Inventories from Wetlands (Hiraishi et al. 2014). EFs for rewetting are taken from Wilson et al. (2016). A similar approach is used for nutrient emissions occurring during land transformation and land occupation. If more information on the location of peat extraction is available the decision tree provided in Annex 1 can be used to select specific national EF.

Fuel consumption data for white and black peat are collected from peat producers in Germany. Moreover, plausibility tests are conducted and the variation of some parameters summarised, which can be used for sensitivity analysis. However, the latter is not part of this paper. Relevant data and references for peat extraction are provided in Table 1 and for leaching in Table 2.

Table 2 Leaching emissions from peatland preparation, peat extraction and peatland restoration

	Drainage and/or land preparation	Peat extraction (PE)	Peatland restoration
Nitrate (kg·ha^{-1}·yr^{-1})	16×duration/PE_period	16	PE×DOC_ratio
Ammonium (kg·ha^{-1}·yr^{-1})	5.4×duration/PE_period	5.4	PE×DOC_ratio
Organic bound N (kg·ha^{-1}·yr^{-1})	4.6×duration PE_period	4.6	PE×DOC_ratio
Phosphate (kg·ha^{-1}·yr^{-1})	0.19×duration/PE_period	0.19	PE×DOC_ratio
DOC (kg·ha^{-1}·yr^{-1})	310×duration/PE_period	310	240
DOC_ratio			240/310

2.2 Life Cycle Impact Assessment (LCIA)

The PEF development and amendments are well documented (Sala et al. 2017, 2018; Fazio et al. 2018, b; Saouter et al. 2018). First, we screen the suitability of PEF's environmental impact categories, and second, we will discuss those EF impact categories that are dominated by the foreground activities and not by background datasets. Environmental Footprint 3.0 version (EF3.0) is used for this study. The suitability of relevant PEF indicators for assessing peat extraction is discussed below.

2.2.1 Land use

The recommended midpoint model for land use is a dimensionless soil quality index (SQI) based on LANCA (Bos et al. 2016). The soil quality index builds upon the aggregation of four indicators from LANCA (Sala et al. 2019). PEF's approach for land use approach does not provide elementary flows for the transformation from or to (drained) peatland; hence land use impacts from peat extraction cannot be properly addressed. Moreover, the LANCA indicator mechanical filtration, used to calculate the soil quality index, is not available for peatland. In the LANCA documentation it is verbatim stated "The soil class *X* displays peatland. The *kf*-value of peatlands is dependent on the degree of decomposition and has to be determined specifically. Therefore, this class has not been included into LANCA®" (Beck et al. 2010). LANCA® characterisation factors for mechanical filtration in peatland are not provided (Bos et al. 2016).[6] Hence, the soil quality indicator of PEF is not suitable for peat extraction and will therefore not used in this study.

2.2.2 Water footprint

[7]Using the AWARE approach (UNEP 2016) is challenging for peat, because drainage of peatland does hardly affect water availability or consumption at the watershed level. The use of water can be specified for all technical processes involved. However, freshwater is drained from peatland and will sooner or later enter coastal estuarine and marine ecosystems (Wang et al. 2016), but the amount varies between years and is usually not exactly known. This applies also for rewetting exhausted peat extraction sites; the amount of water additionally stored in rewetted peatlands is not exactly known. Hence, neither the amount of drained freshwater from peatland nor the amount for rewetting is included in the results shown in Table 3.[8]

Water stress or water scarcity is usually not an issue in peatland regions. Therefore, this indicator is of minor relevance for peat and peat-containing products. Hence, it is questionable whether the corresponding footprint weighting factor is appropriate when peat systems are assessed.

2.2.3 Eutrophication

Eutrophication in EF3.0 is expressed for three different environmental compartments, namely, eutrophication of freshwater, marine water and terrestrial systems (Zampori and Pant 2019). The latter is relevant for the utilisation of growing media when nutrients are added, but it is not for peat extraction; moreover peat layers are constantly removed. For freshwater and marine eutrophication, the respective RECIPE methods are used. RECIPE considers for freshwater 12 elementary flows (only N) and for marine eutrophication 17 elementary flows (only P) (Bach and Finkbeiner 2017). RECIPE does not consider impacts from biological material (DOC, BOD, or COD[5]) for eutrophication, which is suitable in most peat-related cases because peat is nutrient poor and the eutrophication in respective areas is determined by the nutrient content rather than released organic matter.

3 Results and discussion

Results for white peat from drained peatland, previously used peatland and white peat transported over long distance are shown in Table 3. Table 4 shows[9] disaggregated results

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[6] GHG emissions from peat use, calculated according to PAS 2050–1.

[7] Energy content of peat (20 MJ·kg.$^{-1}$_{dry}).

[5] Biological Oxygen demand (BOD) and Chemical Oxygen Demand (COD).

[8] Without drainage and rewetting.

[9] Without drainage and rewetting.

Table 3 LCIA results of 1 m^3 white peat from pristine peatland, previously used land and white peat transported over long distances

Environmental impact category	Abbreviation and unit	From pristine peatland	From previously used peatland	From previously used peatland with long-term transport	Contribution from land use for the previous column (%)	Contribution from energy (diesel and electricity) (%)
Acidification	Acid (Mole of H+$_{eq..}$)	2.6E−02	2.4E−02	1.1E−01	0	100
Climate change — total	CC-total (kg $CO_{2\,eq.}$)	3.1E+01 (+1.8E+02)	2.6E+01 (+1.8E+02)	3.0E+01 (+1.8E+02)	42 (92)	58 (8)
Ecotoxicity, freshwater — total	ET fw (CTU_e)	7.8E+01	6.8E+01	1.0E+02	23	77
Eutrophication, freshwater	Eutro fw (kg $P_{eq.}$)	2.6E−04	2.2E−04	2.3E−04	88	12
Eutrophication, marine	Eutro ma. (kg $N_{eq.}$)	4.1E−02	3.5E−02	1.0E−02	43	57
Eutrophication, terrestrial	Eutro ter. (Mole of $N_{eq.}$)	1.2E−01	1.1E−01	3.9E−01	-	100
Human toxicity, cancer — total	HT cancer (CTUh)	1.2E−09	1.2E−09	1.9E−09	<1	99
Human toxicity, non-cancer — total (CTUh)	HT non-cancer (CTUh)	1.1E−07	1.0E−07	1.4E−07	5	95
Ionising radiation, human health	Ion HH (kBq $U_{235\,eq.}$)	1.4E+00	1.4E+00	1.4E+00	0	100
Ozone depletion	OD (kg CFC-11 $_{eq.}$)	4.3E−11	4.3E−11	4.3E−11	0	100
Particulate matter	PM (disease incidences)	2.1E−06	2.1E−06	3.6E−06	59	41
Photochemical ozone formation, human health	PCOF (kg $NMVOC_{eq.}$)	3.1E−02	2.8E−02	1.3E−02	1.2	99
Resource use, fossils	Res. fossil (MJ)	8.7E+01 (+1.9E+03)	8.3E+01 (+1.9E+03)	1.0E+02 (+1.9E+03)	0 (90)	100 (10)
Resource use, mineral and metals	Res. min.&met. (kg $Sb_{eq.}$)	1.1E−06	1.0E−06	1.3E−06	0	100
Water use	WU (m^3 $_{world\,equiv.}$)	6.9E−01	6.9E−01	7.1E−02	?	100
Land use	LU (pt)	-	-	-	-	-

for peat extraction from previously used peatland, i.e. without environmental impacts from drainage and long-distance transport.

A number of environmental impacts are associated with the energy used for peat extraction, transport and processing and consequently determined by the background data. The right column in Table 3 shows the contribution of energy production and consumption to the environmental impact categories. Diesel consumed for peat extraction, electricity used for peat processing and transport are the main contributors to acidification, with ocean transport contributing the most. Ocean transport and diesel production are the main contributors to HT-cancer and HT-non-cancer, with heavy metals to air and freshwater the contributing emissions. The picture looks similar for freshwater ecotoxicity where more than 40% is caused by emissions from transport and diesel consumption. Ion-HH, OD and Res M&M are mainly caused by the electricity used for peat processing.

Land use and peat extraction activities contribute the most to CC, Eutro, PM and the fossil resources. White peat extraction and processing causes 31 kg CO_{2eq} per m^3 when transported over long distances, and 26 kg CO_{2eq} per m^3 when extracted close to the growing media producer. During the use phase peat is completely oxidised, which results in 183 kg CO_{2eq} per m^3 and corresponds

Table 4 LCIA results of 1 m³ white peat from previously used land separated into four life cycle stages

Environmental impact category	Abbreviation and unit	Total	Land transformation	Land occupation	Peat processing	Transport (20 km)
Acidification	Acid (Mole of H+ eq.)	2.4E−02	9.2E−04	1.3E−02	7.6E−03	2.0E−03
Climate change — total	CC-total (kg $CO_{2 eq.}$)	2.6E+01 (1.8E+02)[4]	3.1E+00	1.1E+01	1.1E+01	6.7E−01
Ecotoxicity, freshwater — total	ET fw (CTUe)	6.8E+01	1.2E+01	2.6E+01	2.4E+01	6.2E+00
Eutrophication, freshwater	Eutro fw (kg Peq.)	2.2E−04	9.2E−05	1.2E−04	8.9E−06	2.4E−06
Eutrophication, marine	Eutro ma. (kg Neq.)	3.5E−02	1.2E−02	2.0E−02	2.1E−03	8.8E−04
Eutrophication, terrestrial	Eutro ter. (Mole of Neq.)	1.1E−01	4.8E−03	6.9E−02	2.2E−02	9.9E−03
Human toxicity, cancer — total	HT cancer (CTUh)	1.2E−09	2.3E−11	3.3E−10	6.9E−10	1.3E−10
Human toxicity, non-cancer — total (CTUh)	HT non-cancer (CTUh)	1.0E−07	4.1E−09	5.8E−08	3.0E−08	7.9E−09
Ionising radiation, human health	Ion HH (kBq U235 eq.)	1.4E+00	3.7E−04	5.3E−03	1.4E+00	2.4E−03
Ozone depletion	OD (kg CFC-11 eq.)	4.3E−11	9.9E−15	1.4E−13	4.2E−11	6.5E−14
Particulate matter	PM (disease incidences)	2.1E−06	1.3E−09	2.0E−06	5.4E−08	1.2E−08
Photochemical ozone formation, human health	PCOF (kg NMVOCeq.)	2.8E−02	2.2E−03	1.7E−02	6.4E−03	1.8E−03
Resource use, fossils	Res. fossil (MJ)	8.3E+01 (+1900)	1.3E+00	1.9E+01	5.4E+01	8.7E+00
Resource use, mineral and metals	Res. min.&met. (kg Sbeq.)	1.0E−06	1.0E−08	1.5E−07	8.0E−07	6.7E−08
Water use	WU (m³ world equiv.)	6.9E−01	1.1E−03	1.6E−02	6.6E−01	7.4E−03
Land use	LU (pt)	-	-	-	-	-

with a fossil resource use of approximately 1900 MJ per m³ assuming a calorific value of 20 MJ per kg (Uppenberg et al. 2001). Peat is a fossil resource and extracted; thus, all GHG emissions are aggregated rather than separately reported as fossil, biogenic and from land use. If required, it can be easily calculated with the information provided. GHG emissions from the utilisation of white peat are substantially higher than GHG emissions from extraction and processing. The same applies for the use of fossil resources as peat is a fossil resource. PM is mainly caused by peat extraction and ocean transport; if the latter is not required more than 95% is caused by peat extraction. Eutro marine is caused by emissions of various nitrogen species, approximately 70% from nutrient emissions and 30% due to energy use; in summary more than 90% is caused by land preparation and peat extraction. Phosphate emissions from land preparation and occupation cause approximately 90% of Eutro fw.

Results for black peat are shown in Table 5. The system is separated into five life cycle stages. Additionally, to the life cycle stages shown in Table 4,[10] GHG emissions from stockpiling for 1 year at the extraction site are included[11].

In contrast to white peat GHG emissions from stockpiling are singled out, because black peat is usually stored to dry at the extraction site. In peat extraction areas approximately 2% of the area is used for stockpiles. Similar to white peat the diesel consumed for peat extraction and electricity used for peat processing are the main contributors to acidification; ocean transport is not part of the system but would have a similar effect on acidification as for white peat.

Diesel production is the main contributor to HT-cancer and HT-non-cancer, with heavy metals to air and freshwater

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[10] CO_2 emissions from using black peat calculated as for white peat (C-content×44/12).

[11] Without drainage and rewetting.

Table 5 LCIA results of 1 m³ black peat from previously used land separated into five life cycle stages

Abbreviation and unit	Total	Land transformation	Land occupation	Peat stockpiling	Peat processing	Transport (20 km)
Acid (Mole of H+ eq.)	4.2E−02	6.2E−04	2.4E−02		1.3E−02	4.5E−03
CC-total(kg CO₂ eq.)	5.1E+01 (257)	2.1E+00	1.6E+01	2.3E+01	8.8E+00	1.5E+00
ET fw (CTU_e)	8.3E+01	7.9E+00	3.3E+01	8.3E−02	2.7E+01	1.4E+01
Eutro fw (kg P eq.)	1.7E−04	6.3E−05	8.7E−05		1.0E−05	5.5E−06
Eutro ma. (kg N eq.)	3.6E−02	8.2E−03	2.1E−02		4.9E−03	2.0E−03
Eutro ter. (Mole of N eq.)	2.1E−01	3.3E−03	1.3E−01		5.3E−02	2.3E−02
HT cancer (CTUh)	1.7E−09	1.6E−11	6.1E−10		7.5E−10	2.9E−10
HT non-cancer (CTUh)	1.8E−07	2.8E−09	1.1E−07		5.5E−08	1.8E−08
Ion HH (kBq U₂₃₅ eq.)	1.2E+00	2.5E−04	9.8E−03		1.2E+00	5.7E−03
OD (kg CFC-11 eq.)	3.6E−11	6.8E−15	2.6E−13		3.5E−11	1.5E−13
PM (disease incidences)	1.5E−06	8.8E−10	1.4E−06		5.5E−08	2.9E−08
PCOF (kg NMVOC eq.)	5.4E−02	1.5E−03	3.2E−02	2.6E−03	1.4E−02	4.1E−03
Res. fossil (MJ)	1.1E+02 (+3300)	9.0E−01	3.5E+01		5.5E+01	2.0E+01
Res. min.&met. (kg Sb eq.)	1.2E−06	7.0E−09	2.7E−07		7.5E−07	1.5E−07
WU (m³ world equiv.)	6.1E−01	7.7E−04	3.0E−02		5.6E−01	1.7E−02
LU (pt)	-	-	-		-	-

the most relevant emissions. The picture looks similar for freshwater ecotoxicity where emissions from diesel used for peat extraction, transport and processing contribute the most. Ion-HH, OD and Res M&M are mainly caused by the electricity (EU-28-mix) used for peat processing. That of course depends on the electricity mix, and may change when national electricity mixes are used. The environmental impacts discussed so far are determined by the background datasets.

The contributors to the environmental impacts, e.g. fossil resource or acidification, are the same as for white peat, although the figures change. The main difference for black peat compared to white peat is the consideration of stockpile emissions. Methane emissions occur during stockpiling (Nykänen et al. 1996), although very few long-term measurements have been conducted. CC increased from 26 kg CO₂eq per m³ processed white peat to 51 kg CO₂eq per m³ processed black peat, whereat 23 kg CO₂eq coming from stockpiling. Both GHG emissions from using black peat as well as fossil resource are substantially higher because of the elevated C-content of black peat compared to white peat. The same applies to the GHG emissions from using peat; white peat causes approximately 183 kg CO₂eq per m³ and black peat 257 kg CO₂eq per m³. Nutrient emissions from drainage and peat extraction sites are assumed to be the same for black and white on a per ha basis. This is reasonable as both are frequently different layers of the peat profile at the extraction site. Site-specific information on nutrient leaching from peat extraction sites are scarce.

Fig. 1 System boundary of peat production for growing media
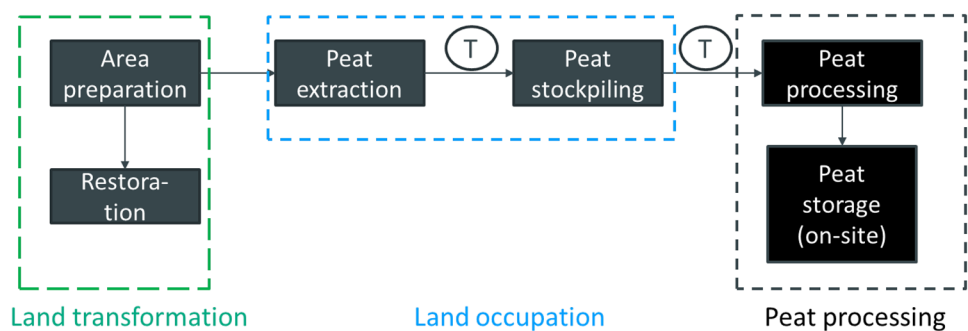
4 Conclusion

Environmental impacts caused by peat extraction, processing and transport are variable and depend on a number of spatial and temporal factors. Peatland restoration might have potential to mitigate the negative climate impact of peat extraction; however, information about the dynamic of annual carbon balances and GHG emissions is limited (Järveoja et al. 2016). In a nutshell, emissions from land use, from peat extraction, from storage and peat processing depend on a number of factors and modelling assumptions. Therefore, it is paramount to describe the data limitation and modelling assumptions, if transparency as well as reliable, reproducible and verifiable results are the final aim.

This paper provides generic values for black and white peat used for horticulture. Data and assumptions are presented in a clear and transparent manner, so that data can be easily adapted to site-specific and/or company-specific conditions.

The PEF approach is used for this study and the corresponding requirements, e.g. for cut-off emissions and complete inventories tested. All land use activities, including land preparation and restoration, must be included as well as the corresponding emissions, i.e. GHG emissions and nutrient emissions. The same applied for emissions due to peat extraction, i.e. emissions from diesel consumption and particulate matter. Although most indicators used for PEF are suitable for assessing peat systems, that does not apply for the land use indicator and it is at least questionable for the water use indicator. The LANCA® characterisation factors for mechanical filtration in peatland are not available. Hence, the aggregated soil quality indicator of PEF is not suitable for peat extraction. The use of water can be specified for all technical processes involved. However, freshwater is constantly drained from peatland, but the amount varies between years and is usually not exactly known. Water scarcity is usually not an issue in regions where peat is extracted; therefore, it is questionable whether the corresponding PEF weighting factor is appropriate. Consequently, it is neither possible to identify the most relevant impact categories based on normalised and weighted results nor to calculate an overall single score.

When land use-related environmental impacts are of interest then climate change, freshwater eutrophication and particulate matter are the most relevant environmental impact categories, with land occupation (peat extraction) as the main contributor. For climate change using peat is much more relevant than its extraction and processing.

This is a cradle-to-gate study that can be used as data source for comparing growing medias of different compositions. However, in that case it must be ensured that the compared systems provide the same function. Solely comparing single compounds of growing media does not provide meaningful information.

Supplementary information.

Declarations

Conflict of interest The author declares no competing interests.

References

Alm J, Shurpali NJ, Minkkinen K, Aro L, Hytönen J, Laurila T, Lohila A, Maljanen M, Martikainen PJ, Mäkiranta P, Penttilä T, Saarnio S, Silvan N, Tuittila E-S, Laine J (2007) Emission factors and their uncertainty for the exchange of CO₂, CH₄ and N₂O in Finnish managed peatlands. Boreal Environ Res 12:191–209

Anonymous - Personal communication with a number of German growing media producers and other experts in the field

Bach V, Finkbeiner M (2017) Approach to qualify decision support maturity of new versus established impact assessment methods—demonstrated for the categories acidification and eutrophication. Int J LCA 22(3):387–397

Barbier EB, Burgess JC (2021) Economics of peatland conservation, restoration, and sustainable management — a policy report for the Global Peatland Initiative. United Nations Environmental Programme. Nairobi 53

Barthelmes AE (2018) Reporting greenhouse gas emissions from organic soils in the European Union: challenges and opportunities. Greifswald, Greifswald Mire Centre 17

Beaulne J, Garneau M, Magnan G, Boucher É (2021) Peat deposits store more carbon than trees in forested peatlands of the boreal biome. Sci Rep 11(1):2657

Beck T, Bos U, Wittstock B, Baitz M, Fischer M, Sedlbauer K (2010) LANCA®: land use indicator value calculation in life cycle assessment. Stuttgart

Bonn A, Allott T, Evans M, Joosten H, Stoneman R (eds) (2014) Peatland restoration and ecosystem services: nature-based solutions

for societal goals. Peatland restoration and ecosystem services: Science, policy and practice. Cambridge, Cambridge University press402–417

Bos U, Horn R, Beck T, Lindner JP, Fischer M (2016) LANCA® — characterization factors for life cycle impact assessment. Version 2.0. Stuttgart

BSI (2012) PAS2050–1: "Assessment of life cycle greenhouse gas emissions from horticultural products - Supplementary requirements for the cradle to gate stages of GHG assessments of horticultural products undertaken in accordance with PAS 2050", British Standards Institution, ISBN 978 0 580 77964 0

Chambers FM, Beilman DW, Yu Z (2010) Methods for determining peat humification and quantifying peat bulk density, organic matter and carbon content for palaeostudies of climate and peatland carbon dynamics. Mires Peat 7(11):1–10

Clearly J. Rourlet NT, Moore TR (2005) Greenhouse gas emisions from Canadian peat extraction. Ambio 34(6):456ff

Daniels SM, Evans MG, Agnew CT, Allott TEH (2012) Ammonium release from a blanket peatland into headwater stream systems. Environ Pollut 163:261–272

Davidson NC (2014) How much wetland has the world lost? Long-term and recent trends in global wetland area. MarFreshw Res 65(10):934–941

EC, (2021) COMMISSION RECOMMENDATION on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations. European Commission, Brussels

Evans CD, Williamson JM, Kacaribu F, Irawan D, Suardiwerianto Y, Hidayat MF, Laurén A, Page SE (2019) Rates and spatial variability of peat subsidence in Acacia plantation and forest landscapes in Sumatra, Indonesia. Geoderma 338:410–421

Eymann L, Mathis A, Stucki M, Amrein S (2015) Torf und Torfersatzprodukte im Vergleich; Eigenschaften, Verfügbarkeit, ökologische Nachhaltigkeit und soziale Auswirkungen. Wädenwill, Zürcher Hochschule für Angewandte Wissenschaften ZHAW 130

FAO (2016) Environmental performance of animal feeds supply chains (version 1). Guidelines for assessment. L. E. A. a. P. P. (LEAP). Rome, Food and Agriculture Organisation of the United Nations (FAO) 132

Fazio S, Castellani, V, Sala S, Schau E, Secchi, M, Zampori L Diaconu E (2018a) Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment methods: New methods and differences with ILCD, EUR 28888 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-79-76742-5, https://doi.org/10.2760/671368, JRC109369.

Fazio S, Zampori L, De Schryver A, Kusche O (2018b) Guide on Life Cycle Inventory (LCI) data generation for the Environmental Footprint, EUR 29560 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-79-98371-9, https://doi.org/10.2760/745658, JRC114593.

Fenner N, Freeman C (2011) Drought-induced carbon loss in peatlands. Nat Geosci 4(12):895–900

Ferretto A, Brooker R, Matthews R, Smith P (2021) Climate change and drinking water from Scottish peatlands: where increasing DOC is an issue? J Environ Manage 300:113648

Gäth S, Anthony F, Becker K-W, Geries H, Höper H, Kersebaum C, Nieder R (1997) Bewertung der standörtlichen Denitrifikationsund Mineralisations/Immobilisations-Potentials von Böden. Mitteilung Der Bodenkundlichen Gesellschaft, Bodenkundliche Gesellschaft 85:1373–1376

Grant RF, Desai AR, Sulman BN (2012) Modelling contrasting responses of wetland productivity to changes in water table depth. Biogeosciences 9:4215–4231

Grießer S (2016) Torfersatzsubstrate für den Erwerbsgartenbau (Anhang 4). Dr.rer.nat. Vechta

Grönroos J, Seppälä J, Koskela S, Kilpeläinen A, Leskinen P, Holma A, Tuovinen J-P, Turunen J, Lind S, Maljanen M, Martikainen P

(2013) Life-cycle climate impacts of peat fuel: calculation methods and methodological challenges. Int J LCA 18(3):567–576

Günther A, Barthelmes A, Huth V, Joosten H, Jurasinski G, Koebsch F, Couwenberg J (2020) Prompt rewetting of drained peatlands reduces climate warming despite methane emissions. Nat Commun 11(1):1644

Hagberg L, Holmgren K (2008) The climate impact of future energy peat production. I. Reports. Stockholm, IVL Swedish Environmental Research Institute Ltd. 74

Hiraishi T, Krug T, Tanabe K, Srivastava N, Jamsranjav B, Fukuda M, Tiffany Troxler T (eds) (2014) 2013 Supplement to the 2006 IPCC guidelines for national greenhouse gas inventories: wetlands. Switzerland, IPCC354

Höglund J, Martinsson F (2013) Comparative review of variations in LCA results and peatland emissions from energy peat utilisation. Stockholm, Swedish Environmental Reserach Instittue

Holden J, Chapman P, Evans M, Hubacek K, Kay P, Warburton J (2006) Vulnerability of organic soils in England and Wales. DEFRA-Report 137

IPCC (2006) IPCC guidelines for national greenhouse gas inventories (agriculture)

ISO (2018) ISO 14067: greenhouse gases — carbon footprint of products — requirements and guidelines for quantification. ISO, Geneva

Järveoja J, Peichl M, Maddison M, Soosaar K, Vellak K, Karofeld E, Teemusk A, Mander Ü (2016) Impact of water table level on annual carbon and greenhouse gas balances of a restored peat extraction area. Biogeosciences 13(9):2637–2651

Joosten H, Tapio-Biström ML, Tol S (2012) Peatlands: guidance for climate change mitigation through conservation, rehabilitation and sustainable use, Food and Agriculture Organization of the United Nations

Kirkinen J, Palosuo T, Holmgren K, Savolainen I (2008) Greenhouse impact due to the use of combustible fuels: life cycle viewpoint and relative radiative forcing commitment. Environ Manage 42(3):458

Kløve B (2001) Characteristics of nitrogen and phosphorus loads in peat mining wastewater. Water Res 35(10):2353–2362

Koskinen M, Tahvanainen T, Sarkkola S, Menberu MW, Laurén A, Sallantaus T, Marttila H, Ronkanen A-K, Parviainen M, Tolvanen A, Koivusalo H, Nieminen M (2017) Restoration of nutrient-rich forestry-drained peatlands poses a risk for high exports of dissolved organic carbon, nitrogen, and phosphorus. Sci Total Environ 586:858–869

Laine J, Minkkinen K, Trettin C (2009) Carbon cycling in northern peatlands. American Geophysical Union

Laine MPP, Strömmer R, Arvola L (2013) Nitrogen release in pristine and drained peat profiles in response to water table fluctuations: a mesocosm experiment. Appl Environ Soil Sci 2013:694368

Leifeld J, Menichetti L (2018) The underappreciated potential of peatlands in global climate change mitigation strategies. Nat Commun 9(1):1071

Li C, Grayson R, Holden J, Li P (2018) Erosion in peatlands: recent research progress and future directions. Earth-Sci Rev 185:870–886

Limpens J, Berendse F, Blodau C, Canadell JG, Freeman C, Holden J, Roulet N, Rydin H, Schaepman-Strub G (2008) Peatlands and the carbon cycle: from local processes to global implications — a synthesis. Biogeosciences 5(5):1475–1491

Limpens J, Heijmans MM, Berendse F (2006) The nitrogen cycle in boreal peatlands. Boreal Peatland Ecosystems Ecological Studies (Analysis and Synthesis). W. R. K. V. D.H., Sringer, Berlin, Heidelberg 188

Lunt P, Allott T, Anderson P, Buckler M, Coupar A, Jones P, Labadz J, Worrall P (2010) Review peatland restoration. Nottingham 45

MacDonald M (2020) Remedial environmental impact assessment report. Dublin, Bord na Móna432

Martin-Ortega J, Allott TEH, Glenk K, Schaafsma M (2014) Valuing water quality improvements from peatland restoration: evidence and challenges. Ecosyst Serv 9:34–43

Marttila H, Karjalainen S-M, Kuoppala M, Nieminen ML, Ronkanen A-K, Kløve B, Hellsten S (2018) Elevated nutrient concentrations in headwaters affected by drained peatland. Sci Total Environ 643:1304–1313

Moore TR, Large D, Talbot J, Wang M, Riley JL (2018) The stoichiometry of carbon, hydrogen, and oxygen in peat. J Geophys Res Biogeosci 123(10):3101–3110

Murdiyarso D, Purbopuspito J, Kauffman JB, Warren MW, Sasmito SD, Donato DC, Manuri S, Krisnawati H, Taberima S, Kurnianto S (2015) The potential of Indonesian mangrove forests for global climate change mitigation. Nat Clim Change 5(12):1089–1092

Murphy F, Devlin G, McDonnell K (2015) Benchmarking environmental impacts of peat use for electricity generation in Ireland—a life cycle assessment. Sustainability 7(6):6376–6393

Nieminen M (2004) Export of dissolved organic carbon, nitrogen and phosphorus following clear-cutting of three Norway spruce forests growing on drained peatlands in Southern Finland. Silva Fenn 38(2):123–132

Nykänen H, Silvola J, Alm J, Martikainen PJ (1996) Fluxes of greenhouse gases CH_4, CO_2 and N_2O on some peat mining areas in Finland. Northern Peatlands in global climatic change, Hyytiälä, Finland, Academy of Finland

Ojanen P, Minkkinen K, Alm J, Penttilä T (2010) Soil–atmosphere CO_2, CH_4 and N_2O fluxes in boreal forestry-drained peatlands. For Ecol Manage 260(3):411–421

Pakere I, Blumberga D (2017) Energy efficiency indicators in peat extraction industry — a case study. Energy Procedia 113:143–150

Parish F, Sirin A, Charman D, Joosten H, Minayeva T, Silvius M, Stringer L (Eds.) (2008) Assessment on peatlands, biodiversity and climate change: main report. Malaysia, Global Environment Centre, Kuala Lumpur and Wetlands International, Wageningen 206

Parry LE, Holden J, Chapman PJ (2014) Restoration of blanket peatlands. J Environ Manage 133:193–205

Peano L, Loerincik Y (2012) Comparative life cycle assessment of horticultural growing media based on peat and other prowing media constituents. Bruessels, QUANTIS 156

Pedersen E, Remmen A (2022) Challenges with product environmental footprint: a systematic review. Int J LCA 27(2):342–352

Sala S, Crenna E, Secchi M, Pant, R (2019) Global normalisation factors for the Environmental Footprint and Life Cycle Assessment, EUR 28984 EN, Publications Office of the European Union, Luxembourg, https://doi.org/10.2760/88930, JRC109878.

Sala S, Benini L, Castellani V, Vidal Legaz B, De Laurentiis V, Pant R (2019) Suggestions for the update of the Environmental Footprint Life Cycle Impact Assessment. Impacts due to resource use, water use, land use, and particulate matter, EUR 28636 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-79-69335-9, https://doi.org/10.2760/78072, JRC106939.

Sala S, Cerutti A, Pant, R (2017) Development of a weighting approach for the Environmental Footprint, EUR 28562 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-79-68041-0 (print),978-92-79-68042-7 (pdf), https://doi.org/10.2760/945290 (online), JRC106545.

Salm J-O, Maddison M, Tammik S, Soosaar K, Truu J, Mander Ü (2012) Emissions of CO_2, CH_4 and N_2O from undisturbed, drained and mined peatlands in Estonia. Hydrobiologia 692(1):41–55

Saouter E, Biganzoli F, Ceriani L, Versteeg D, Crenna E, Zampori L, Sala S, Pant R (2018) Environmental Footprint: update of Life Cycle Impact Assessment methods — ecotoxicity freshwater, human

toxicity cancer, and non-cancer. Luxembourg, Publications Office of the European Union120

Sarkkola SE (2007) Greenhouse impacts of the use of peat and peatlands in Finland. S. Sarkkola. Helsinki

Schaller C, Hofer B, Klemm O (2022) Greenhouse gas exchange of a NW German peatland, 18 years after rewetting. J Geophys Res Biogeosci 127(2): e2020JG005960

Seppälä J, Grönroos J, Koskela S, Holma A, Leskinen PJ, Liski J, Tuovinen JP, Laurila T, Turunen J, Lind S, Maljanen M, Martikainen P, Kilpeläinen A (2010) Climate impacts of peat fuel utilisation chains — a critical review of the Finnish and Swedish life cycle assessments. Helsinki, Finnish Environment Institute 69

Shukla PR, Skeg J, Buendia EC, Masson-Delmotte V, Pörtner HO, Roberts DC, Zhai P, Slade R, Connors S, van Diemen R, Ferrat M, Haughey E, Luz S, Neogi S, Pathak M, Petzold J, Portugal Pereira J, Vyas P, Huntley P, Kissick K, Belkacemi M, Malley J (eds.) (2019) Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Switzerland, IPCC 906

Silvan N, Silvan K, Väisänen S, Soukka R, Laine J (2012) Excavation-drier method of energy peat extraction reduces long-term climatic impact. Boreal Environ Res 17:263–276

Stichnothe H (2021) Carbon footprint of black peat from degraded peatland previously used for agriculture in Germany. The 16th International Peatland Congress, Tallinn, International Peat Society

Stolbikova G, Chertkova E (2021) Peat storage losses investigation. E3S Web of Conferences, SDEMR-2021 278

Strack M, Waddington JM (2008) Spatiotemporal variability in peatland subsurface methane dynamics. J Geophys Res Biogeosci 113(G2)

Strobl K, Kollmann J, Teixeira LH (2019) Integrated assessment of ecosystem recovery using a multifunctionality approach. Ecosphere 10(11):e02930

Stucki M, Wettstein S, Mathis A, Amrein S (2019) Erweiterung der Studie "Torf und Torfersatzprodukte im Vergleich". Wädenwill, Zürcher Hochschule für Angewandte Wissenschaften ZHAW 85

Sundh I, Nilsson M, Mikkelä C, Granberg G, Svensson BH (2000) Fluxes of methane and carbon dioxide on peat-mining areas in Sweden. Ambio 29(8):499–503

Tanneberger F, Tegetmeyer C, Busse S, Joosten H (2017) The peatland map of Europe. Mires Peat 19:1–17

Tissari J, Yli-Tuomi T, Raunemaa T, Tiitta P, Nuutinen J, Willman P, Lehtinen K, Jokiniemi J, Tiitta M, Lehtinen P, Jokiniemi, (2006) Fine particle emissions from milled peat production. Boreal Environ Res 11:283–293

Tuukkanen T, Marttila H, Kløve B (2014) Effect of soil properties on peat erosion and suspended sediment delivery in drained peatlands. Water Resour Res 50(4):3523–3535

Tuukkanen T, Marttila H, Kløve B (2017) Predicting organic matter, nitrogen, and phosphorus concentrations in runoff from peat extraction sites using partial least squares regression. Water Resour Res 53(7):5860–5876

UNEP (2016) Global guidance for Life Cycle Impact Assessment indicators: volume 1. L. C. Initiative

Uppenberg S, Zettenberg L, Åhman M (2001) Climate impact from peat utilisation in Sweden. IVL Report. Stockholm, Swedish Environmental Research Institute

van Beek CL, Droogers P, van Hardeveld HA, van den Eertwegh GAPH, Velthof GL, Oenema O (2007) Leaching of solutes from an intensively managed peat soil to surface water. Water Air Soil Pollut 182(1):291–301

Vassiljev A, Annus I, Kändler N, Kaur K (2018) Modelling of the effect of drained peat soils to water quality using MACRO and SOILN models. Proceedings 2(11): 619

Vassiljev A, Annus I, Kändler N, Kaur K (2019) Modelling of nitrogen concentrations in water from drained peat soils. J Water Supply Res Tech 69(3): 288–297

Waddington JM, Plach J, Cagampan JP, Lucchese M, Strack M (2009) Reducing the carbon footprint of Canadian peat extraction and restoration. Ambio 38(4):194–200

Wang H, Richardson CJ, Ho M, Flanagan N (2016) Drained coastal peatlands: a potential nitrogen source to marine ecosystems under prolonged drought and heavy storm events—a microcosm experiment. Sci Total Environ 566–567:621–626

Wilson D, Dixon SD, Artz RRE, Smith TEL, Evans CD, Owen HJF, Archer E, Renou-Wilson F (2015) Derivation of greenhouse gas emission factors for peatlands managed for extraction in the Republic of Ireland and the United Kingdom. Biogeosciences 12(18):5291–5308

Wilson D, Blain D, Couwenberg J, Evans CD, Murdiyarso D, Page SE, Renou-Wilson F, Rieley JO, Strack M, Tuittila ES (2016) Greenhouse gas emission factors associated with rewetting of organic soils. Mires Peat 17(Article 4):1–28

Wind-Mulder HL, Rochefort L, Vitt DH (1996) Water and peat chemistry comparisons of natural and post-harvested peatlands across Canada and their relevance to peatland restoration. Ecol Eng 7(3):161–181

Zampori L, Pant R (2019) Suggestions for updating the Product Environmental Footprint (PEF) method. JRC Technical Reports. Luxembourg, Publications Office of the European Union 246

Zetterberg L, Uppenberg S, Åhman M (2004) Climate impact from peat utilisation in Sweden. Mitig Adapt Strateg Glob Change 9(1):37–76