The influence of anthropogenic land use on Finnish peatland area and carbon stores 1950–2015

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SUMMARY

This study presents a new data synthesis of Finnish peatland area and carbon (C) store in peat from 1950 to 2015. We present updated results from the most comprehensive compilation of Finnish peat soil properties with associated C accumulation rates from undrained mires and C sources from different forms of anthropogenic land use. Since 1950, different forms of land use of Finnish peatlands have reduced the total peat C store by 3–10 %, approximately 172–510 Tg. The most significant C losses have occurred from forestry-drained peatlands, but significant losses have also occurred from agricultural peat soils, peat extraction, and other forms of peatland exploitation such as building water reservoirs. However, the C accumulation of undrained mires and especially the increased biomass production of drained peatlands have partly compensated for the anthropogenic C losses. The total C store of peatland vegetation biomass (trees, seedlings, ground vegetation, detritus and below-ground roots) was estimated to have increased by 92 Tg due to intensive peatland drainage. The present total C store of Finnish peatland ecosystems was estimated at 5618 Tg, which includes 5079 Tg as peat. The total C store estimate is approximately 1–7 % lower compared to the 1950s. Today, the undrained mires still represent a significant national C sink, with the rate of C sequestration estimated at 0.82 Tg yr^{-1}. However, across all land uses the present peat soil is a C source by 3.7–10.0 Tg yr^{-1}. Significant anthropogenic C losses from peat soil underline the urgent need for sustainable C management of all peatlands, including the preservation of the C store in existing natural mires, stopping land clearing on undisturbed organic soils, and improving the peatland hydrology by restoration to create long-term C sinks especially within the large unproductive drainage area and northern aapa mire area.

KEY WORDS: carbon, drainage, Finland, land use, peatlands

INTRODUCTION

Boreal and subarctic peatlands have accumulated about 370–1055 Pg (Gt) of carbon (C) in peat during the Holocene (Gorham 1991, Maltby & Immerzi 1993, Turunen *et al.* 2002, Yu *et al.* 2010, Page *et al.* 2011, Nichols & Peteet 2019). The most commonly used estimate of 436 Pg C is based on a large synthesis of northern peatlands (Loisel *et al.* 2014). The wide range of global C store estimates mainly reflects uncertainty in the thickness of peat deposits. Peatlands constitute at least 20 % of the global soil C pool (Post *et al.* 1982) and approximately 50 % of the 863 Pg of C currently held in the atmosphere as CO_2 (Le Quéré *et al.* 2018).

Peatlands are the most important reservoir of C in Finland. The total land area of Finland is 30.4 million (M) hectares (ha) (National Land Survey of Finland 2019), of which about 30 % is classified as peatland (Finnish Statistical Yearbook of Forestry 2014). Generally, a high abundance of peat indicates a significant net transfer of C to the soil. The estimated C store in peat is eight-fold larger compared to the C store of tree stands and five-fold larger compared to the forest soil C of Finland (Turunen 2008). Overall, approximately two-thirds of the C reservoir of ecosystems in Finland is in peat (Kauppi *et al.* 1997, Turunen 2008).

The use of peatlands for forestry drainage, agriculture, energy production, road building and peat extraction has reduced the total peatland area of Finland. Since 1950, forestry drainage has been the most extensive land use applied to Finnish peatlands. Historically, approximately 5.7 Mha of the peatland area in Finland has been drained for forestry (Finnish Statistical Yearbooks of Forestry 1979–2014). Today, the area of forestry-drained peatlands is 4.65 Mha, which exceeds the undrained peatland area of 4.11 Mha (Finnish Statistical Yearbook of Forestry 2014). Compared to the results of the Third National

Forest Inventory of Finland 1951–1953 (Ilvessalo 1956, 1957a, 1957b), the total area of every mire type group of different nutrient status has decreased (Finnish Statistical Yearbook of Forestry 2014). Furthermore, 1.2 Mha of forestry-drained peatlands and agricultural peat soils have lost their original peat layer since the 1950s (SVT 1954, Ilvessalo 1956, 1957a, 1957b; Myllys *et al.* 2012, Finnish Statistical Yearbook of Forestry 2014, Kekkonen *et al*. 2019).

Knowledge of Finnish peatland C reservoirs and their changes over recent decades is needed to evaluate the role of peatlands in the national C balance and the long-term sustainability of peatland use. Information on past and present peatland area and types, average peat thickness, dry bulk density, C concentrations, peat, tree and understorey biomass sinks, soil greenhouse gas emissions and dissolved organic carbon output rates are needed to evaluate the changes in Finnish peatland area and C store. This study will update present knowledge of the total C store in Finnish peatlands and changes due to the intensive land use from 1950 to 2015. Minkkinen *et al.* (2002) and Turunen (2008) previously presented extensive studies of C store changes in Finnish peatlands. However, there is a need for a national update based on more precise areal and CO_2 estimates of different land use forms such as forestry-drained peatlands and cultivated agricultural peat soils (Myllys *et al.* 2012, Simola *et al.* 2012, Ojanen *et al.* 2013, Korhonen *et al.* 2017, Statistics Finland 2018, Kekkonen *et al*. 2019). All available datasets are brought together to get an update of the changes in the C store since 1950 and to evaluate the present C balance of Finnish peatlands. All land use forms on peatlands are considered and their effects on peatland area and the total C store are evaluated. Factors causing uncertainties in the C store estimates will be identified.

In this study, both the terms ‘mire’ and ‘peatland’ are used. A mire is a peatland where peat is currently being formed. A peatland is an area with or without vegetation, with a naturally accumulated peat layer at the surface, including mires drained for forestry, agriculture, horticulture and energy production (Joosten & Clarke 2002). Additionally, the terms biological and geological peatlands are used. In Finnish classification, biological peatlands have a peat layer on top of the mineral soil or an understorey vegetation with more than 75 % of mire vegetation (e.g. Cajander 1913, Laine *et al.* 2018, Korhonen *et al.* 2017). Geological peatlands have a peat thickness more than 30 cm and an individual peatland area more than 20 ha (Virtanen *et al.* 2003). For clarity, both biological and geological peatlands can be either treeless or forested.

METHODS

Peatland area

The area of undrained and forestry-drained peatlands and the distribution of peatland types in 1950 were obtained from the Third National Forest Inventory of Finland 1951–1953 (Ilvessalo 1956, 1957a, 1957b). Overall, the National Forest Inventory (NFI) uses systematic cluster sampling where the statistical results are derived from the field sampling plots (Korhonen *et al.* 2017). The changes in areas from 1950 to 1978 were obtained from Keltikangas *et al.* (1986). Area changes from 1978 to 2015 were calculated using the annual statistics of forestry-drained areas (Finnish Statistical Yearbooks of Forestry 1979–2014). Calculations for both undrained and drained peatlands were made using five regions and ten peatland type groups (Figure 1, Table 1). The

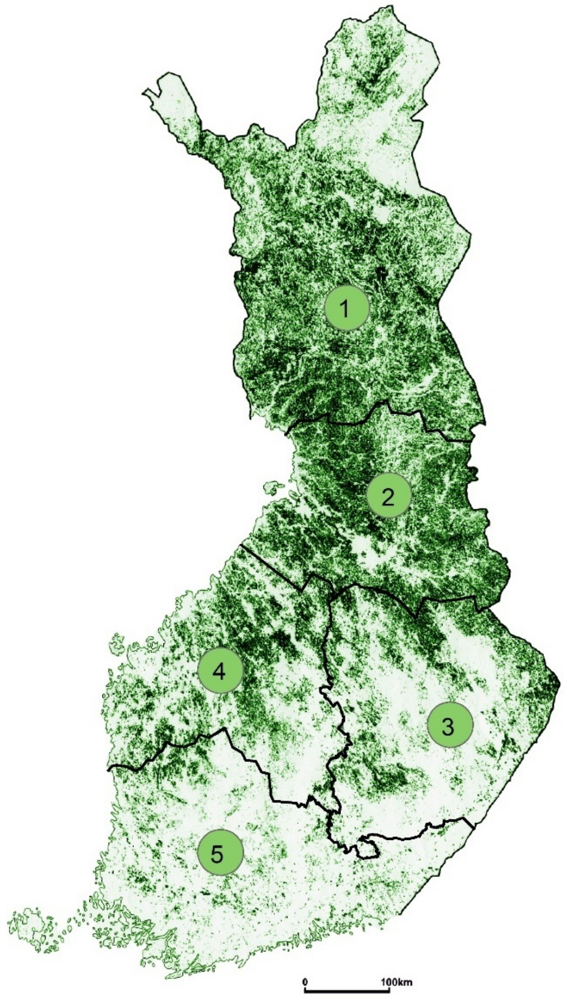

Figure 1. Peatland distribution in Finland (green colour) and the outlines of the five regions used in this study. 1 = Lapland, 2 = northern Ostrobothnia, 3 = eastern Finland, 4 = western Finland, 5 = southern Finland.

general approach is adopted from Minkkinen (1999). However, the total peatland area estimates of all National Forest Inventories (Ilvessalo 1956, 1957a, 1957b, Finnish Statistical Yearbook of Forestry 2014) were used to calibrate the final area estimates. The reason for this is that by following the regional development of the drainage area (Keltikangas *et al.* 1986, Finnish Statistical Yearbooks of Forestry 1979–2014) we get a total existing drained area of 5.7 Mha, which is too high compared to the present-day peatland area found in NFIs (Finnish Statistical Yearbook of Forestry 2014, Figure 2A). In NFIs, all biological peatlands are classified (Korhonen *et al.* 2017). Additionally, the thickness of the organic layer is measured down to 2 metres and the type of subsoil below the organic layer determined. Thus, if the habitat is not classified as a peatland, it can be concluded that the peat layers of former peatlands have been lost through decomposition. However, based on the NFI inventory results from different

Table 1. The peatland type groups. The classification is based on Minkkinen (1999) and Turunen *et al.* (2002). The original (undrained) site types are paired with the drained site types into which they develop following drainage (Laine 1989).

Peatland type group	Mire type	Finnish drained peatland forest type	Ecological classification of peatlands
1	Eutrophic paludified hardwood - spruce forest, LhK Herb-rich hardwood - spruce swamp, RhK Eutrophic hardwood - spruce fen, VLK	Rhtkg (treed)	Eutrophic forested peatlands
2	Paludified *Vaccinium myrtillus* spruce forest, KgK *Vaccinium myrtillus* spruce swamp, MK *Vaccinium vitis-idaea* spruce swamp, PK	Mtkg I (treed)	Meso - oligotrophic forested peatlands
3	Herb-rich sedge fen, RhSN Eutrophic fen, VL Eutrophic flark fen, RiL Herb-rich flark fen, RhRiN	Mtkg II (treeless)	Meso - eutrophic treeless peatlands
4	Eutrophic birch fen, KoL Herb-rich sedge birch - pine fen, RhSR Eutrophic pine fen, LR Tall-sedge hardwood - spruce fen, VSK Herb-rich sedge hardwood - spruce fen, RhSK	Mtkg II (sparsely treed)	Meso - eutrophic sparsely treed peatlands
5	Spruce - pine swamp, KR Paludified pine forest, KgR *Carex globularis* pine swamp, PsR *Carex globularis* spruce swamp, PsK	Ptkg I (treed)	Oligotrophic forested peatlands
6	Tall-sedge fen, VSN Flark fen, VRiN	Ptkg II (treeless)	Oligotrophic open fens
7	Tall-sedge pine fen, VSR Cottongrass - sedge pine fen, TSR	Ptkg II (sparsely treed)	Oligotrophic fen-like sparsely treed peatlands
8	Low-sedge *Sphagnum papillosum* fen, LkKaN Low-sedge fen, LkN *Sphagnum fuscum* bog, RaN	Vatkg (treeless)	Ombro - oligotrophic open bogs
9	Dwarf-shrub pine bog, IR Cottongrass pine bog, TR	Vatkg (treed)	Ombro - oligotrophic pine bogs
10	Sphagnum fuscum pine bog, RaR Ridge-hollow pine bog, KeR Low-sedge *Sphagnum papillosum* pine fen, LkR	Jätkg (sparsely treed)	Ombrotrophic pine bogs

decades, it is difficult to conclude the exact areal loss between different peatland type groups. Generally, it may be reasonable to assume that most of the lost forestry-drained peatland area includes the relatively shallow peatlands and mire margins (e.g. Korhonen *et al*. 2017). According to NFI results, the peatland area including the undrained and forestry-drained peatlands has decreased by 0.95 Mha since the 1950s (Ilvessalo 1956, 1957a, 1957b; Finnish Statistical Yearbook of Forestry 1979–2014). The drainage area weighted calibration was done within the shallowest peatland types which include eutrophic and meso-oligotrophic forested peatlands in Groups 1, 2 and 5 (Table 1). In 1950, the total area of these shallow peatland groups was approximately 2.9 Mha with an area weighted mean peat thickness of 45 cm (Ilvessalo 1956, 1957a, 1957b). The historical time series obtained for different peatland type groups are shown in Figure 2B.

The area estimates of the cultivated agricultural peat soils are based on SVT (1954), Erviö (1982), Myllys *et al*. (2012), Statistics Finland (2018) and Kekkonen *et al*. (2019). The recent area estimate of Kekkonen *et al*. (2019) is largely based on NFI datasets and thematic maps of multi-source NFI, satellite images, aerial photographs and digital maps, including temporarily uncultivated fields, managed uncultivated fields or perennial set-asides.

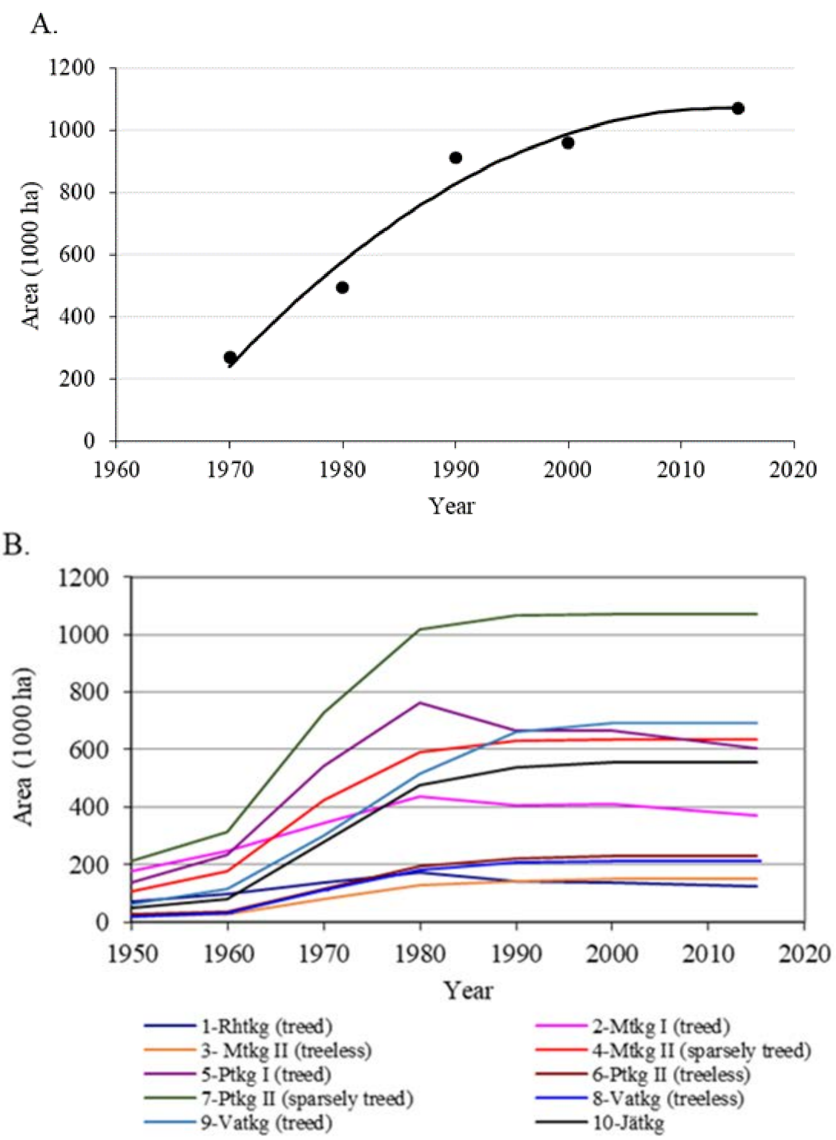

Figure 2. A) The peatland area difference (black dots) between the annual statistics of forestry-drained areas (Keltikangas *et al*. 1986, Finnish Statistical Yearbooks of Forestry 1979–2014) and the total peatland area estimates of the National Forest Inventories (Finnish Statistical Yearbook of Forestry 2014). The curve is a fitted non-linear equation $Y=b_0 + b_1\times \ln(yr) + b_2\times\ln(yr)^2$, $R^2 = 0.97$. B) Forestry-drained peatland area in Finland by peatland type groups from 1950 to 2015 (see Table 1 for the peatland type groups).

Additionally, the grasslands on organic soils, which are mostly abandoned agricultural fields, were included in the calculations (Statistics Finland 2018).

The estimates of active peat extraction areas are based on the published annual statistical information in magazines 'Turveteollisuus' (1975–1990), 'Suo ja Turve' (1991–2003), 'Bioenergia' (2003–2015) and the industry statistics held by the Bioenergy Association of Finland (Hannu Salo, personal communication 2019). However, the areal data derived from NFIs (Statistics Finland 2018) and the Topographic Database of the National Land Survey of Finland (2013) clearly show larger total areas, especially between 1990 and 2015. This total area shows all peat extraction areas regardless of activity and is therefore included in the area estimates as 'non-active'.

The information for artificial lakes and water reservoirs on original peatland areas is based on Järvenpää (2003). The results of Selin (1999) were used to estimate the peatland area under roads and dumps. The distribution of peatland exploitation in Finland in 1950 and 2015 is shown in Figure 3.

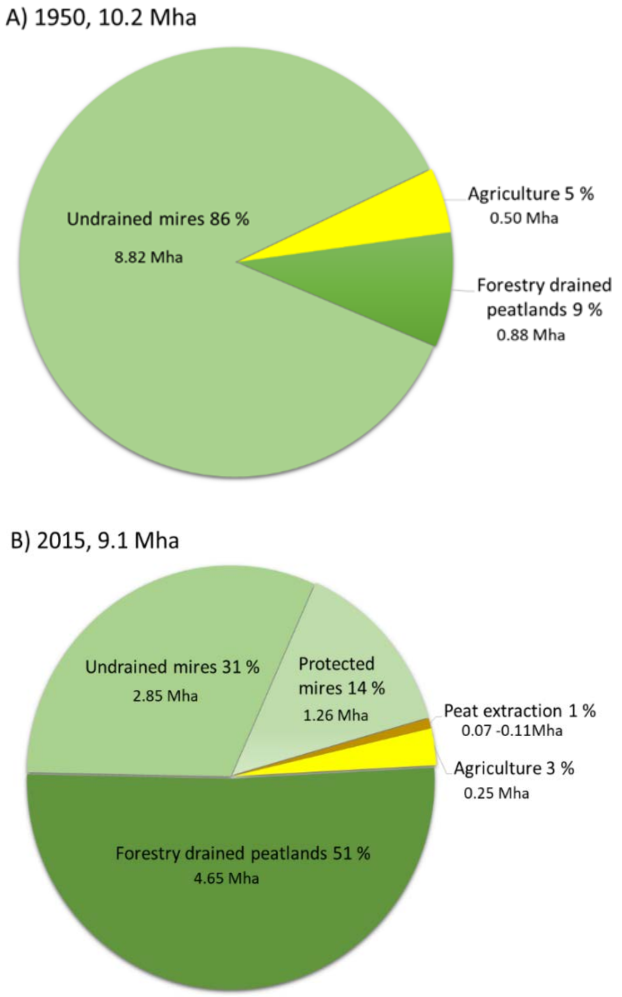

Figure 3. A) Mire exploitation in Finland in 1950 and B) in 2015.

C store

In peatland ecosystems, the total C store includes peat, buried wood in peat, vegetation, and C in the mineral subsoil under peat deposits. The decomposition degree of the buried wood varies from a highly decomposed mass to hard and undecomposed stem and stump material. In this study, the wood material buried in peat is considered to be part of the total peat volume. The magnitude of the actual C store change was evaluated by comparing the C store estimates in 1950 and 2015 based on the development of the peatland area estimates identified in the National Forest Inventories (Ilvessalo 1956, 1957a, 1957b; Finnish Statistical Yearbook of Forestry 2014). The average mass of dry organic matter per unit area was taken from Turunen *et al.* (2002), where the mass values represent the mean peat layer thickness of different peatland type groups within the Finnish mire vegetation regions. For a more detailed description, see Turunen *et al.* (2002). The C store values for each peatland type group were calculated using an average C concentration of 52.3 % (5,312 samples) from the Geological Survey of Finland Database (2019).

In peatland ecosystems, a large amount of biomass is also found in trees (tree stem, roots, stump, foliage, branch). Total tree stand volume in 1950 and 2015 were based on Hökkä *et al.* (2002) and Finnish Statistical Yearbook of Forestry (2014). For tree stems, an average dry bulk density of 426.5 kg m^{-3} (Finnish Statistical Yearbook of Forestry 2014) and 50 % C in dry mass (Mäkinen *et al*. 2006) were used. The obtained tree mass estimates were converted to total biomass estimates based on Korhonen *et al.* (2017). According to Korhonen *et al.* (2017), the stem volume is approximately 57 % of the total biomass. The tree stem volume (m^3) can be converted to total biomass (tonnes dry weight) using a conversion factor of 0.71. Furthermore, the distribution of total tree stand C store of Finnish peatlands was estimated using the average tree stand volume of 39.1 and 63.1 m^3 ha^{-1} (Hökkä *et al.* 2002) for undrained and forestry-drained peatlands, respectively. For the understorey biomass (tree seedlings < 1.5 cm, ground vegetation, detritus and below-ground fine roots < 1 cm), the average biomass values of 698 g m^{-2} and 1948 g m^{-2} were used for undrained and drained peatlands, respectively (Laiho 1997). The dry mass of understorey biomass was converted into the carbon equivalent, based on 50 % C in dry mass (Mäkinen *et al*. 2006). For the mineral subsoil beneath the peat, the results of Turunen *et al*. (1999) were used.

The lack of agricultural peat soil inventories and of information about original peat thickness makes it difficult to estimate the original C store of these cultivated peat soils. However, it is reasonable to assume that agricultural peat soils originally had relatively shallow peat layers, especially in the large cultivated areas of western Finland (Ilvessalo 1957b). An area-weighted mean thickness of 1.1–1.4 m was used for the cultivated peat soils (Virtanen *et al.* 2003). The original C store of agricultural peat soils was estimated using a mean dry bulk density of 0.091 g cm^{-3} (49,953 samples; Mäkilä 1994) and a mean C concentration of 52.3 % (5,312 samples) from the Geological Survey of Finland Database (2019).

For other forms of peatland exploitation (water reservoirs, artificial lakes, roads and dumps), there are no actual inventory data to verify the cumulative peat C loss. For water reservoirs and artificial lakes, we assumed conservatively that 30–60 % of the original C store has been lost. For areas with more intensive building, such as roads and dumps, we assumed that all the peat C has been lost. Values used for the original peatland C store were a mean dry bulk density of 0.091 g cm^{-3}, a C concentration of 52.3 % and a peat thickness of 1.4 m (Mäkilä 1994, Virtanen *et al*. 2003, Geological Survey of Finland Database 2019).

In Finland, there are no official statistics that consider the amount of peat extracted throughout industrial history. However, the peat industry has published annual statistics in the magazines 'Turveteollisuus' (1975–1990), 'Suo ja Turve' (1991–2003) and 'Bioenergia' (2003–2015). The cumulative total of peat extracted from 1970 to 2015 is based on these statistics and verified with the industry statistics held by the Bioenergy Association of Finland (Hannu Salo, personal communication 2019). In this study, the peat extraction information covers both major and minor peat companies. For extracted peat, a mean dry bulk density of 0.178 g cm^{-3} and a mean C concentration of 55 % were used (Alakangas 2000).

C sinks and sources

In undrained peatlands, the C accumulation estimates are based on the long-term rates of C accumulation (LORCA) during the entire Holocene (Turunen *et al.* 2002). LORCA values represent the net C accumulation in peat, including C losses in the form of DOC and through forest fires. Turunen *et al.* (2002) quantified detailed LORCA in different peatland vegetation regions in boreal and subarctic Finland. LORCA was connected to the mean thickness and the areal information of different peatland type groups within the Finnish peatland vegetation regions. In boreal and subarctic regions, the average LORCA can range from 15 to 35 g m^{-2} yr^{-1} depending on the peatland type and geographical location. Generally, the average LORCA estimates are significantly higher in the raised bog region compared to the aapa mire region. For more details, see Tolonen & Turunen (1996) and Turunen *et al.* (2002). In peatland ecosystems, the mineral subsoil under peatlands formed by paludification is an additional C sink and accounts for some 5 % of the peatland C budget (Turunen *et al*. 1999, Turunen & Moore 2003). The average LORCA of 0.5 g m^{-2} yr^{-1} was applied as a net C accumulation in the mineral subsoil for both undrained and drained peatlands (Turunen *et al*. 1999).

For forestry-drained peatlands, the C store change from 1950 to 2015 described earlier was critically evaluated by the new soil CO_2 balance results of Ojanen *et al.* (2013) and the C store change study of Simola *et al.* (2012). The results of Ojanen *et al.* (2013) represent the current soil CO_2 balance of forestry-drained peatlands, whereas the results of Simola *et al.* (2012) represent a long-term C store change after drainage. The results for forestry-drained peatlands used in this study represent a wide range of sites from the most fertile herb-rich type (Rhtkg) to the poor dwarf shrub type (Vatkg). For forestry-drained peatlands we used the average tree C biomass sink of 73 g m^{-2} yr^{-1}, derived from Statistics Finland (2018) as a five-year average (2010–2015) by dividing the annual biomass removals of organic soils by the corresponding area. For undrained peatlands we used a C value of 36 g m^{-2} yr^{-1}, which is half of the value applied for drained peatlands. These values are close to the corresponding average annual increments of tree stand in drained and undrained peatlands (Hökkä *et al.* 2002). The treeless peatland area of approximately 1.49 Mha (Finnish Statistical Yearbook of Forestry 2014) is excluded from the annual tree biomass calculation.

The results of Regina *et al.* (2019) and Maljanen *et al.* (2007) were used to estimate the average CO_2 and CH_4 losses from agricultural peat soils. The results of Regina *et al.* (2019) were divided into two groups: (1) organic soils growing annual crops and (2) perennial crops. The annual C loss as yield was included in the calculations. The average CO_2-C losses from annual crops and perennial crops were 732 and 404 g m^{-2} yr^{-1}, respectively (Regina *et al.* 2019). The corresponding average CH_4-C estimates were -0.04 and 0.11 g m^{-2} yr^{-1}, respectively (Regina *et al.* 2019). For the abandoned grasslands on organic soils we used average CO_2-C and CH_4-C loss estimates of 88 g m^{-2} yr^{-1} (Maljanen *et al.* 2007) and

0.11 g m^{-2} yr^{-1}, respectively (Regina *et al.* 2019). For active peat extraction areas, the average CO_2-C and CH_4-C losses used were 262 g m^{-2} yr^{-1} and 1.69 g m^{-2} yr^{-1}, respectively (Nykänen *et al.* 1996, Sundh *et al.* 2000, Alm *et al.* 2007, Shurpali *et al.* 2008, Hyvönen *et al.* 2009). Based on the synthesis in Seppälä *et al.* (2010), the best estimate for average CO_2-C and CH_4-C losses for the 'non-active' extraction area, which includes surrounding areas and those under preparation or removed temporarily or permanently from working, were 172 g m^{-2} yr^{-1} and 1.69 g m^{-2} yr^{-1}, respectively. These average emissions include extraction strips, ditches, stockpiles and winter emissions.

Fluxes of dissolved organic carbon (DOC) were applied for all drained peatlands based on the annual development of these land use forms between 1950 and 2015. The average DOC output rate of 10 g m^{-2} yr^{-1} (Sallantaus 1992, Rantakari *et al.* 2010) was used for forestry-drained peatlands, agricultural peat soils and peat extraction areas.

RESULTS

Peatlands in the 1950s

In the 1950s the total peatland area, including cultivated agricultural peat soils, was estimated to be 10.2 Mha, (SVT 1954; Ilvessalo 1956, 1957a, 1957b). The undrained mire area was 8.82 Mha, the forestry-drained peatland area 0.88 Mha, and the cultivated peatland area was estimated as 0.50 Mha (SVT 1954; Ilvessalo 1956, 1957a, 1957b). At the time, 86 % of the peatlands were in a natural state. In the 1950s, other forms of peatland exploitation were marginal.

The original and present distributions of the different peatland type groups are shown in Figure 4 (Ilvessalo 1956, 1957a, 1957b; Finnish Statistical Yearbook of Forestry 2014). The comparison is based on the ecological classification of peatlands (Laine 1989), which lists peatland types from nutrient rich eutrophic peatlands to nutrient poor ombrotrophic bogs (Table 1). Undrained and drained peatlands are combined based on their ecological classification. A more detailed description of the drained peatland type groups is given in the Appendix. For comparison, the present peatland type distribution of the studied geological peatlands (2.3 Mha) is also shown in Figure 4C (Geological Survey of Finland Database 2019). Generally, the NFI results seem to create a reliable basis for evaluation of the state and development of different peatland type classes (Ilvessalo 1956, 1957a, 1957b; Finnish Statistical Yearbook of Forestry 2014). In the original

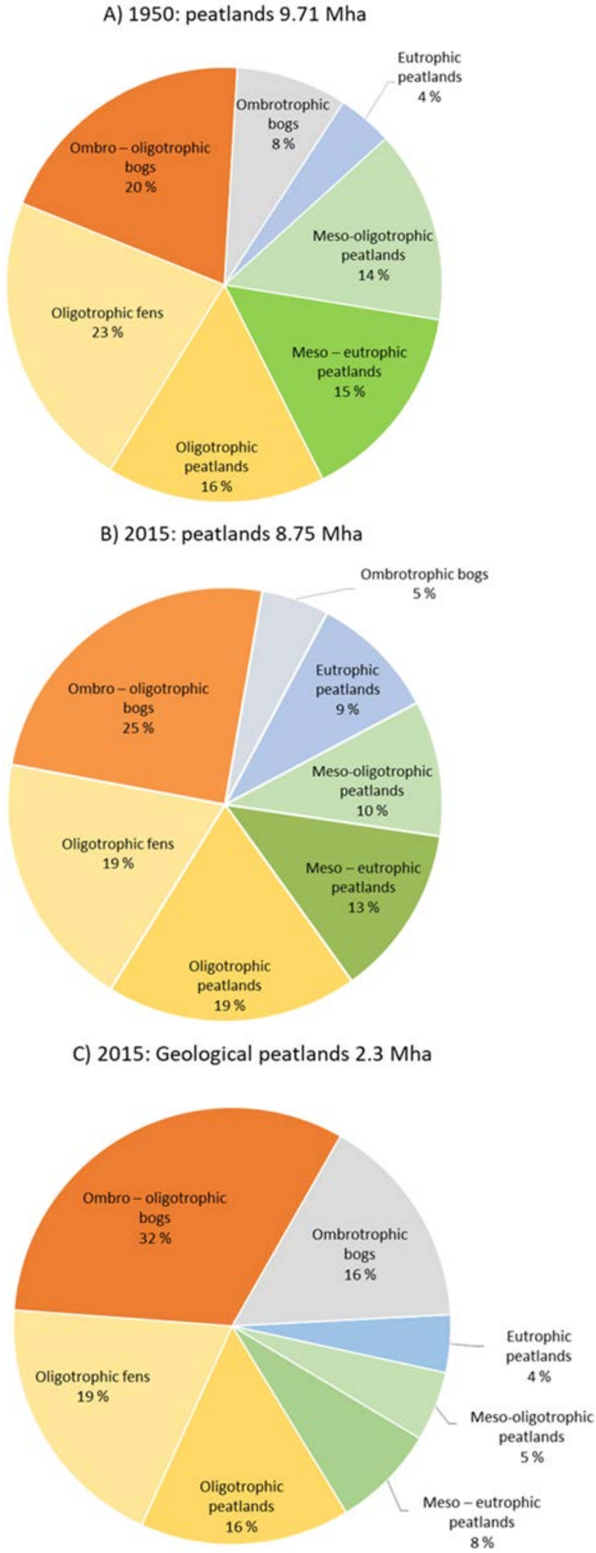

Figure 4. A) The distribution of peatlands based on the ecological classification peatland type distribution excluding the cultivated agricultural peat soils in 1950 B) in 2015 and C) the peatland type distribution of geological peatlands in 2015 (Ilvessalo 1956, 1957a, 1957b; Finnish Statistical Yearbook of Forestry 2014, Geological Survey of Finland Database 2019).

NFI data (Ilvessalo 1956, 1957a, 1957b), the area-weighted mean thickness of different peatland type groups shown in Table 1 was 1.1 m. The mean thickness of Finnish geological peatlands (5.1 Mha) is 1.4 m (Virtanen *et al.* 2003).

In 1950, the total peat C store of Finnish peatland ecosystems was estimated at 5384–5456 Tg (Table 2). This peat C store estimate included 4708 Tg in undrained peatland areas (8.82 Mha), 414 Tg in forestry-drained peatland areas (0.88 Mha) and 262–334 Tg in the cultivated area of peat soils (0.5 Mha). Mineral subsoil under peat deposits is also an additional C store of Finnish peatland ecosystems and was estimated at approximately 299 Tg.

In 1950, the total volume of tree stands in Finnish peatlands was estimated at 252 Mm^3 (Hökkä *et al.* 2002) or 76 Tg C, which included 59 Tg and 17 Tg in undrained and drained peatlands, respectively (Table 2). In 1950, the total amount of understorey biomass in Finnish peatlands was estimated at 70 Tg, which included 62 and 8 Tg in undrained and drained peatlands, respectively. Thus, in 1950, Finnish peatlands would have had about 146 Tg C in biomass. In 1950, the total C store of Finnish peatland ecosystems, including the mineral subsoil, was estimated at approximately 5865 Tg. The estimates of the peatland C store in 1950, changes from 1950 to 2015, and the present-day C store are summarised in Table 2.

In 1950, the large undrained peatland area was also a significant C sink as peat. The annual rate of C sequestration into peat can be estimated at 1.84 Tg yr^{-1} (0.83 and 1.01 Tg yr^{-1} for the southern raised bog and the northern aapa mire regions, respectively). The C sink of tree biomass in undrained and drained peatlands was estimated at 3.3 Tg yr^{-1}, which included 2.7 and 0.6 Tg yr^{-1} in undrained and drained peatlands, respectively (Table 2).

Undrained peatlands 1950–2015

Since 1950, forestry drainage has been the most extensive land use applied to Finnish peatlands. In 1980, the area drained for forestry exceeded the natural peatland area (Ilvessalo 1956, 1957a, 1957b; Finnish Statistical Yearbook of Forestry 1979–2014). Today, the total peatland area of Finland including undrained peatlands and forestry-drained peatlands is 8.76 Mha. The undrained peatland area is approximately 4.11 Mha (Finnish Statistical Yearbook of Forestry 2014), which includes 0.7 Mha in the southern raised bog region and 3.4 Mha in the northern aapa mire region.

Between 1950 and 2015, the total peat C accumulation of the gradually decreased undrained peatland area was estimated at 88 Tg (Figure 5, Table 2). Additionally, a small C sink into the mineral subsoil was estimated at 1.3 Tg, comprising 0.7 and 0.6 Tg for undrained and drained peatlands between 1950 and 2015 (Table 2).

In 2015, the C store of the undrained peatland area was estimated at 2365 Tg as peat (Table 2). The total C store of undrained peatland biomass was estimated at 51 Tg (Table 2), comprising 22 and 29 Tg for tree biomass and understorey biomass C, respectively. Thus, the present total C store of Finnish undrained peatland ecosystems (peat, tree and understorey biomass) is about 2416 Tg. Annually, the rate of peat C sequestration was estimated at 0.82 Tg yr^{-1} (Table 2). Correspondingly, the annual C biomass sink of trees was estimated to be 0.95 Tg yr^{-1} (Statistics Finland 2018).

Forestry-drained peatlands 1950–2015

In total, approximately 5.7 Mha of the peatland area has been drained for forestry (Finnish Statistical Yearbooks of Forestry 1979–2014). Drainage has been most intensive in southern and eastern Finland, where 88–90 % of the peatland area has been drained, in contrast to 23 % in Lapland. Within forestry-drained peatlands the peatland types most commonly drained are oligotrophic forested mires (Group 5) and oligotrophic fen-like sparsely treed mires (Group 7, Table 1), with a total area of 2.3 Mha, which is about 40 % of the total peatland area under drainage and about 80 % of their original area before drainage (Minkkinen *et al.* 2002). Drainage has occurred least on the originally treeless peatlands (Groups 3, 6 and 9), of which about 80 % are in their natural state.

According to the results of the National Forest Inventories (Ilvessalo 1956, 1957a, 1957b; Finnish Statistical Yearbook of Forestry 2014), 0.95 Mha of the original peatland area have lost their peat layers since 1950. Today, the forestry-drained peatland area is estimated at 4.65 Mha (Finnish Statistical Yearbook of Forestry 2014). The C store change of forestry-drained peatlands from 1950 to 2015 was evaluated based on the combined soil CO_2-C balance results of Ojanen *et al.* (2013) and fluxes of dissolved organic carbon (DOC) for drained peatlands (Sallantaus 1992, Rantakari *et al.* 2010). Additionally, the results of the historical C store change studies of Simola *et al.* (2012) were applied for the forestry-drained peatlands. Due to major differences between the CO_2-C balance evaluation methods and, particularly, the different timescales applied in these studies, two independent scenarios were applied for the peat CO_2-C balance of forestry-drained peatlands. In Scenario 1 (S1), the soil C balance of forestry-drained peatlands varies depending on their nutrient status (Ojanen *et al.*

Table 2. Estimated carbon (C) store, C sequestration (+) and C removal (-) of Finnish peatlands from 1950 to 2015. The C balance 2015 of different land use forms is also shown. * = Average 1990–2015 due to seasonal peat extraction differences.

Land use form	1950 C store (Tg)	1950 C balance (Tg yr^{-1})	1950–2015 Cumulative C sequestration or removal (Tg)	2015 C store (Tg)	2015 C balance (Tg yr^{-1})
Undrained mires, peat	4708	+1.84	+88	2365	+ 0.82
Biomass of undrained mires:					
Tree biomass	59	+2.7	-	22	+0.95
Understorey biomass	62	-	-	29	-
Forestry-drained, peat:	414			2358 to 2696	
Scenario 1:					
CO_2, CH_4 emissions		-0.1	-10		-0.2
DOC output		-0.1	-24		-0.5
Scenario 2:					
CO_2, CH_4 emissions and DOC output		-1.3	-360		-7.0
Forestry-drained, biomass:					
Tree biomass	17	+0.6	-	143	+3.4
Understory biomass	8	-	-	44	-
Agricultural peat soils:	262 to 334			151 to 223	
CO_2, CH_4 emissions	-	-2.5	-109		-1.4
DOC output	-	-0.1	-2.3		-0.03
Peat extraction areas:					
Harvested peat C	-	-	-73	-	-2.2*
CO_2, CH_4 emissions			-6.8		-0.2
DOC output			-0.3		-0.01
Water reservoirs and artificial lakes	-	-	-11 to -23	-	-
Roads, dumps and building projects	-	-	-24	-	-
Mineral subsoil	299	-	+1.3	300	-
Peat	5384 to 5456	-1.0 to -2.1	-172 to 510	4874 to 5284	-3.7 to -10.0
Biomass	146	+3.3	-	238	+4.4
Total	5829 to 5901	+1.2 to 2.3	-	5413 to 5822	+0.6 to -5.7

2013). According to Ojanen *et al.* (2013) the peat soil is, on average, a C source of +52 g m^{-2} yr^{-1} at the fertile herb-rich and *Vaccinium myrtillus* type sites, but a C sink of -19 g m^{-2} yr^{-1} at the poor *Vaccinium vitis-idaea* and dwarf shrub type sites. In S1, additional C loss also occurs due to DOC export (Sallantaus 1992, Rantakari *et al.* 2010). In Scenario 2 (S2), C losses through gas emissions and DOC export are included in the total long-term C store change with no clear correlation with site fertility (Simola *et al.* 2012). According to Simola *et al.* (2012), the peat soil is a C source of 150 g m^{-2} a^{-1} on average. In S1, when the corresponding C loss and C accumulation estimates were applied to the development of forestry-drained peatland area between 1950 and 2015, the total C loss by gas emissions and DOC export was estimated at 34 Tg. In S2, the total C loss was estimated at 360 Tg (Figure 6, Table 2). In S1 and S2, the annual rate of C loss was estimated at 0.7 and 7.0 Tg yr^{-1}, respectively (Table 2).

In S1 and S2, the difference between C loss estimates was ten-fold. Therefore, alternative comparisons were accomplished to verify the

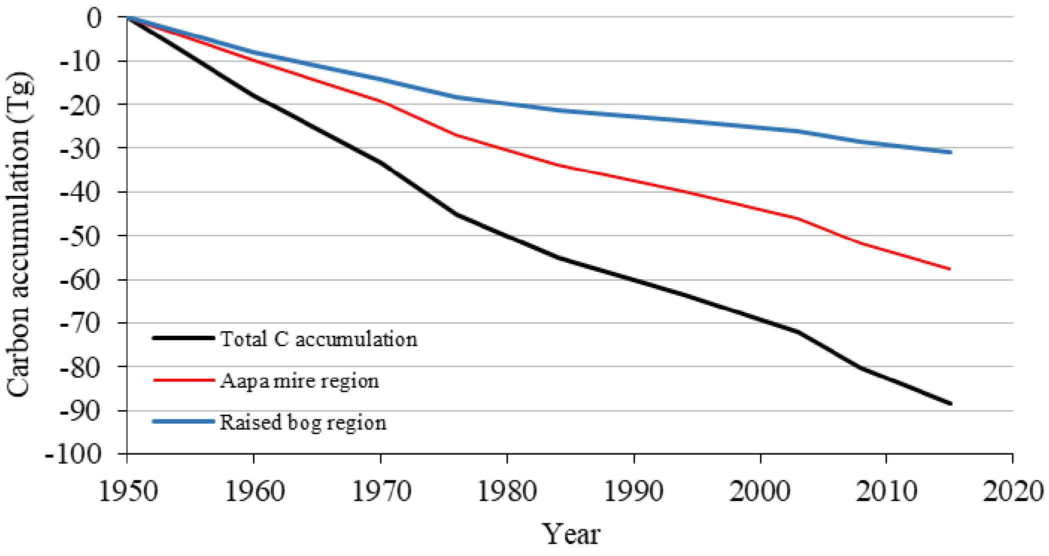

Figure 5. Cumulative C accumulation (Tg) of undrained mire area between 1950 and 2015. The C accumulation in the southern raised bog region and the northern aapa mire region are also shown.

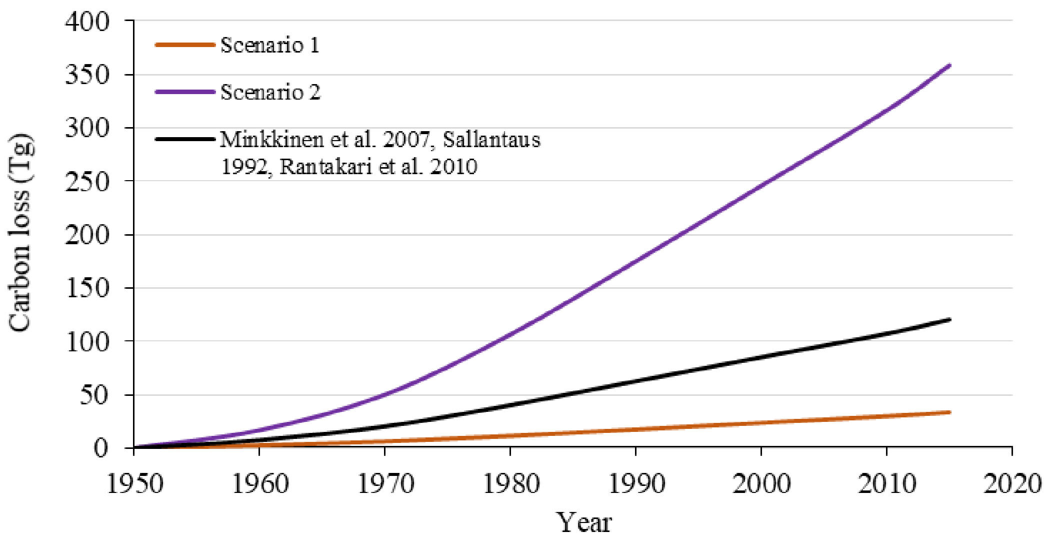

Figure 6. Cumulative peat C loss (Tg) of forestry-drained peatland 1950–2015 according to Scenarios 1 and 2. A cumulative C loss based on combined CO_2 estimates of Minkkinen *et al.* (2007) and DOC estimates of Sallantaus (1992) and Rantakari *et al.* (2010) are shown for comparison.

possible magnitude of C loss due to forestry drainage since the 1950s. To evaluate the original C store of the lost peatland area (0.95 Mha), we used the mean thickness of shallow peatland types indicated in the Third National Forest Inventory of Finland (Ilvessalo 1956, 1957a, 1957b). The shallowest peatland types include eutrophic and meso-oligotrophic forested mires within Groups 1, 2 and 5 (Table 1). The total area of these selected shallow mire types was approximately 1.59 Mha and the area weighted mean peat thickness was 20 cm. Generally, it may be reasonable to assume that most of the lost forestry-drained peatland area includes the relatively shallow peatlands and mire margins (e.g. Korhonen *et al.* 2017). Based on the NFI inventory results from different decades, it is difficult to deduce the exact areal loss between different peatland type groups. There seems to be a general shift in peatland classification towards nutrient rich peatlands since 1950 (Ilvessalo 1956, 1957a, 1957b; Finnish Statistical Yearbook of Forestry 2014). For example, the proportion of the richest peatland type, eutrophic forested mires, was 4 % in the 1950s but 14 % in the latest national forest inventory (Ilvessalo 1956, 1957a, 1957b; Finnish Statistical Yearbook of Forestry 2014). However, by undertaking a simple and rough C budgeting exercise based on a lost peatland area of 0.95 Mha, an average peat layer thickness of 20 cm, a mean dry bulk density of 0.091 g cm^{-3} and a C concentration of 52.3 %, we get a total net C loss estimate of 91 Tg since 1950. This can be considered as a conservative estimate of total C loss since it takes into account the lost C store of shallow peatlands but no other C loss by CO_2 emissions and DOC export from the remaining forestry-drained peatlands. Additionally, a cumulative peat C loss based on heterotrophic soil respiration (Minkkinen *et al.* 2007), below-ground litter input (Laiho *et al.* 2003, Statistics Finland 2018) and DOC estimates (Sallantaus 1992, Rantakari *et al.* 2010) was calculated for forestry-drained peatlands (Figure 6). This cumulative C loss estimate (121 Tg) is of the same magnitude as the value calculated for the shallow peatland area. Based on these alternative C loss estimates, it was concluded that a minimum of 120–360 Tg has been lost due to forestry drainage since 1950.

In 2015, the total C biomass of forestry-drained peatlands was estimated as 187 Tg, comprising 143 and 44 Tg for tree biomass and understorey C biomass, respectively (Table 2). The annual C sink of tree biomass was estimated at 3.4 Tg yr^{-1} (Statistics Finland 2018). Additionally, the mineral subsoil under the peat deposits has been a small additional C sink of 1.3 Tg between 1950 and 2015, comprising 0.6 and 0.7 Tg for drained and undrained peatlands, respectively (Table 2).

In 2015, the total peat C store of the forestry-drained peatland area (4.65 Mha) was estimated to be between 2358 and 2696 Tg (Table 2). Overall, based on S1 and S2 and the development of total biomass, the present total C store of Finnish forestry-drained peatlands (peat, tree and understorey biomass) is approximately 2545–2883 Tg.

Cultivated agricultural peat soils 1950–2015

Since 1950, the total area classified as cultivated peat soils (0.5 Mha) has decreased by approximately 0.2 Mha (Erviö 1982, Myllys *et al.* 2012, Kekkonen *et al*. 2019). According to Erviö (1982), the cultivated area estimate in 1982 was between 0.24 and 0.42 Mha. For recent years, the Finnish Soil Database (Myllys *et al.* 2012) gave an area estimate of 0.25 Mha for the cultivated organic soils. Similarly, Kekkonen *et al*. (2019) gave an estimated total of 0.26 Mha for cultivated organic soils. However, according to Statistics Finland (2018) there is an additional grassland area on organic soils, which consists mostly of abandoned agricultural fields with a total area of 68,000 ha in 2015. According to Statistics Finland (2018) the total cultivated agricultural peat soil area is about 0.33 Mha, which is approximately 12.9 % of the total cultivated area. In 1950, the total annual C loss from Finnish cultivated peat soils by CO_2 and CH_4 emissions and DOC flux was estimated as 2.6 Tg yr^{-1} (Table 2).

Integrated estimates of C losses from agricultural peat soils via gas emissions were calculated assuming a simple cubic decrease of agricultural peat soils between the inventory years 1950 and 2015 (Figure 7a; SVT 1954, Myllys *et al.* 2012, Statistics Finland 2018, Kekkonen *et al*. 2019). The total C loss by gas emissions from cultivated agricultural peat soils was estimated at 109 Tg and the corresponding C loss through DOC flux as 2.3 Tg (Table 2). The total 1950–2015 cumulative C loss of cultivated agricultural peat soils is shown in Figure 7B.

In 2015, the total C store of the cultivated area of peat soils is about 151–223 Tg (Table 2). The total combined annual C loss of Finnish cultivated peat soils by gas emissions and DOC flux can be estimated approximately as 1.4 Tg yr^{-1} (Table 2).

Peat extraction 1950–2015

Before 1970, peat extraction activity was marginal; in 1970, the extraction area was about 3,500 ha. Between 1990 and 2015, the area under active peat extraction has been between 38,200 and 63,500 ha (Figure 8A, data based on magazines ‘Turveteollisuus’ (1975–1990), ‘Suo ja Turve’

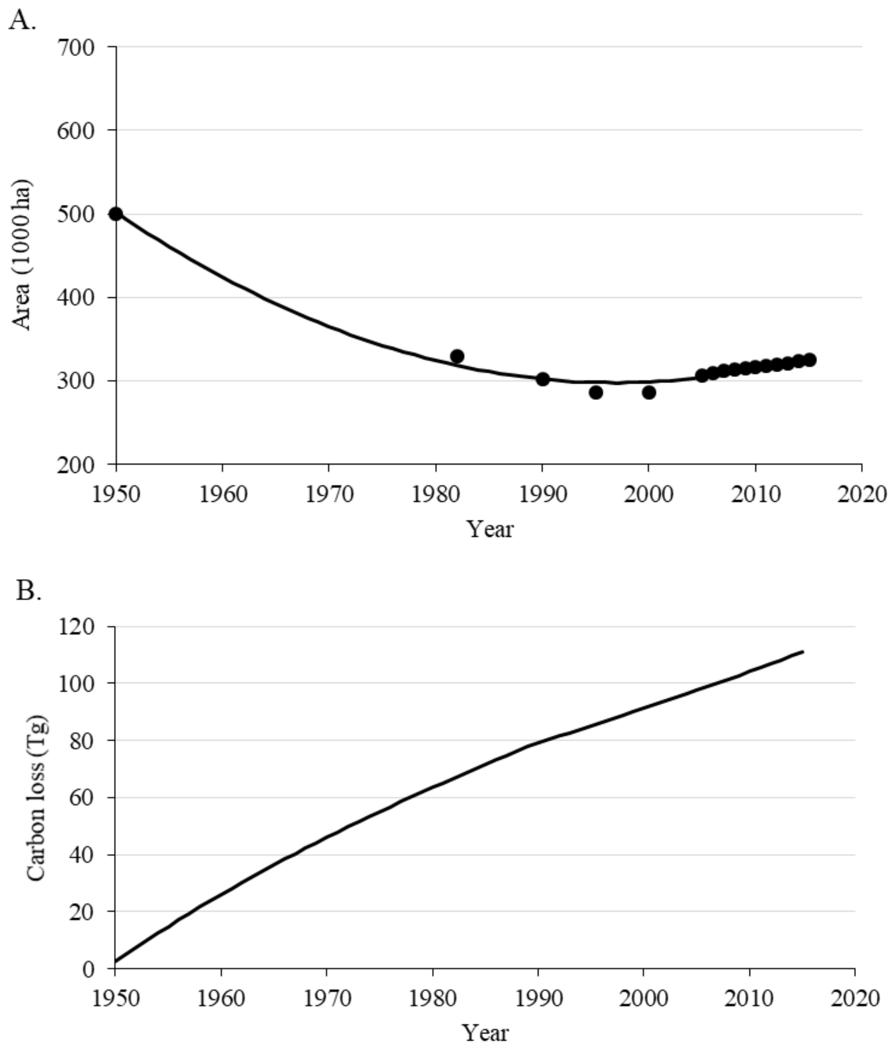

Figure 7. A) Development of cultivated agricultural peat soil area 1950–2015 in Finland (SVT 1954, Erviö 1982, Myllys *et al.* 2012, Statistics Finland 2018 and Kekkonen *et al*. 2019). The curve is a fitted cubic equation $Y=b_0 + (b_1 \times yr) + (b_2 \times yr^2) + (b_3 \times yr^3)$, $R^2 = 0.99$. B) Cumulative C loss (Tg) of cultivated agricultural peat soils 1950–2015. The annual peat C loss as CO_2, CH_4, DOC and as yield were included in the calculations.

(1991–2003), 'Bioenergia' (2003–2015), Hannu Salo, personal communication 2019). Based on different data sources, estimates of the total area of peat extraction throughout the past decades cover a large range. According to Statistics Finland (2018), the total peat extraction area between 1990 and 2015 increases from 81,100 to 114,100 ha (NFIs data, Figure 8A). For comparison, the Topographic Database of the National Land Survey of Finland (2013) gives a similar total estimate of 99,500 ha. The reason for different area estimates may be that the statistical data show areas currently used or prepared for peat extraction, whereas the NFIs data show all peat extraction areas regardless of activity. Since 1950, it is likely that approximately 114,000 ha of peatlands have been used for peat extraction.

During the last decades the annual variation of peat extraction (peat for energy production and horticultural peat) has been large, depending on the weather conditions. For example, between 1990 and 2015, the amount of extracted peat varied between 6.0 and 41.6 Mm^3 (data based on magazines 'Turveteollisuus' (1975–1990), 'Suo ja Turve' (1991–2003), 'Bioenergia' (2003–2015), Hannu Salo, personal communication 2019). In the same period, the average amount of annually extracted peat was about 22.4 Mm^3 and thus the C removed was about 2.2 Tg yr^{-1}. The total amount of peat extracted since the 1970s has been about 741 Mm^3 (Figure 8B) or 73 Tg of C (Table 2).

Between 1970 and 2015, the total C loss by gas emissions and DOC flux from past and present peat

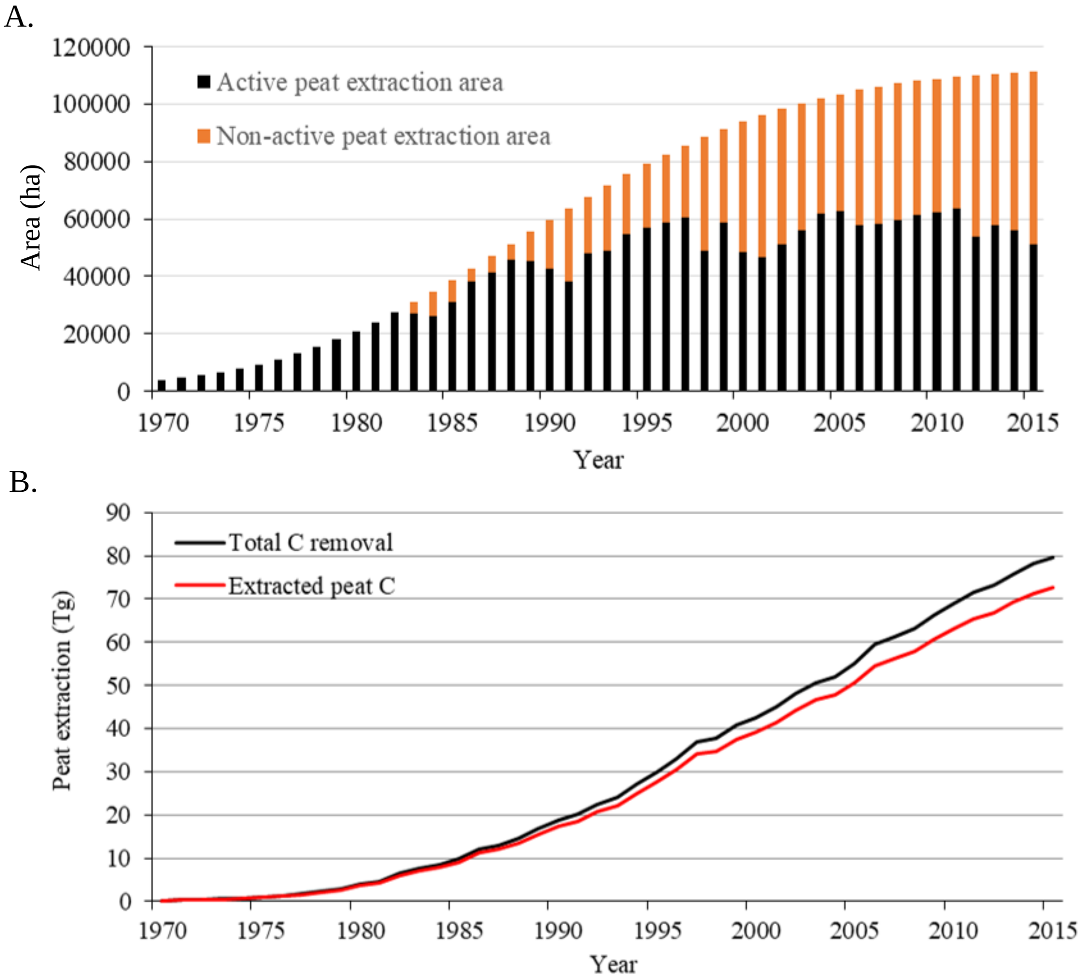

Figure 8. A) Development of industrial peat extraction area in Finland. Statistical data (black) shows areas currently used or prepared in peat extraction (data based on magazines 'Turveteollisuus' (1975–1990), 'Suo ja Turve' (1991–2003), 'Bioenergia' (2003–2015), Hannu Salo, personal communication 2019), whereas the NFIs data (black+orange) shows all cumulative extraction areas regardless of activity (Statistics Finland 2018). B) The cumulative amount of extracted peat C and the total removal including the removal of CO_2, CH_4 and DOC from peat extraction sites in Finland from 1970 to 2015 (extracted peat data is based on magazines 'Turveteollisuus' (1975–1990), 'Suo ja Turve' (1991–2003), 'Bioenergia' (2003–2015), Hannu Salo, personal communication 2019).

extraction areas was estimated at 6.8 Tg and 0.3 Tg, respectively (Table 2). Thus, the total C loss of peat extraction areas by gas emissions and DOC flux was about 7.1 Tg and does not include removal of C via peat extraction. The total annual C loss including the CO_2, CH_4 and DOC loss of peat extraction sites was estimated at 2.4 Tg yr^{-1} (Table 2).

Other forms of peatland exploitation 1950–2015

Relatively large land areas have been lost under water reservoirs, artificial lakes, roads and dumps. Altogether, 240 water level regulation projects have been carried out in Finland, affecting water levels in over 300 lakes corresponding to approximately one third of the Finnish lake area (Finnish Environment Institute 2019). In this study we have used the data of 24 artificial water reservoirs over 50 ha in size, and approximately 54,000 ha of peatlands under the water (Järvenpää 2003). The largest reservoirs are situated in northern Finland including Lokka and Porttipahta. These two reservoirs alone have a combined area of 47,800 ha under water (Karesniemi 1975, Ruuhijärvi & Kukko-oja 1975, Järvenpää 2003). The C losses caused by water reservoirs were estimated at 11–23 Tg (Table 2). According to Selin (1999), a total of 37,000 ha of peatlands are under roads and dumps. The C losses caused by building projects were estimated at 24 Tg (Table 2). The total C losses caused by peatland exploitation were estimated at 35–47 Tg (Table 2).

DISCUSSION

Development of peatland area

In the 1950s, the total peatland area was estimated to be 10.2 Mha, including the cultivated agricultural peat soils (Ilvessalo 1956, 1957a, 1957b; SVT 1954). At the same time, a total 8.8 Mha of peatlands were in a natural state (Ilvessalo 1956, 1957a, 1957b). The use of peatlands for forestry drainage, agriculture, peat extraction and other land use has reduced the total peatland area of Finland by approximately 1.2 Mha. The largest area loss has occurred within forestry-drained peatlands. Since 1950, 17 % of the original mire area drained for forestry has lost its peat layer (Ilvessalo 1956, 1957a, 1957b; Finnish Statistical Yearbook of Forestry 2014). Crucial questions are whether the results of the national inventory are correct and whether the peat mass of this peatland area has been totally or only partially lost?

The results of Reinikainen *et al.* (2000) showed that the distribution and abundance of peatland vegetation has changed over the last 50 years, making the plant communities more similar to those of mineral soil forests. This change in vegetation, and a possibility of the remaining organic material becoming mixed with mineral soil, may be reflected in the results of national forest inventories where some peatlands are classified as forestry land. Some differences may originate from the general estimation characteristics used in National Forest Inventories as indicated by Virkkala *et al.* (2000). Additionally, some areas of cultivated peat soils have been used for forestry and may be classified as forestry land. However, there is no data to challenge the results of the national forest inventory (Finnish Statistical Yearbook of Forestry 2014). On the contrary, it is reasonable to assume that many forestry-drained peatlands and agricultural peat soils originally had a relatively shallow organic layer and have gradually lost their original peat layer (Korhonen *et al.* 2017, Kekkonen *et al.* 2019). In comparison, the mean thickness of Finnish geological peatlands (5.1 Mha) is only 1.4 m (Virtanen *et al.* 2003). Also, the area of cultivated agricultural peat soils has decreased significantly from a large area of 500,900 ha in 1950 to 320,000 ha in 2015 (SVT 1954, Myllys *et al.* 2012, Kekkonen *et al.* 2019, Statistics Finland 2018). The cultivated peat area loss is notable because the clearance of peat soil for agriculture has been relatively large since 1990, approximately 42,900 ha, mostly from the forestry-drained peatlands (Kekkonen *et al.* 2019).

In 2015, the peatland area of Finland including undrained peatlands and forestry-drained peatlands is 8.76 Mha (Finnish Statistical Yearbook of Forestry 2014). Considering the agricultural peat soils and peat extraction areas, the total peatland area of Finland is estimated at 9.08 Mha (Myllys *et al.* 2012, Finnish Statistical Yearbook of Forestry 2014, Statistics Finland 2018, Kekkonen *et al*. 2019). In summary, 51 % (4.65 Mha) of the present peatland area is drained for forestry, 45 % (4.11 Mha) is undrained, 3.5 % (0.32 Mha) is in agriculture and 1.3 % is in active peat extraction or removed temporarily or permanently from the extraction business (0.11 Mha).

Overall, the updated inventories of total peatland area, the historical change and the current estimates of different land use areas can be considered relatively reliable. However, the results of Sallinen *et al.* (2019) indicate that the actual peatland area may be somewhat smaller (8.3 Mha) than the results of NFI (Finnish Statistical Yearbook of Forestry 2014), which are based on field observations from the statistical sample sites. Also, there is some variation with other areal peatland data. According to Sallinen *et al.* (2019), the area of drained peatlands is about 58 %, and thus the drained and undrained peatland areas are approximately 4.8 and 3.5 Mha, respectively. Furthermore, there is some uncertainty in the statistics that consider the total cumulative peat extraction area. Between 1990 and 2015, the active peat extraction area has been between 38,200 and 63,500 ha annually (data based on magazines ‘Turveteollisuus’ (1975–1990), ‘Suo ja Turve’ (1991–2003), ‘Bioenergia’ (2003–2015), Hannu Salo, personal communication 2019). However, in the NFIs, the total peat extraction area between 1990 and 2015 increases up to 114,100 ha (Statistics Finland 2018). The corresponding area estimate in the Topographic Database of the National Land Survey of Finland (2013) is 99,500 ha and Sallinen *et al.* (2019) give an estimate of 112,800 ha based on GIS analysis. The differences between extraction area estimates may originate from the fact that some areas are reported to be under active use or preparation, whereas the larger total cumulative area includes all extraction areas regardless of activity, e.g. peatlands under extraction or preparation, sites removed temporally or permanently from extraction, and sites used for after-use activities (Statistics Finland 2018). In view of the large range in areal estimates, a reassessment of national land use that considers peat extraction and after-use practices is clearly called for. Overall, the technically suitable area for peat extraction (> 1.5 m peat thickness) in Finland is estimated as 1.2 Mha, including protected mire areas (Virtanen *et al*. 2003). However, when the technically suitable peat reserves of the protected mire areas are excluded, the suitable peat extraction area is reduced to approximately 0.8 Mha. Therefore, approximately 14 % of the technically suitable peatland area of Finland has already been used for peat extraction.

Generally, it is worth noting that there are also significant geographical differences in different parts of Finland based on the forestry drainage activity. Drainage has been most intensive in southern and eastern Finland, where 88–90 % of the peatland area has been drained, in contrast to 23 % in Lapland. The impacts of drainage are not just limited to the soil C balance but also include a decrease in the diversity of peatlands (Kaakinen *et al.* 2018). In southern Finland, about 83 % of peatland types were evaluated as endangered. The most endangered peatland types include meso-eutrophic fens and spruce swamps (Kaakinen *et al.* 2018). The present protected peatland area of Finland is about 1.26 Mha or 14 % of the current peatland area (Figure 3B). Regionally, the protection situation is unbalanced, since 66 % (0.85 Mha) of all protected peatlands are situated on state-owned land in Northern Finland (Kaakinen *et al*. 2018).

Evaluation of C accumulation and C loss estimates

For Finnish undrained peatlands, the CO_2-C sink estimates used in this study are based on the long-term rates of C accumulation (LORCA) during the entire Holocene (Tolonen & Turunen 1996, Clymo *et al.* 1998, Turunen *et al.* 2002, Turunen 2003). The LORCA can be considered as a true C sink because the peat mass decreases with time due to continuous aerobic and anaerobic decay and leaching processes from the peat. It is important to acknowledge that the higher estimates of recent apparent rates of carbon accumulation (RERCA) grossly overestimate LORCA (e.g. Pitkänen *et al*. 1999, Turunen *et al*. 2004) as the peat is still actively decomposing in the surface layers. Additionally, severe C losses (order of 100 g m^{-2} yr^{-1}) can occur even in years with an average temperature close to and precipitation well above the long-term means (Alm *et al.* 1999). The Finnish LORCA results are of the same magnitude as the previous synthesis for northern peatlands (Turunen 2003, Yu *et al.* 2010, Loisel *et al.* 2014) with an average LORCA of 18–23 g m^{-2} yr^{-1}.

The LORCA results have been verified by multiyear C exchange balance studies based on the mean NEE-C, CH_4-C exchange and net DOC loss measurements. For example, Roulet *et al.* (2007) found that the mean contemporary 6-year (1998–2004) C exchange balance from a northern ombrotrophic bog is comparable to the LORCA values obtained from peat cores from the same bog for the last 3,000 years (14–22 g m^{-2} yr^{-1}). However, a knowledge of peatland type distribution is essential to evaluate the magnitude of areal C sinks. The difference in LORCA between the raised bog and aapa mire regions of Finland varies significantly, between approximately 15 and 35 g C m^{-2} yr^{-1} (Tolonen & Turunen 1996; Turunen *et al.* 2002). Additionally, considerable variation has been found between different peatland type groups. Generally, ombrotrophic and ombro-oligotrophic bogs are most efficient at C accumulation and the lowest rates have been found in oligotrophic and mesotrophic open fens (Klarqvist 2001, Turunen *et al*. 2002).

The detailed LORCA results in different peatland vegetation regions and peatland type groups in boreal and subarctic regions such as Finland show that the undrained peatlands represent a significant C sink. Between 1950 and 2015, the total C accumulation of the gradually decreasing undrained peatland area is estimated at 88 Tg. However, the extensive use of peatlands has significantly reduced the total annual C sink of Finnish peatlands. In this study, the annual rate of C sequestration into peat in 2015 was estimated at 0.82 Tg yr^{-1} compared to 1.84 Tg yr^{-1} in the 1950s. Thus, the present C sink is less than half compared to 1950s, when 90 % of the peatlands were undrained. The updated net annual C sink of undrained peatlands is in the same magnitude of 0.79 Tg yr^{-1} reported in Turunen *et al.* (2002). An alternative perspective to the magnitude of annual net C sink of Finnish peatlands is to convert the C mass into a peat volume in situ. Using the average dry bulk density value of 0.091 g cm^{-3} (Mäkilä 1994, Geological Survey of Finland Database 2019), the total volume of accumulated peat is approximately 18 Mm^3 yr^{-1}. For comparison, using the method of average growth rate (0.32 mm yr^{-1}) for Finnish undrained peatland area, Mäkilä *et al.* (2002) concluded that the corresponding volume of accumulated peat was 14 Mm^3 yr^{-1}.

The large-scale drainage of peatlands has changed the net uptake of C in Finnish peatlands. In all land use options of organic soil areas, the permanent lowering of the water table exposes normally water saturated surface peat layers and creates a high potential for CO_2 emissions due to peat decomposition and DOC export through ditches (Alm *et al.* 2007). Furthermore, forestry drainage has greatly reduced emissions of CH_4 (Nykänen *et al.* 1998).

When considering Finnish peatlands, the major source of uncertainty is still the representativeness of the soil CO_2 gas balance and C store inventory studies in forestry-drained peatlands (e.g. Minkkinen *et al.* 2007, Simola *et al.* 2012, Ojanen *et al.* 2013). The fundamental difference between the gas measurements and historical C store change involves the monitored timescale and the possible sources of error identified within the studies. Considering the two scenarios used for forestry-drained peatlands in this study, the results of Ojanen *et al.* (2013) represent the current soil CO_2 balance of forestry-drained peatlands, whereas the C store inventory study of Simola *et al.* (2012) represents a 20–30 year net C store change after drainage. Both approaches include uncertainties.

In gas measurement studies, the change in soil C pool is very sensitive to litter input and decomposition processes connected with site fertility, annual water table depths and temperature (e.g. Minkkinen *et al.* 2007, Ojanen *et al.* 2013). The estimation of soil C pool change is based on the subtraction of decomposition of soil organic matter from litter input into the soil (Ojanen *et al.* 2012, 2013). However, the separation of different soil respiration components (heterotrophic soil respiration, belowground litter and autotrophic respiration associated with root biomass) is highly uncertain (e.g. Godbold *et al.* 2003, Ostonen *et al.* 2005, Ojanen *et al.* 2013) and a possible major source of error in gas measurements.

In C store inventory studies, a long-term repeated sampling approach is necessary to verify the relatively small C store change compared to the total C volume within peat profiles. The difficulty of the C store change of the inventory method is to obtain peat profiles from the exact same sites with accurate reference levels for comparison (Sakovets & Germanova 1992, Minkkinen & Laine 1998, Simola *et al.* 2012). Overall, for the total soil C balance, it is crucial that the important DOC export should always be included in the total C budgets when evaluating the development of C balance after drainage (Fraser *et al.* 2001, Roulet *et al.* 2007) and comparing different study methods. In published gas measurement studies, the magnitude of DOC export is rarely measured or evaluated. In long-term inventory C change studies, the C loss via DOC is included in the total C change budget. However, the general difference in soil C balance between gas balance and inventory studies is large even when the DOC export is included in the total C balance of gas measurement studies.

When estimating the soil C store change of forestry-drained peatlands, we can find some similarities but also significant differences in the soil C balance between gas balance and inventory studies (Simola *et al.* 2012, Ojanen *et al.* 2013). First, there is a large scale of variation within and between different peatland type groups caused by drainage. Nutrient rich meso-eutrophic peat soils are, on average, clear C sources. Similarly, Sakovets & Germanova (1992) found a large peat C loss of 32 g m^{-2} yr^{-1} in a nutrient rich site in Karelia 20 years after drainage. Second, sites with both decreased and increased C stores have been found on forestry-drained peatlands. However, on average, large differences occur in the magnitude of the soil C balance (g m^{-2} yr^{-1}). According to Ojanen *et al.* (2013), only the most fertile site types of herb-rich and *Vaccinium myrtillus* sites (Table 1: Groups 1–4) were an average C source of 35–82 g m^{-2} yr^{-1}. All other sites, from oligotrophic forestry-drained sites to poor ombrotrophic pine bogs (Table 1: Groups 5–10) were C sinks of 3–46 g m^{-2} yr^{-1}. According to the soil CO_2 balance study of Ojanen *et al.* (2013), it is notable that especially the oligotrophic forestry-drained sites are the most significant C sinks with values even higher than the average LORCA estimates of undrained peatlands (18–23 g m^{-2} yr^{-1}, Turunen *et al.* 2002, Yu *et al.* 2010, Loisel *et al.* 2014). However, the C store inventory results of Simola *et al.* (2012) indicate an average net loss of 150 g m^{-2} yr^{-1} from all forestry-drained peatlands. According to Minkkinen *et al.* (2007), the heterotrophic soil respiration from drained organic soils is dependent on the fertility. In LULUCF reporting, the results of Minkkinen *et al.* (2007) and litter production (Laiho *et al.* 2003) are used to evaluate the soil C balance of forestry-drained peatlands (Statistics Finland 2018). According to LULUCF reporting, when the emissions and removals are considered, only the most nutrient poor sites of forestry-drained peatlands act as minor soil C sinks. It is clear that the actual C balance status of oligotrophic forestry-drained sites is crucial in overall C budget calculation since these peatland types (Table 1: Groups 5 and 7) are most commonly drained within peatland forestry (Minkkinen *et al.* 2002).

Generally, the high soil C accumulation results of forestry-drained peatlands are in contradiction with many corresponding studies indicating that the water-level drawdown caused by drainage has significantly affected the soil C balance by increasing the soil CO_2 emissions (Braekke 1987, Silvola *et al.* 1996, Turetsky & St. Louis 2006; Pitkänen *et al.* 2012, 2013). Similarly, peatlands are sensitive to the thickness of the aerobic surface layer and can change from C sinks to C sources in years when the summer water table is below the long-term average level (Shurpali *et al.* 1995, Waddington & Roulet 1996, Ohlson & Økland 1998, Alm *et al.* 1999, Belyea & Clymo 2001). The reason for sensitivity is clear as decay is fastest in the zone of water-table fluctuation, intermediate in sites above the water table and slowest in waterlogged peat (e.g. Belyea 1996). Thus, as acrotelm thickness increases, possible increases in productivity are offset by increases in cumulative decay. Supporting this, a large reduced total peatland area found in this study signals a significant net transfer of C to the atmosphere.

Overall, it is plausible that the results of both gas measurement studies and C store inventory studies are correct and just represent the actual monitored timescales. The results of Lohila *et al.* (2011) suggest that forestry drainage may increase the CO_2 uptake rate in forested nutrient poor peatland ecosystems, possibly by increased woody litter input and below-ground productivity. According to Minkkinen *et al.* (2002), reasons for the relatively high C sequestration may also be the relatively minor water level drawdown at many drained sites in Finland (< 40 cm). Over subsequent decades, subsidence and compaction of peat causes the surface to sink and this makes the difference in water table depth from natural sites smaller than the water level drawdown immediately after the drainage. Additionally, in many nutrient poor drained sites, the effect of drainage on water level drawdown has been relatively minor and, thus, the establishment of the tree stand has been ineffective. In some of the unproductive drainage areas, it is also likely that the growth of *Sphagnum* mosses has continued, although with a lower growth rate, and thus increased the water table level naturally. This could partly explain the lower C loss or even small accumulation rates in nutrient poor forestry-drained peatlands linked to the water table (Minkkinen *et al.* 2007, Ojanen *et al*. 2013). However, no extensive C balance studies of drained and nutrient poor peatlands are available to verify the magnitude and possible range in the present soil C balance. Furthermore, the effect of increased aerobic conditions may be reduced by decreased peat pH, temperature and litter quality. The results of Toberman *et al.* (2010) suggest that long-term drainage for forestry has resulted in the reduction of extracellular phenol oxidase activity in the surface peat layers. With pH reduction, this may lead to an increased concentration of soluble phenolics in the soil and inhibition of the hydrolytic decomposition of soil organic matter (Freeman *et al*. 2001).

Export of dissolved organic carbon (DOC) is an important form of C output from peatland catchments, forestry-drained peatlands, cultivated agricultural peat soils and peat extraction areas. Generally, the DOC export from temperate and boreal terrestrial catchments generally range from 1 g m^{-2} yr^{-1} to 50 g m^{-2} yr^{-1}, with the largest export from catchments with high runoff or a high proportion of wetlands within the catchment (e.g. Aitkenhead & McDowell 2000, Roulet *et al.* 2007). In forested catchments in Finland, the average leaching of total organic C is approximately 5–6 g m^{-2} yr^{-1} (Kortelainen & Saukkonen 1998). Rantakari *et al.* (2010) report annual total organic C loads as high as 8–14 g m^{-2} for peatland dominated catchments. In this study, the average DOC output rate of 10 g m^{-2} yr^{-1} (Sallantaus 1992, Rantakari *et al.* 2010) was used for forestry-drained peatlands, agricultural peat soils and peat extraction areas. These export estimates are consistent with values observed in other peatland catchments (e.g. Waddington & Roulet 1997, Aitkenhead & McDowell 2000, Fraser *et al.* 2001, Worrall *et al.* 2003, Billett *et al*. 2004, Roulet *et al.* 2007). In Finland, as far as we know there are very few DOC studies available, particularly from cultivated agricultural peat soils. The results of Rekolainen (1989) suggest that leaching from agricultural land is comparable to the total leaching from forested areas, even though leaching from forested land is much lower per unit surface area (Kortelainen & Saukkonen 1998).

A lack of comprehensive DOC export studies on all drained organic soils causes uncertainties in estimates of the total C store and C export. In peatland forestry, recently published nutrient export studies from Finland indicate that forestry-drained peatlands contribute to water quality much more than previously estimated (Nieminen *et al.* 2017, 2018). The discharge of total nitrogen (N) and phosphorus (P) concentrations were over two times higher in 60 year old drainage areas compared to natural and more recently drained sites (Nieminen *et al.* 2017). The reasons behind an increased nutrient and C loss may be linked to the fact that the ditches in many shallow peatland sites and supplementary drainage areas reach the mineral soil below the peat. Water contact with mineral subsoils may induce very long-term erosion and thus long-term export of N and P (Holden *et al*. 2007; Nieminen *et al*. 2017, 2018). Another reason behind the larger nutrient loss may be that the data from earlier studies comes mostly from relatively young drainage areas drained 20– 30 years ago, and therefore exclude the highly decomposed peat layers in old drainage areas which are eroded more easily (Tuukkanen *et al*. 2014). Additionally, past extensive forest fertilisation and the general management history in drained peatlands may also have induced long-term nutrient exports (Cummins & Farrell 2003a, 2003b, Päivänen & Hånell 2012, Nieminen *et al*. 2018). Furthermore, climatic warming increases peat and thus organic N mineralisation more in older than in recently drained areas because of lower water levels induced by higher transpiration demand of the larger tree stand (Sarkkola *et al*. 2010). Generally, it is possible that the effect of DOC export from older drainage areas within forestry-drained peatlands and cultivated agricultural peat soils has been underestimated. To support this, a very large C loss was found within shallow forestry-drained peatlands in this study. However, it remains unclear what is the magnitude, variation and long-term trend of DOC output from different drained organic soils including forestry-drained peatlands and agricultural peat soils.

Parallel to the effects of drainage on the soil C balance, the possible climate-driven drying of European peatlands (Swindles *et al.* 2019) may lead to drastic loss of peat C stores through enhanced aerobic decomposition by further water-table drawdown (Ise *et al.* 2008). Climate model projections for Europe generally agree on continued warming and reduced growing season moisture availability into the twenty-first century (Jacob *et al.* 2018). The C balance studies of drained peatlands and future climate predictions highlight the importance of the wise use of peat and peatlands. The key aspects of sustainable management will be to maintain and enhance crucial peatland ecosystem services, primarily by improving the peatland hydrology through restoration, especially within the large unproductive drainage area and northern aapa mire area.

The future land use of Finnish peatlands under changing climatic conditions remains partly an open question. Productive forestry-drained peatlands are likely to be used for forestry but with much more cautious soil management, logging and extraction practices (e.g. Lehtonen *et al*. 2019). The nutrient poor and unproductive drainage area of Finland is also large and involves more uncertainty. It is likely that some areas will be left under passive restoration, but many *Sphagnum* dominated areas may also have pressure for other land use options such as *Sphagnum* moss harvesting (Ludwig 2019). Large areas may also be appropriate for active restoration in order to return their long-term C and other nutrient sink functions, diversity of vegetation communities, and hydrological ecosystem services. However, in the decades following the restoration of boreal forestry-drained peatlands, there is likely to be climatic warming until the C accumulation of peat can offset the methane emissions associated with rewetting and restoration (Ojanen & Minkkinen 2020). Small scale peatland restoration has been applied mainly on state-owned land and mire protection areas in Finland by the Metsähallitus enterprise (Alanen & Aapala 2015). The present total restoration area is approximately 33,300 ha (Anttila *et al*. 2019, The Sixth National Report on the Conservation of Biodiversity in Finland 2019).

Carbon store change 1950–2015

In this study, the total mean C store of present Finnish peatland ecosystems was estimated at 5618 Tg, which includes 5079 Tg as peat. Since 1950, different forms of anthropogenic land use of Finnish peatlands have decreased the total peat C store by 3–10 %, approximately 172–510 Tg. Overall, the most significant C losses have occurred from forestry-drained peatlands, but significant losses have also occurred from agricultural peat soils, peat extraction and other forms of peatland exploitation such as building water reservoirs. The peat C store estimate is approximately 5–10 % lower compared to previous studies (Salmi 1950, Kauppi *et al*. 1997, Minkkinen *et al.* 2002, Turunen 2008). Overall, it was concluded that when the soil CO_2-C balance and DOC output results (Sallantaus 1992, Rantakari *et al.* 2010, Ojanen *et al.* 2013) were applied to the development of the forestry-drained peatland area of Finland between 1950 and 2015, the total C loss during the decades was underestimated. This underestimation was obvious when comparing the estimated C loss results (S1) to the total net C loss from the shallow peatland area of 0.95 Mha. Since 1950, the minimum C loss from this shallow peatland area alone was estimated at 91 Tg, whereas the soil CO_2-C balance and DOC output results gave an estimate of only 34 Tg for the whole forestry-drained peatland area. Of course it is plausible that part of the C mass is still mixed with the mineral soil. However, the magnitude of total C loss cannot be explained based on present gas balance measurements. In S2, based on the C store inventory estimates (Simola *et al.* 2012), the total C loss was evaluated as high as 360 Tg, which is likely to be an overestimate because the actual C loss of the nutrient poor and unproductive drainage area may be significantly less than the 150 g m^{-2} yr^{-1} used in this study. It looks likely that the actual net C loss of forestry-drained peatlands since the 1950s is between the values obtained by using the LULUCF estimates (Laiho *et al*. 2003, Minkkinen *et al*. 2007, Statistics Finland 2018) and Simola *et al*. (2012). Naturally, the C store change estimate for forestry-drained peatlands depends on the representativeness of soil CO_2 gas balance estimates and includes large uncertainty. However, it seems inevitable that a much greater C loss has occurred in relatively shallow peatland areas and mire margins than the present C balance estimates indicate. Even if the C budgeting exercise applied in this study were only a rough approximation of the development of the C store of

Finnish peatlands, it makes several important points. First, it reveals the magnitude of the minimum C loss caused by drainage since the 1950s. Second, the results for lost peatland area suggest that the past combined average CO_2 and DOC losses from peat have been significantly larger than expected and this C loss alone can be estimated at 145 g m^{-2} yr^{-1}. This C loss is of the same magnitude as the mean of 150 g m^{-2} yr^{-1} found by Simola *et al.* (2012) for deeper forestry-drained peatlands. However, Braekke (1987) found an even larger C loss of 290 g m^{-2} yr^{-1} in a forestry-drained and fertilised ombrotrophic pine bog with peat layers approximately 3 m deep. Third, this exercise demonstrates the importance of sustainable use of peatlands; the water-level drawdown caused by drainage has clearly had a significant effect on the soil C balance by increasing the soil CO_2 emissions and DOC export of forestry-drained peatland areas. Overall, it can be concluded that approximately 120–360 Tg of C has been lost as peat, due to forestry drainage alone, since 1950.

Since the 1950s, the increased biomass production of drained peatlands has partly compensated for the anthropogenic C losses. The total volume of the tree stand of Finnish peatlands has more than doubled from 252 to 551 Mm^3 (Hökkä *et al.* 2002, Finnish Statistical Yearbook of Forestry 2014, Korhonen *et al.* 2017). Similar results have been found in several studies (Sakovets & Germanova 1992, Minkkinen & Laine 1998, Turunen 2008). In this study, the total C store of peatland vegetation biomass (trees, seedlings, ground vegetation, detritus and below-ground roots) was estimated to have increased by 63 % or 92 Tg due to intensive peatland drainage. The change ‘vegetation biomass’/‘peat’ quotient is also clear. In 1950, the total C biomass found in the vegetation biomass was 2.7 % of the total peat C mass. This is slightly higher compared to Gorham (1991), who estimated that about 1.5 % of the total C is found as vegetation biomass, while 98.5 % occurs in the form of peat. In 2015, however, as much as 4.9 % of the total peatland C occurred in the form of plant biomass. Due to increased biomass production of the forestry-drained peatlands and C accumulation in undrained mires, the total C store estimate of Finnish peatlands is on average only 1–7 % lower compared to the 1950s.

Although the general effect of forestry drainage on total tree biomass has been significant, the effects of drainage on tree stand growth have been poor over large peatland areas. Generally, the total unproductive drainage area where establishment of the tree stand has been ineffective is about 10–20 % of the total forestry-drained area (Mikola 1989, Hökkä *et al.* 2002, Kojola *et al.* 2013, Kojola 2014, Laiho *et al.* 2016, Korhonen *et al.* 2017). However, it is unclear how large the actual unproductive drainage area might be. The reason for this is that the definition for unproductive drainage area varies between different studies and can be based on the canopy cover, annual increment of stems (m^3 ha^{-1} yr^{-1}) or the determined level of stem volume (m^3 ha^{-1}) on forestry-drained peatlands. According to Kojola *et al*. (2013), the total unproductive drainage area is 843,000 ha and most of the area is located on drained peatland forest dwarf-shrub type with pine (Vatkg, 58 %) and drained peatland forest lichen type with pine (Jätkg, 10 %). According to Laiho *et al*. (2016), the peatland area of unproductive land (778,000 ha) is close to the estimate given by Kojola *et al.* (2013). Therefore, it is plausible that slightly lower estimates of total plant biomass should probably be used for the total unproductive drainage area.

The actual C store change of peatlands under large hydroelectric reservoirs such as Lokka and Porttipahta in northern Finland remains an open question. The results of Huttunen *et al*. (2002) showed that, more than 20 years after flooding, the reservoirs were still largely supersaturated with dissolved CO_2 and CH_4. The results of Huttunen *et al*. (2002) indicated a long-term capacity of flooded peat deposits to release nutrients and support high primary production and heterotrophic bacterial production. The flooded biomass and its trophic state were identified as probable factors regulating gas production with the annual primary production C rate between 23 and 65 g m^{-2} in these water reservoirs. These results represent open water conditions. There are indications that CO_2, CH_4 and N_2O emissions during the spring over-turn, for example, can be significantly larger and should thus be included in the total C emission estimates (Huttunen *et al*. 2002).

Carbon balance change 1950–2015

In 1950, the large undrained mire area was a significant C sink as both peat and tree biomass. The annual rate of C sequestration into peat was estimated at 1.84 Tg yr^{-1}. However, the large annual C loss of Finnish agricultural peat soils (0.5 Mha) by gas emissions and DOC flux was estimated at 2.6 Tg yr^{-1} (Table 2). Furthermore, the C loss of forestry-drained peatlands (0.88 Mha) was 0.2–1.3 Tg yr^{-1} depending on the C emission estimates used (Simola *et al.* 2012, Ojanen *et al*. 2013). The total annual C sink of tree biomass in undrained and drained peatlands was estimated at 3.3 Tg yr^{-1}. Thus, the total C sink of Finnish peatlands can be estimated between 1.2 and 2.3 Tg yr^{-1} (Table 2).

Since 1950, different forms of anthropogenic land use of Finnish peatlands have changed the annual C balance. In 2015 the C sequestration rate of undrained mires had decreased by 55 %, to 0.82 Tg yr^{-1}, and the C loss of forestry-drained peatlands had increased to 0.7–7.0 Tg yr^{-1}. The C loss of agricultural peat soils and peat extraction areas can be estimated at 1.4 and 2.4 Tg yr^{-1}, respectively. Overall, it can be concluded that the present peat soil is a C source of 3.7–10.0 Tg yr^{-1}. In LULUCF reporting, Statistics Finland (2018) estimates the total C source of Finnish organic soils to be approximately 4.2 Tg yr^{-1}, which is at the lower end of our C loss range. However, considering the biomass sinks of forestry-drained peatlands and undrained mires, Finnish peatlands act as a small total net C sink of 0.6 Tg yr^{-1} or as a large C source of 5.7 Tg yr^{-1} (Table 2). Overall, considering the wide range and uncertainty of soil C balance estimates of forestry-drained peatlands, the alternative approaches applied in this study to evaluate the soil C balance estimates (e.g. Figure 6) and the research based estimates used in LULUCF reporting (Statistics Finland 2018), it is likely that the peatlands act as a total net C source or the total C balance is close to a steady-state situation.

The results of this study raise serious concerns related to the sustainable land use of peatlands, particularly by showing that considerable CO_2-C and DOC exports have occurred after drainage. Shallow peatlands seem to be particularly vulnerable to large C losses. Already 0.95 Mha have lost their peat layers and almost 1.8 Mha of the remaining peatlands are less than 30 cm in thickness (Finnish Statistical Yearbook of Forestry 2014). Further CO_2-C balance studies of forestry-drained peatland types, especially the oligotrophic peatland types (which include fens), are needed to verify the CO_2-C balance status of these peatlands in Finland. It may be that fens are much more sensitive than bogs to C balance changes due to water-level drawdown and climate change (Bridgham *et al.* 2008, Tahvanainen 2011, Wu & Roulet 2014). The results of Tahvanainen (2011) show that hydrological disturbance in the catchment can affect the ecosystem balance of aapa mires even when the mire itself has not been drained. Additionally, hydrological changes through ombrotrophication can promote the growth of *Sphagnum* over fen vegetation, leading to a severe change in the diversity of fen biota, but at the same time increasing the C accumulation in fens (Tahvanainen 2011).

Generally, the high importance of the large peat C store and long-term C sinks or C sources depending on the peatland drainage status should be fully recognised. The estimated C store in peat is six-fold larger compared to the C store of total tree biomass and four-fold larger compared to the forest soil C of Finland (Figure 9).

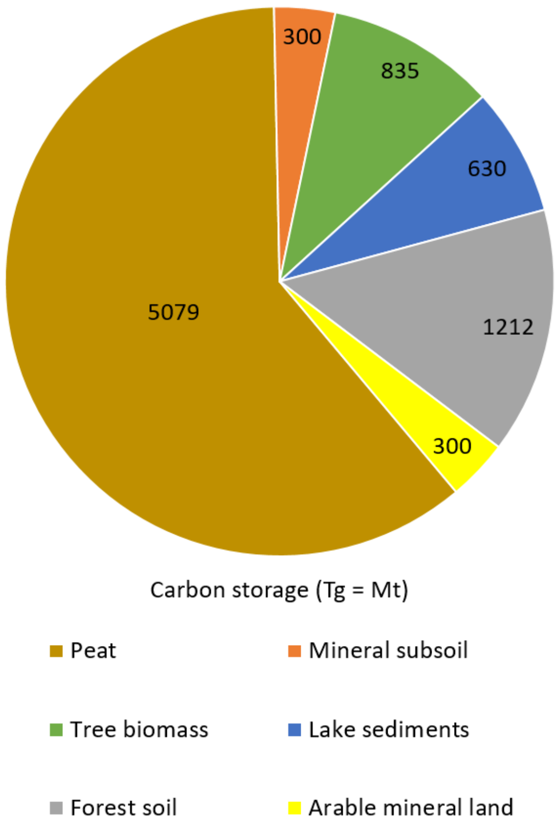

Figure 9. The peat carbon store for 2015 estimated in this study. Additionally, the distribution of other carbon stores of Finland are shown (Liski & Westman 1997, Turunen *et al.* 1999, Pajunen 2004, Kortelainen *et al.* 2004, Heikkinen 2016, Korhonen *et al.* 2017).

Anthropogenic disturbance through different forms of land use transforms the C dynamics of peatlands, usually by terminating peat formation and C sequestration and thus creating a persistent source of atmospheric CO_2. With non-sustainable C management, even a relatively small change in the large peat C store can result in significant C losses which are difficult to compensate with other terrestrial C sinks. An accurate assessment of natural C stores and anthropogenic carbon dioxide (CO_2) emissions is needed to better predict the C cycle, support the development of climate policies, and project future climate change.

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AUTHOR CONTRIBUTIONS

The study idea and design were developed in collaboration with SV and JT. JT is the lead author who wrote the article with SV providing significant comments, suggestions, and discussions during different stages of the work.

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Appendix

In the Finnish classification of drained peatlands in practical forestry, the post-drainage successional plant communities of recently drained areas have been traditionally classified based on their original mire type. However, the older drainage areas have been classified into so called "drained peatland forest types". The drained peatland types follow Laine (1989). A short description of drained peatland forest types is given below.

Rhtkg = drained peatland forest herb-rich type.

- Tree stand mainly composed of spruce (*Picea abies*) with a mixture of birch (*Betula pubescens*) and alder (*Alnus glutinosa*).
- Typical species include *Rubus idaeus, Sorbus aucuparia, Rhamnus frangula, Athyrium filix-femina, Dryopteris expansa, Matteuccia struthiopteris, Thelypteris connectilis, Filipendula ulmaria, Viola sp., Pyrola sp., Calamagrostis purpurea, Rhizomnium sp., Plagiomnium sp., Sphagnum. squarrosum, S. warnstorfii, S. centrale*.
- Peat typically highly decomposed sedge-wood peat.

Mtkg I = drained peatland forest *Vaccinium myrtillus* type.

- Tree stand dominated by spruce (*Picea abies*) with a mixture of birch (*Betula pubescens*).
- Typical species include *Dryopteris carthusiana, Trientalis europaea, Equisetum sylvaticum, Linnea borealis, Maianthemum bifolium, Orthilia secunda, Hylocomium splendens, Polytrichum commune*.
- Peat typically highly decomposed *Sphagnum*-wood peat.

Mtkg II = drained peatland forest *Vaccinium myrtillus* type.

- Tree stand dominated by pine (*Pinus sylvestris*) with a mixture of birch (*Betula pubescens*). Small size spruce (*Picea abies*) is usually found in the understorey layer.
- Typical species similar to Mtkg I type. Usually plenty of *Dryopteris carthusian, Trientalis europaea, Maianthemum bifolium,Vaccinium myrtillus and Vaccinium vitis-idaea*
- Peat typically moderately decomposed *Sphagnum*-sedge peat.

Ptkg I = drained peatland forest *Vaccinium vitis-idaea* type.

- Tree stand varies from spruce (*Picea abies*) to pine forest (*Pinus sylvestris*) with a mixture of birch (*Betula pubescens, B. pendula*).
- Typical species include *V. vitis-ideae, V. myrtillus, V. uliginosum, Ledum palustre, Pleurozium schreberi, Polytrichum commune*
- Peat typically moderately decomposed *Sphagnum*-wood peat.

Ptkg II = drained peatland forest *Vaccinium vitis-idaea* type.

- Mainly pine (*Pinus sylvestris*) with a mixture of birch (*Betula pubescens*).
- Species similar to Ptkg I type.
- Peat typically *Sphagnum*-sedge or sedge-*Sphagnum* peat.

Vatkg = drained peatland forest dwarf-shrub type.

- Tree stand dominated by pine (*Pinus sylvestris*) with some birch (*Betula pubescens*).
- Typical species include *Ledum palustre, Betula nana, Chamaedaphe calyculata, Vaccinium uliginosum, Vaccinium vitis-ideae, V. myrtillus, Pleurozium schreberi, Dicranum polysetum*.
- Peat typically weakly decomposed cotton grass (*Eriophorum*)-*Sphagnum* peat.

Jätkg = drained peatland forest lichen type.

- Sparse tree stand dominated by pine (*Pinus sylvestris*) with some birch (*Betula pubescens*).
- Typical species include *Cladonia arbuscula, Cladonia rangiferina, Calluna vulgaris, Empetrum nigrum,Polytrichum strictum, Pleurozium schreberi, Sphagnum fuscum, S. angustifolium*.
- Peat typically weakly decomposed *Sphagnum* peat.