BOREAL ENVIRONMENT RESEARCH 29: 65–76
ISSN 1797-2469 (online)

Helsinki 27 March 2024

Effect of partial harvesting on exports of dissolved organic carbon and nutrients from drained boreal pine mires

Mika Nieminen[1)*], Leena Stenberg[1)], Kersti Leppä[1)], Annalea Lohila[2)], Kari Minkkinen[3)], Paavo Ojanen[1)3)], Mika Korkiakoski[2)], Timo Penttilä[1)] and Sakari Sarkkola[1)]

[1)] *Natural Resources Institute Finland, Helsinki, Latokartanonkaari 9, FI-00790 Helsinki, Finland*
[2)] *Finnish Meteorological Institute, Climate System Research, Erik Palménin Aukio 1, FI-00101 Helsinki, Finland*
[3)] *Department of Forest Sciences, University of Helsinki, Box 27, FI-00014, Helsinki, Finland*
**corresponding author's e-mail: mika.nieminen@luke.fi*

Received 16 Oct. 2023, final version received 22 Dec. 2023, accepted 9 Jan. 2024

Nieminen M., Stenberg L., Leppä K., Lohila A., Minkkinen K., Ojanen P., Korkiakoski M., Penttilä T. & Sarkkola S. 2024: Effect of partial harvesting on exports of dissolved organic carbon and nutrients from drained boreal pine mires. *Boreal Env. Res.* 29: 65–76.

Continuous cover forestry, where forests are managed only by partial harvestings, has been proposed to mitigate forestry-induced carbon and nutrient exports to receiving water courses. We studied the effects of two partial harvest treatments, strip-cutting at five sites and single-tree harvesting at the other site, on nutrient and dissolved organic carbon (DOC) exports from drained peatland forests. We found that, as well as clear-cutting, partial harvesting may also increase exports from peatland forests. The comparison of our results with earlier studies suggested that other factors than the harvest method, such as harvested stem volume per catchment area, are more important in controlling nutrient and DOC exports. Future research is still needed to produce exact export estimates for partially harvested drained peatland forests.

Introduction

Approximately 15 million hectares of peat soils have been drained for forestry in temperate and boreal zones, and one third of this area is located in Finland (Paavilainen and Päivänen 1995). Most of these forests are nearing the age of regeneration, and the rate of forest harvesting on drained peatlands is expected to undergo a rapid increase during the next decade. Harvesting induces significantly larger nutrient and carbon exports from drained peatlands compared with mineral soil forests (Nieminen *et al.* 2017), thus, efficient methods are needed for the mitigation detrimental impacts on water quality.

A major problem in managing water quality from harvested peatland forests is that dissolved organic fractions constitute a significant proportion of increased carbon and nutrient exports and that there are no efficient purification methods to mitigate their exports (Nieminen *et al.* 2017). For example, wetland buffer areas, which are efficient in reducing the exports of sediments and dissolved inorganic nutrients (Nieminen *et al.* 2005, Väänänen *et al.* 2008, Vikman *et al.* 2010), may not retain significant amounts of dissolved organic fractions. When a wetland buffer

Editor in charge of this article: Hannu Marttila

is constructed below a harvest area by restoring a section of drained peatland, nutrient and carbon exports may increase for several years, surpassing those of a harvesting option without a wetland buffer (Nieminen *et al.* 2020). Other methods to mitigate nutrient and carbon exports, such as sediment pits and ponds and peak runoff control dams, may be efficient in controlling the transport of sediments and adhered particulate fractions of nutrients and carbon (Haahti *et al.* 2017). However, it is important to note that these methods may have limited impact on reducing the exports of dissolved nutrient and carbon fractions.

Owing to the lack of efficient purification methods, it might be feasible to focus on decreasing the release of dissolved carbon (DOC) and dissolved nutrients from harvested peatland forests rather than trying to capture them from discharged water flow. A partial harvest treatment instead of clear-cutting has been proposed to efficiently decrease carbon and nutrient exports from drained peatland forests (Nieminen *et al.* 2017, 2018, Palviainen *et al.* 2021). Partial harvest of the drained peatland forests can also significantly decrease on-site CO_2 emissions compared with clear-cutting (Korkiakoski *et al.* 2023).

Partial harvests could potentially decrease the nutrient exports significantly, primarily due to the retention and uptake of nutrients by the remaining trees. Also, the transpiration and interception of water by the remaining tree stand would keep the water table at lower levels than in clear-cut areas, thus perhaps significantly decreasing the exports of easily soluble and redox-sensitive elements. However, there is very limited knowledge on the effects of partial harvest on nutrient and carbon exports from drained peatland forests (Nieminen *et al.* 2017, 2018).

Partial harvest in boreal peatland forests, which are mainly dominated by coniferous tree species, i.e., Norway spruce (*Picea abies* (L.) Karst.) or Scots pine (*Pinus sylvestris* L.), can be executed in various ways (Saarinen *et al.* 2020). Single-tree harvesting may be a feasible option for shade-tolerant species such as spruce, whereas shade-intolerant species require larger canopy openings for their regeneration and growth than enabled by single-tree harvesting. Strip harvestings or harvests of small-scale canopy openings (gaps) have thus been proposed as a feasible partial harvesting option for Scots pine and other shade-intolerant species (Saarinen *et al.* 2020).

Our aim was to study if partial harvesting is a smaller source of nutrients and DOC to receiving water courses from Scots pine-dominated drained peatland forests than their clear-cutting. Our hypothesis is that partial harvesting results in significantly smaller exports than those reported after clear-cuts in similarly drained peatland forests.

Material and methods

Study sites and field work

The study was conducted on eight catchment areas at four locations in Finland (Table 1), in southern Finland at Tuusula (60°27´N, 24°57´E) and Tammela (60°38´N, 23°57´E), and in south-central Finland at Vilppula (62°3´N, 24°29´E) and Parkano (62°02´N, 22°43´E). There was one area that was harvested partially by strip-cutting both at Tuusula ($T_{PH,}$ area 2.4 ha) and Vilppula ($V_{PH,}$ 0.9 ha), three partially harvested strip-cut areas at Parkano (H_{PH1}, 0.6 ha, H_{PH2}, 0.5 ha, H_{PH3}, 0.5 ha), and at Tammela, there were one control area (Ta_C, 3.1 ha), one clear-cut area (Ta_{C-C}, 2.3 ha), and one area that was partially harvested by removing the dominating Scots pine trees ($Ta_{PH,}$ 13.0 ha). The basic characteristics of the Tammela experiment were recently presented by Leppä *et al.* (2020b) and Korkiakoski *et al.* (2023), and the Vilppula and Tuusula experiments by Sarkkola *et al.* (2013). The catchments were artificial catchment areas established by isolating them hydrologically from the surroundings by double-ditching, except Ta_C, which was both artificially isolated and topographically delineated (Leppä *et al.* 2020b).

The long-term annual precipitation in the Tuusula region averages about 680 mm, and 630 mm, 710 mm, and 680 mm in the Tammela, Vilppula, and Parkano regions, respectively (Pirinen *et al.* 2012). The long-term (1971–2010) mean annual temperature at Tuusula is +5.3°C, +4.6°C at Tammela, +3.5°C at Vilppula, and +4.1°C at Parkano. The mean temperatures for July and February are respectively +17.7 and –5.7°C at Tuusula, +16.7 and –6.3°C at Tammela, +16.0 and –7.7°C at Vilppula, and +16.4 and –6.8°C at Parkano.

Before the drainage, Parkano, Vilppula, and Tuusula experimental sites were classified as nutrient-poor Dwarf-shrub pine bogs, while the Tammela site was of a mesotrophic Herb-rich sedge birch-pine fen (Heikurainen and Pakarinen 1982). The Vilppula experiment was drained for forestry in 1908, the Tammela experiment in 1969, the Tuusula experiment probably in 1958, and the Parkano experiment in the 1960s. Ditch cleaning and supplementary ditching have also been carried out in all four experimental sites, but the exact timings of these operations are not known. The tree stand at the Tammela partial harvest site (Ta_{PH}) before harvesting consisted of a mixture of Scots pine (stem volume 166 m^3 ha^{-1}) and Downy birch (*Betula pubescens,* ca. 45 m^3 ha^{-1}) in the dominant layer, with a dense undergrowth of Norway spruce (40 m^3 ha^{-1}). The other partial harvest sites before harvesting consisted of almost pure Scots pine stands with stem volumes of about 165, 155, and 132–189 m^3 ha^{-1} at Tuusula, Vilppula, and Parkano, respectively. Field layer vegetation at Tammela featured mostly herbs (*Dryopteris carthusiana, Trientalis europaea*) and dwarf shrubs (*Vaccinium myrtillus*), while the other sites were covered mostly by dwarf shrubs (*Rhododendron tomentosum*, *Empetrum nigrum*, and *Vaccinium vitis-ideae*).

To characterize the peat soil of the catchments, samples from 5–9 systematically placed sampling locations from each catchment were collected. The samples were dried at 40°C, weighed for their bulk density and analysed for C and N using LECO CHN analyser, and for P, K, Ca, Mg, Al, and Fe with inductively coupled plasma mass spectrometry (ICP-AES), after digestion in chloric acid or extraction with nitric acid (P concentrations at the Ta_{PH}, Ta_{C-C}, and Ta_C catchments with the latter). The peat analysis revealed that particularly the N, K and Mg contents were higher at the Tammela catchments than for the other catchments (Table 2).

The tree stands were harvested in February–March 2016 (Tammela) or in 2017. The catchments were harvested using conventional stem-only harvesting (including only stems down to a diameter of 7 cm). The Tammela clear-cut (Ta_{C-C}) was harvested by removing all trees, while only the dominant pine trees were harvested at Ta_{PH}. The T_{PH}, V_{PH}, H_{PH1}, H_{PH2}, and H_{PH3} catchments were harvested by removing all trees from about 25 m wide strips covering about half of the area. The partial harvests reduced the total stand volume by about 70% at Tammela, and about 50% at the other catchments.

For monitoring water discharge, the outlet ditch of the T_{PH}, V_{PH}, and Ta_{PH} catchments were equipped with a V-notch weir and a capacitance water level logger (TruTrack WT-HR). The water level data was calibrated against manual measurements taken at regular intervals, and discharge was calculated using stage-discharge relationships. In the other catchments, an earth embankment with an outflow pipe was built

Table 1. Basic information on the study catchments. T_{PH} = Tuusula partial harvest, V_{PH} = Vilppula partial harvest, H_{PH1} = Parkano partial harvest catchment 1, H_{PH2} = Parkano partial harvest catchment 2, H_{PH3} = Parkano partial harvest catchment 3, Ta_{PH} = Tammela partial harvest, Ta_{C-C} = Tammela clear-cut, Ta_C = Tammela uncut control.

	Location	Area (ha)	Site type[a]	Tree stand vol (m^3 ha^{-1})	Spruce	Pine	Birch
						% of stand volume	
T_{PH}	60°27'N, 24°57'E	2.4	IR	165	0	99	1
V_{PH}	62° 3'N, 24°29'E	0.9	IR	155	0	100	0
H_{PH1}	62°02'N, 22°43'E	0.6	IR	132	1	97	2
H_{PH2}	62°02'N, 22°43'E	0.5	IR	189	5	94	1
H_{PH3}	62°02'N, 22°43'E	0.5	IR	140	1	97	2
Ta_{PH}	60°38'N, 23°57'E	13.0	RhSR	252	16	66	18
Ta_{C-C}	60°38'N, 23°57'E	2.3	RhSR	185	17	60	23
Ta_C	60°38'N, 23°57'E	3.1	RhSR	210	14	56	30

[a] According to Heikurainen and Pakarinen (1982): IR = Dwarf-shrub pine bog, RhSR = Herb-rich sedge birch-pine fen.

in the outlet ditch and discharge was measured manually at intervals of two-to-four weeks, using a stopwatch and a fixed volume vessel.

Water samples were collected from the outflow pipe of the earth embankment or the overflow of the V-notch weir once or twice a month during 2014–2020 at Tammela and Tuusula, and during 2016–2020 at Vilppula and Parkano. The samples were analyzed for total (unfiltered) N (TN) using flow injection analysis Lachat Quickem 8000 FIA-analyzer (Zellweger Analytics) and for total P (TP) using ascorbic acid method after potassium peroxodisulphate digestion (Vesihallinnon analyysimenetelmät, 1981). Then the samples were filtered through 0.45 µm glass fiber filters (Whatman GF/B) and analysed for dissolved organic carbon (DOC) concentrations using the TOC-VCPH/N analyser (Shimadzu Corporation, Kyoto, Japan), and for dissolved reactive P concentrations (DRP) with the molybdenum blue method according to Murphy and Riley (1962), using Shimadzu UV2401PC (Shimadzu Corporation, Kyoto, Japan), and for dissolved iron and aluminium (Fe and Al) using ICP-emission spectrometer (iCAP 6500 Duo, Thermo Fisher Scientific, Waltham, MA, United Kingdom). In the data analysis, all concentration values below the detection limit of the analyzer were substituted with zero concentration.

Calculations

Daily discharge was modeled using a quasi-3D drained peatland hydrology model (Stenberg *et al.* 2022). Discharge was modelled for sites with only manual discharge measurements, and in case of device failure or unreliable data, also to complete discharge time series for continuously monitored sites. The model computes rainfall and snow interception by the canopy and a moss/litter layer, snow accumulation and melt, infiltration to soil profile, and the total evapotranspiration for each grid column (here, 2 m × 2 m) based on daily meteorology, one-sided leaf-area index (LAI), canopy closure and dominant tree height (Launiainen *et al.* 2019, Leppä *et al.* 2020a).

The resulting source/sink term is used in the below-ground module, which consists of 2-m-deep peat columns and solves lateral water fluxes in the saturated zone according to the Boussinesq equation (Urzainki *et al.* 2020). The calculation of vertical water fluxes in the soil is simplified by assuming that the water table responds immediately to a change in water storage, and that the water content above the water table achieves hydraulic equilibrium instantly (Laurén *et al.* 2021). Discharge is the sum of water entering the ditches, which are described as constant head boundaries when the water table level is above their depth and otherwise as no-flow boundaries (Laurén *et al.* 2021).

To run the discharge model for the study sites, we used the daily meteorological data obtained from the Finnish Meteorological Institute (FMI). It was spatially averaged (resolution of 10 km × 10 km or 1 km × 1 km since July 2016) to our sites according to Aalto *et al.* (2013). Stand characteristics of each site were

Table 2. Bulk density and chemical characteristics of the surface peat (0–20 cm) in each catchment area. For further information on the catchments, see Table 1.

	Bulk density (kg m^{-3})	C (%)	N (%)	P (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	Al (mg kg^{-1})	Fe (mg kg^{-1})
T_{PH}	146	52.7	1.23	465	324	1330	435	876	1020
V_{PH}	125	54.6	1.42	583	390	3315	442	709	964
H_{PH1}	95	53.3	1.46	783	369	1905	554	1426	1930
H_{PH2}	98	54.4	1.72	835	309	1538	388	2075	1835
H_{PH3}	115	54.7	1.77	896	286	1710	377	2430	1765
Ta_{PH}	145	56.7	2.19	768	785	2277	671	1252	1943
Ta_{C-C}	145	57.7	2.13	742	650	2985	715	—	—
Ta_{C}	129	56.4	2.48	930	787	1432	716	1326	1896

— denotes not analysed

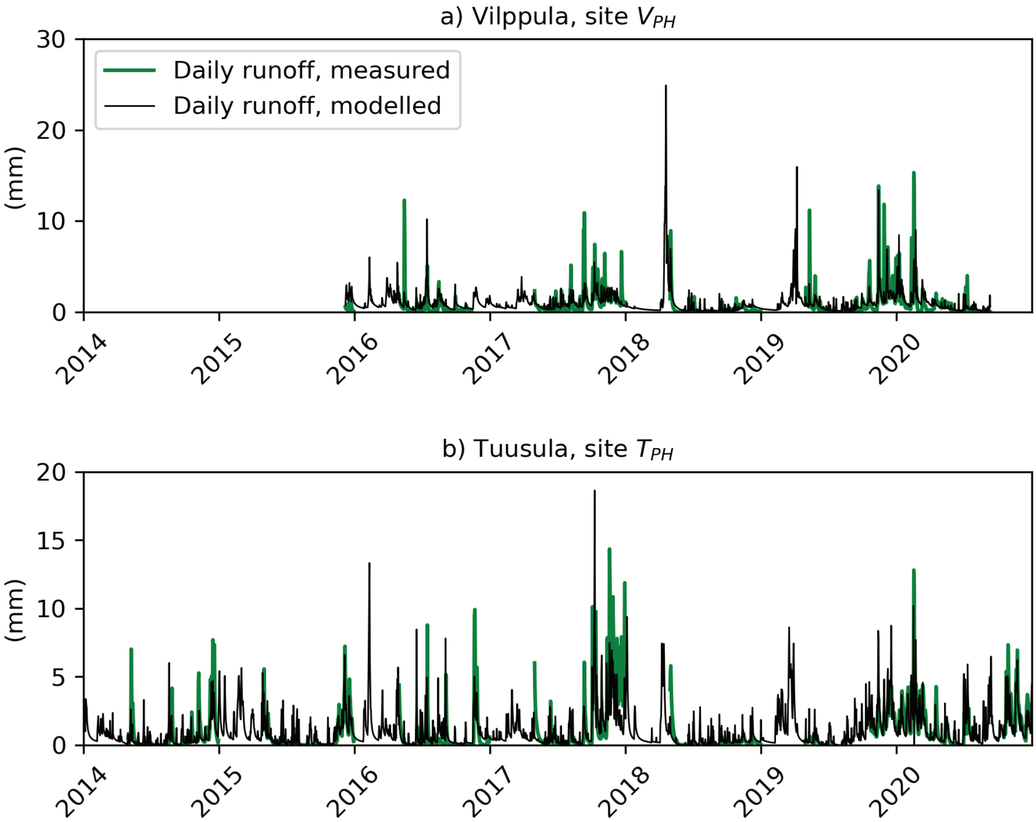

Fig. 1. Time series of measured (green) and modelled (black) daily runoff at sites V_{PH} and T_{PH} during 2014–2020.

parametrized using stand inventory data using the same approach as in Leppä *et al.* (2020a). In addition, the stand characteristics of the unharvested areas of the strip-cut sites (T, V, and H sites) were spatially distributed based on tree locations following the approach by Stenberg *et al.* (2018). For *Carex* peat (site Ta), the peat profiles at the study sites followed the parametrizations outlined in Leppä *et al.* (2020a), while for *Sphagnum* peat (sites T, V and H sites) the parameterization was based on data provided by Päivänen (1973). Ditch depth varied for the sites from 0.8 m (Ta) to 0.4 m (T).

Examples of resulting modelled discharge timeseries in comparison to measurements are shown in Fig. 1. The measured and modelled daily runoff agreed well, except during winter and snow melt periods, when measured runoff peaks were clearly higher. This was interpreted as a failure in measurements, that is, ice and snow in the ditch below the discharge measurement station reduced the delivery of water downstream and thus raised the water level in the weir.

Monthly and annual mean concentrations of nutrients and DOC were calculated as simple averages of concentration values. Due to non-normal distribution of concentration values, non-parametric Mann-Whitney rank-sum test was used to calculate the statistical differences in TN, TP, DRP, DOC, Al, and Fe concentrations between pre- and post-harvest years. Owing to the lack of pre-harvest data from the Ta_{C-C} catchment, concentration data from it were not tested statistically. TP and DRP data from Ta_{PH} and DRP data from Ta_{C} were also not tested for the same reason. The statistical analyses were performed by using SAS Enterprise Guide statistical software ver. 8.3 (SAS Institute, USA).

The exports of nutrients and DOC from the study catchments in kg ha^{-1} year^{-1} were calculated by first summing the measured or simulated daily discharge to produce monthly discharge.

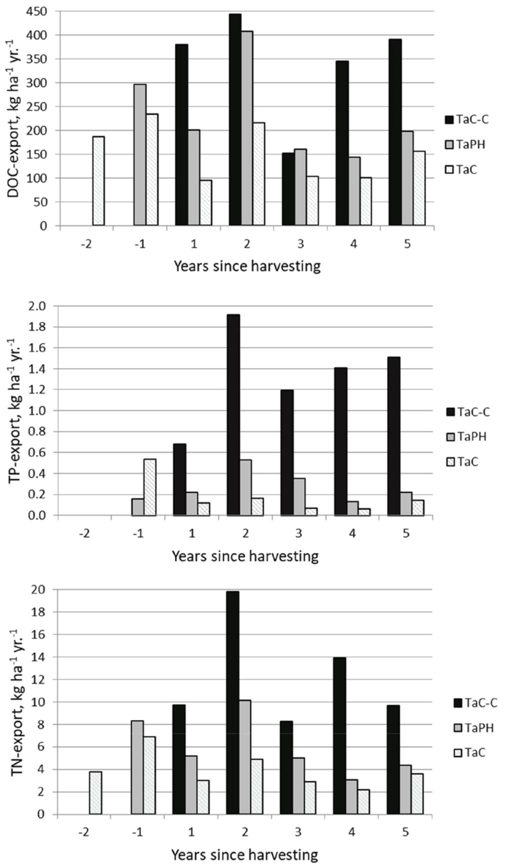

Fig. 2. DOC, TN, and TP exports from the Ta$_{C-C}$, Ta$_{PH}$, and Ta$_{C}$ catchments two years before (2014–2015) and five years (2016–2020) after harvesting.

The monthly discharge was multiplied by the monthly mean nutrient or DOC concentrations to produce their monthly exports. The missing monthly concentration values were produced by interpolation using the closest available concentration values. Finally, the monthly exports were summed to produce the annual exports.

Results

Concentrations

There were generally no differences in DOC, Al, Fe, and nutrient concentrations between pre- and post-harvest periods at the V$_{PH}$, T$_{PH}$, H$_{PH1}$, H$_{PH2}$, and H$_{PH3}$ catchments (Table 3). At the H$_{PH1}$ and T$_{PH}$ catchments, only TP and DRP concentrations during the second year after harvesting (2018) were significantly higher than before harvesting. At the H$_{PH2}$ catchment, TP concentrations were higher than before harvesting during the second and third post-harvest years. Aluminium concentrations at T$_{PH}$ were also higher in 2020 than before harvesting.

At the Tammela catchments Ta$_{PH}$, Ta$_{C-C}$, and Ta$_{C}$, the interpretation of the results is complicated due to missing or insufficient pre-harvest data. TN, TP, DRP, DOC, and Al concentrations after harvesting were higher from the clear-cut Ta$_{C-C}$ catchment than from the partially harvested Ta$_{PH}$ catchment and the uncut Ta$_{C}$ catchments, but Fe concentrations were lower (Table 4). DOC and Al concentrations were significantly higher during the first and second post-harvest years at Ta$_{PH}$ than before harvesting, while TN and TP concentrations from the uncut Ta$_{C-C}$ catchment decreased from 2015 to 2020.

Nutrient and DOC exports

Nutrient and DOC exports from the clear-cut Ta$_{C-C}$ catchment were considerably higher than from the uncut Ta$_{C}$ catchment, particularly during the second year after harvesting (Fig. 2). TN exports during the second year were about five times higher from the Ta$_{C-C}$ catchment than from the Ta$_{C}$ catchment, and TP exports over ten times higher. All exports were lower in the partially harvested area than in the clear-cut area. TN and DOC exports from the partially harvested Ta$_{PH}$ catchment after harvesting were generally less than two times higher than from the uncut Ta$_{C}$ catchment, and TP exports two to five times higher.

DOC, TN, and TP exports were 15–60% higher from the partially harvested T$_{PH}$, V$_{PH}$, H$_{PH1}$, H$_{PH2}$, and H$_{PH3}$ catchments after harvesting, except at the T$_{PH}$ and HP$_{H2}$ catchments, where TP exports were >200% higher after harvesting (Table 5). Al exports were 16–30% higher after harvesting at the T$_{PH}$, H$_{PH1}$, H$_{PH2}$, and H$_{PH3}$ catchments, but seven times higher at the V$_{PH}$ catchment. Iron exports from the partially harvested H$_{PH2}$ and H$_{PH3}$ catchments were not higher after harvesting but were 30–50% higher at the T$_{PH}$ and H$_{PH1}$ catchments, and 150% at the V$_{PH}$ catchment after harvesting.

Table 3. Annual average TN, TP, DRP, DOC, Al, and Fe concentrations (mg l^{-1}) in waters discharging from the VPH, TPH and HPH1, HPH2, and HPH3 catchments (±SD) before (2014–2016) and after (2017–2020) harvesting. Significant differences ($p < 0.05$) from the pre-harvest years are denoted in bold. N = number of water samples.

Site	Year	N	TN	TP	DRP	DOC	Al	Fe
H_{PH1}	2016	7	1.20±0.19	0.039±0.012	0.009±0.002	69.5±11.8	0.86±0.17	2.39±0.65
H_{PH1}	2017	10	1.13±0.14	0.032±0.012	0.008±0.006	71.7±12.5	0.86±0.11	2.68±0.54
H_{PH1}	2018	7	1.72±0.94	**0.076±0.043**	**0.024±0.021**	81.2±21.7	0.93±0.18	2.41±0.34
H_{PH1}	2019	8	1.34±0.22	0.048±0.004	0.014±0.004	76.9±15.0	0.84±0.17	2.50±0.70
H_{PH1}	2020	8	1.25±0.23	0.041±0.010	0.010±0.005	68.8±15.4	0.84±0.15	2.10±0.87
H_{PH2}	2016	7	1.15±0.21	0.027±0.006	0.006±0.002	69.0±16.3	0.77±0.18	1.21±0.46
H_{PH2}	2017	11	1.22±0.20	0.026±0.011	0.005±0.001	76.2±13.1	0.79±0.18	1.20±0.35
H_{PH2}	2018	7	1.47±0.39	**0.043±0.012**	0.008±0.004	87.6±24.9	0.92±0.21	1.51±0.54
H_{PH2}	2019	8	1.44±0.25	**0.045±0.014**	0.012±0.015	83.6±18.9	0.79±0.23	1.31±0.48
H_{PH2}	2020	8	1.19±0.29	0.035±0.007	0.007±0.003	67.5±20.1	0.74±0.18	1.04±0.43
H_{PH3}	2016	6	0.94±0.21	0.020±0.003	0.000±0.000	56.7±15.2	0.97±0.23	0.95±0.28
H_{PH3}	2017	10	0.90±0.24	0.016±0.007	0.000±0.000	55.1±15.5	0.90±0.22	0.87±0.29
H_{PH3}	2018	7	1.11±0.30	0.025±0.006	0.000±0.000	67.8±20.2	0.91±0.20	1.13±0.41
H_{PH3}	2019	8	1.07±0.29	0.022±0.006	0.000±0.000	59.4±15.7	0.96±0.32	0.86±0.33
H_{PH3}	2020	8	0.85±0.31	0.019±0.004	0.000±0.000	47.5±19.3	0.85±0.24	0.68±0.35
T_{PH}	2014	11	1.38±0.20	0.036±0.014	0.007±0.004	71.9±11.4	0.84±0.20	0.92±0.25
T_{PH}	2015	18	1.50±0.27	0.040±0.018	0.010±0.016	67.8±15.9	0.90±0.19	0.90±0.37
T_{PH}	2016	12	1.51±0.38	0.040±0.014	0.006±0.003	74.2±20.8	0.98±0.18	0.94±0.29
T_{PH}	2017	10	1.57±0.23	0.063±0.059	0.033±0.049	88.7±26.0	0.99±0.17	1.12±0.49
T_{PH}	2018	13	1.48±0.28	**0.186±0.172**	**0.138±0.161**	88.3±30.5	0.98±0.24	1.11±0.48
T_{PH}	2019	14	1.35±0.18	0.077±0.050	0.040±0.046	85.7±14.3	0.79±0.27	0.97±0.33
T_{PH}	2020	20	1.28±0.25	0.065±0.032	0.028±0.022	75.3±18.7	**1.14±0.34**	0.99±0.31
V_{PH}	2016	7	1.15±0.30	0.020±0.006	0.000±0.000	75.0±21.1	0.11±0.03	0.33±0.08
V_{PH}	2017	10	1.42±0.32	0.017±0.004	0.006±0.002	96.2±25.1	0.16±0.04	0.38±0.13
V_{PH}	2018	7	1.41±0.27	0.027±0.005	0.009±0.001	89.1±19.6	0.16±0.04	0.37±0.11
V_{PH}	2019	9	1.44±0.28	0.019±0.003	0.006±0.001	92.9±19.5	0.15±0.04	0.36±0.09
V_{PH}	2020	8	1.18±0.17	0.018±0.006	0.006±0.001	75.3±13.0	0.14±0.02	0.31±0.07

Table 4. Annual average TN, TP, DRP, DOC, Al, and Fe concentrations (mg l^{-1}) in waters discharging from the Ta$_{\mathrm{PH}}$, Ta$_{\mathrm{C\text{-}C}}$, and Ta$_{\mathrm{C}}$ catchments (±SD) before (2014–2015) and after harvesting (2016–2020). Significant differences ($p < 0.05$) from the pre-harvest years are denoted by bold. Note that the data from Ta$_{\mathrm{C\text{-}C}}$ and TP and DRP data from Ta$_{\mathrm{PH}}$ and DRP data from Ta$_{\mathrm{C}}$ were not tested due to the lack of pre-harvest data. *N* = number of water samples.

Site	Year	N	TN	TP	DRP	DOC	Al	Fe
Ta$_{\mathrm{PH}}$	2014	12	1.45±0.53	—	—	56.0±10.4	—	—
Ta$_{\mathrm{PH}}$	2015	23	1.61±0.41	—	—	53.3±11.1	0.37±0.13	3.39±1.42
Ta$_{\mathrm{PH}}$	2016	24	1.61±0.35	0.111±0.102	0.045±0.047	**66.9±17.3**	**0.51±0.12**	4.46±2.10
Ta$_{\mathrm{PH}}$	2017	22	1.69±0.25	0.094±0.036	0.048±0.019	**67.2±12.7**	**0.50±0.10**	3.60±0.77
Ta$_{\mathrm{PH}}$	2018	10	1.59±0.49	0.139±0.108	0.073±0.050	52.3±9.8	0.33±0.12	3.07±1.27
Ta$_{\mathrm{PH}}$	2019	9	1.35±0.21	0.058±0.017	0.023±0.008	63.8±12.7	0.43±0.08	3.13±0.97
Ta$_{\mathrm{PH}}$	2020	7	1.29±0.22	0.064±0.043	0.022±0.016	57.9±10.9	0.42±0.09	3.26±1.34
Ta$_{\mathrm{C\text{-}C}}$	2016	16	3.08±0.96	0.198±0.117	0.059±0.048	115.5±24.0	0.80±0.17	2.55±0.40
Ta$_{\mathrm{C\text{-}C}}$	2017	18	1.64±0.41	0.285±0.157	0.025±0.018	84.5±12.0	0.55±0.06	3.10±0.94
Ta$_{\mathrm{C\text{-}C}}$	2018	6	1.24±0.35	0.320±0.158	0.040±0.029	71.3±13.4	0.44±0.06	2.41±0.63
Ta$_{\mathrm{C\text{-}C}}$	2019	9	2.84±0.69	0.286±0.083	0.239±0.090	70.1±17.5	0.45±0.09	1.11±0.33
Ta$_{\mathrm{C\text{-}C}}$	2020	7	1.84±0.50	0.287±0.082	0.227±0.086	74.4±17.3	0.48±0.09	1.41±0.50
Ta$_{\mathrm{C}}$	2015	16	1.85±0.62	0.179±0.130	-	58.4±13.4	0.40±0.13	5.58±2.60
Ta$_{\mathrm{C}}$	2016	24	1.63±0.42	0.156±0.137	0.055±0.047	55.4±13.2	0.38±0.12	4.56±2.62
Ta$_{\mathrm{C}}$	2017	22	**1.38±0.29**	**0.061±0.047**	0.023±0.014	56.9±13.9	0.42±0.11	**3.30±0.94**
Ta$_{\mathrm{C}}$	2018	9	1.40±0.40	0.072±0.058	0.032±0.026	50.3±10.3	0.35±0.14	3.35±1.45
Ta$_{\mathrm{C}}$	2019	9	**1.34±0.27**	**0.038±0.014**	0.012±0.009	61.5±12.7	0.41±0.08	3.37±1.39
Ta$_{\mathrm{C}}$	2020	7	**1.25±0.24**	**0.050±0.032**	0.018±0.015	54.2±10.4	0.41±0.08	3.33±1.53

There were no clear correlations between peat properties and nutrient and DOC exports after partial harvesting except that TN exports were higher from the Ta_{PH} catchment than from the other catchments. Ta_{PH} catchment had clearly higher N contents in peat than the other catchments (Table 2).

Discussion

This is the first study to report DOC and nutrient exports from drained peatland forests after partial harvesting. The results supported our hypothesis on smaller nutrient exports from partially harvested than clear-cut drained Scots pine mires only partly. In the partially harvested Ta_{PH} catchment, the DOC, TP, and TN exports were significantly lower compared with those from the clear-cut $Ta_{C\text{-}C}$ catchment, but TP exports from the partially harvested Ta_{PH}, T_{PH}, and H_{PH2} catchments did not show a reduction compared with previously observed exports from clear-cuts on corresponding drained Scots pine peatlands (Kaila *et al.* 2014). Similarly, while DOC exports were lower from the partially harvested Ta_{PH} catchments than from the clear-cut $Ta_{C\text{-}C}$ catchment, they did not show a significant reduction compared with clear-cut sites under similar conditions reported by Nieminen *et al.* (2015). This suggests that variations in nutrient exports from drained peatland forests following harvesting are affected more by site-specific factors and environmental conditions during harvesting than by the harvesting method (e.g., Kaila *et al.* 2014).

One factor that may significantly contribute to nutrient exports is the amount of harvested wood. Intensive harvests in terms of harvested stem volume result in much larger amounts of nutrient-rich harvest residues left on site after harvesting than those that remove small amounts of stem wood. Also, intensive harvest results in a more significant reduction of nutrient uptake, forest evapotranspiration and a greater rise in water level compared with less intensive harvesting practices (Leppä *et al.* 2020a), which may be reflected as high exports of particularly the easily soluble and redox-sensitive nutrients (Nieminen *et al.* 2017). One reason why partial harvesting in this study did not result in much lower exports than clear-cuts in earlier studies (e.g. Kaila *et al.* 2014) could be attributed to the fact that the harvestings were not significantly less intensive in terms of harvested stem volume. Partial harvesting at the Ta_{PH} site was actually much more intensive as regards to harvested stem volume than the clear-cuts in the sites studied by Kaila *et al.* (2014). The study by Miettinen *et al.* (unpubl. data) indicated that there may be a strong positive correlation in drained peatland forests between harvested stem volume (per catchment area) and harvest-induced TN and TP exports. Thus, the amount of harvested volume per catchment area could be a factor that correlates with the variation in nutrient exports more strongly than the specific harvesting method, whether it involves clear-cutting, strip-cutting, or single-tree harvesting.

The Ta site was clearly more fertile than the others, particularly regarding the peat nitrogen

Table 5. Mean annual DOC, TN, TP, DRP, Al, and Fe exports (kg ha^{-1} year^{-1}) from the T_{PH}, V_{PH}, and H_{PH1}, H_{PH2}, and H_{PH3} catchments before (2016) and after harvesting (2017–2020).

Site	Before/After	DOC	TN	TP	DRP	Al	Fe
T_{PH}	Before	220	5.6	0.13	0.03	3.3	2.7
	After	329	6.1	0.44	0.27	4.3	4.0
V_{PH}	Before	232	3.5	0.06	0.01	0.3	1.0
	After	358	5.1	0.10	0.03	2.4	2.5
H_{PH1}	Before	199	3.5	0.11	0.03	2.4	6.9
	After	281	5.0	0.17	0.05	3.3	8.9
H_{PH2}	Before	236	3.9	0.09	0.02	2.7	4.6
	After	307	5.4	0.28	0.04	3.3	4.8
H_{PH3}	Before	183	3.1	0.07	0.01	3.0	3.1
	After	211	3.7	0.08	0.02	3.5	3.1

contents (Table 2). This, together with the intensity of harvesting, were probably the reasons why clear-cutting on that site resulted in very high exports of nitrogen (Kaila *et al.* 2015, Nieminen *et al.* 2017). The high variation in TP and DRP exports following harvesting in our study sites corresponds with that from earlier studies, where the extra export caused by clear-cutting has varied from a few tens of grams to several kilograms per hectare (Nieminen 2004, Rodgers *et al.* 2010, Kaila *et al.* 2014). It was believed earlier that high P exports following harvesting are mostly related to low amounts of P-sorbing Al- and Fe-hydroxides in peat, but recent studies do not clearly support that view (e.g., Kaila *et al.* 2014, 2015). Other mechanisms, such as the ratio of Fe to P and the rate of water level rise after harvesting, may control P exports more strongly (Kaila *et al.* 2014, Nieminen *et al.* 2017).

The scientifically most appropriate way to study the effects of different land-use measures on nutrient exports is the calibration period/control area method (e.g., Kaila *et al.* 2015). That method enables estimating treatment effects so that other factors than the treatment under investigation, such as different site characteristics between control and treatment areas or differences in between-year weather conditions, have significantly less effect on treatment-induced nutrient export estimates as in our study, where treatment impacts can only be estimated as differences in exports between pre- and post-harvest periods (at T, V, H) or differences between control and treatment areas (Ta). That is because we either did not have control areas (T, V, H) or sufficiently long pre-harvest calibration period data (Ta) to estimate harvest effect with the calibration period/control area method. It should therefore be noted that the differences in nutrient exports between control and harvest areas or pre- and post-harvest years in our study may not only be related to harvestings, but also to such differences in site characteristics and weather conditions that can potentially affect nutrient exports.

We also did not use flow-weighted nutrient and carbon concentrations in our calculations, as we did not have measured flow data for most of our study catchments. If there is a clear negative or positive relationship between flow and nutrient concentrations, our way of using simple arithmetic concentrations in calculating nutrient exports may give smaller or higher export estimates than when using flow-weighted concentrations. However, the sites for which concurrent flow and concentration data were available did not indicate strong relationship between flow and concentrations.

Even though critical evaluation of the calculation methods is important, it should be noted that our aim was not so much to produce exact export estimates for partial harvest as to study if there is a risk for increased nutrient and DOC exports from drained peatland forests after partial harvesting. Our study indicated that, as well as clear-cuttings, partial harvests may also enhance nutrient exports to water courses from drained peatland forests. Their contribution should thus also be considered when assessing the water quality effects of different forest management options, but more research is still needed to produce exact and representative export estimates for different types of partial harvests in drained peatland forests.

It is important to acknowledge that while partial harvestings may also lead to increased exports of DOC and nutrients, managing peatland forests through repeated partial harvestings can still be a more environmentally responsible management option compared with clear-cutting. This is primarily due to the potential reduction in the need for ditch network maintenance, which is a necessary operation after clear-cutting but may not be needed after partial harvesting (Nieminen *et al.* 2018). Refraining from ditch network maintenance operations can decrease particularly the exports of suspended solids and adhered nutrients (Joensuu *et al.* 2002). Furthermore, managing peatland forests with repeated partial harvestings, particularly those that remove the largest trees, can also contribute to decreased nutrient exports. This is because the tree stands remain smaller than in mature stands under clear-cut-based forestry practices. Drying out of drained peatlands due to evapotranspiration of the growing and maturing tree stands and resulting enhanced peat decomposition has been proposed as one explanation for the reported increasing nutrient and DOC exports from drained peatland forests over time since drainage (Nieminen *et al.* 2022). Increasing harvesting intensity also negatively affects the coverage and recovery of surface vegetation, which captures nutrients.

In conclusion, our findings indicated that, as well as clear-cutting, partial harvesting may also lead to increased DOC and nutrient exports to water courses. This study included relatively nutrient-poor or medium-fertile sites (Ta), and the most nutrient-rich sites, which are potentially the largest sources of exports (Kaila *et al.* 2015), were not studied. More research is still needed to produce exact estimates of nutrient and DOC export for different partial harvest methods and identify the mechanisms controlling exports on various drained peatland forest sites.

Acknowledgements: The study was financially supported by the Academy of Finland project CCFPeat (no. 310203).

References

Aalto, J., Pirinen, P., Heikkinen, J. &; Venäläinen, A. 2013. Spatial interpolation of monthly climate data for Finland: comparing the performance of kriging and generalized additive models. Theoretical and Applied Climatology 112: 99–111. https://doi.org/10.1007/s00704-012-0716-9

Asmala, E., Carstensen, J. &; Räike, A. 2019. Multiple anthropogenic drivers behind upward trends in organic carbon concentrations in boreal rivers. Environmental Research Letters 14. 10 p. https://doi.org/10.1088/1748-9326/ab4fa9

Haahti, K., Nieminen, M., Finér, L., Marttila, H., Kokkonen, T., Leinonen, A. &; Koivusalo, H. 2017. Model-based evaluation of sediment control in a drained peatland forest after ditch network maintenance. Canadian Journal of Forest Research 48: 130–140. https://doi.org/10.1139/cjfr-2017-0269

Heikurainen, L. &; Pakarinen, P. 1982. Peatland classification. In: Laine, J. (ed.), Peatlands and their utilization in Finland, pp. 53–62. Finnish Peatland Society, Finnish National Committee of International Peat Society.

Joensuu, S., Ahti, E. &; Vuollekoski, M. 2002. Effects of ditch network maintenance on the chemistry of run-off water from peatland forests. Scandinavian Journal of Forest Research 17: 238–247.

Kaila, A., Laurén, A., Sarkkola, S., Koivusalo, H., Ukonmaanaho, L., Xiao, L., Asam, Z-u-Z., O´Driscoll, C. &; Nieminen, M. 2015. The effect of clear-felling and harvest residue removal on nitrogen and phosphorus export from drained Norway spruce mires in southern Finland. Boreal Environment Research 20: 693–706.

Kaila, A., Sarkkola, S., Laurén, A., Ukonmaanaho, L., Koivusalo, H., Xiao, L., O´Driscoll, C., Asam, Z-u-Z., Tervahauta, A. &; Nieminen, M. 2014. Phosphorus export from drained Scots pine mires after clear-felling and bioenergy harvesting. Forest Ecology and Management 325: 99–107. https://doi.org/10.1016/j.foreco.2014.03.025

Korkiakoski, M. Ojanen, P., Tuovinen, J-P., Minkkinen, K., Nevalainen, O., Penttilä, T., Aurela, M., Laurila, T. &; Lohila, A. 2023. Partial cutting of a boreal nutrient-rich peatland forest causes radically less short-term on-site CO2 emissions than clear-cutting. Agricultural and Forest Meteorology 332: 109361. https://doi.org/10.1016/j.agrformet.2023.109361

Launiainen, S., Guan, M., Salmivaara, A. &; Kieloaho, A.-J. 2019. Modeling boreal forest evapotranspiration and water balance at stand and catchment scales: a spatial approach. Hydrology and Earth System Sciences 23: 3457–3480. https://doi.org/10.5194/hess-23-3457-2019.

Laurén, A., Palviainen, M., Launiainen, S., Leppä, K., Stenberg, L., Urzainki, I., Nieminen, M., Laiho, R. &; Hökkä, H. 2021. Drainage and Stand Growth Response in Peatland Forests –-Description, Testing, and Application of Mechanistic Peatland Simulator SUSI. Forests 12: 293. https://doi.org/10.3390/f12030293

Leppä, K., Hökkä, H., Laiho, R., Launiainen, S., Lehtonen, A., Mäkipää, R., Peltoniemi, M., Saarinen, M., Sarkkola, S. &; Nieminen, M. 2020a. Selection cuttings as a tool to control water table level in boreal drained peatland forests. Frontiers in Earth Science 8: 576510. https://doi.org/ 10.3389/feart.2020.576510

Leppä, K., Korkiakoski, M., Nieminen, M., Laiho, R., Hotanen, J-P., Kieloaho, A-J., Korpela, L., Laurila, T., Lohila, A., Minkkinen, K., Mäkipää, R., Ojanen, P., Pearson, M., Penttilä, T., Tuovinen, J-P. &; Launiainen, S. 2020b. Vegetation controls of water and energy balance of a drained peatland forest: Responses to alternative harvesting practices. Agricultural and Forest Meteorology 295: 108198. https://doi.org/10.1016/j.agrformet.2020.108198

Murphy, J. &; Riley, P. J. 1962. A modified single solution method for the determination of phosphate in natural waters. Analytica Chimica Acta 22: 31–36. https://doi.org/10.1016/S0003-2670(00)88444-5

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 Fennica 38: 123–132.

Nieminen, M., Sarkkola, S. &; Laurén, A. 2017. Impacts of forest harvesting on nutrient, sediment and dissolved organic carbon exports from drained peatlands: A literature review, synthesis and suggestions for the future. Forest Ecology and Management 392: 13–20. https://doi.org/10.1016/j.foreco.2017.02.046

Nieminen M., Ahti E., Nousiainen H., Joensuu S. &; Vuollekoski M. 2005. Capacity of riparian buffer zones to reduce sediment concentrations in discharge from peatlands drained for forestry. Silva Fennica 39: 371. https://doi.org/10.14214/sf.371

Nieminen, M., Hasselquist, E. M., Mosquera, V., Ukonmaanaho, L., Sallantaus, T. &; Sarkkola, S. 2022.

Post-drainage stand growth and peat mineralization impair water quality from forested peatlands. Journal of Environmental Quality 00: 1–11. https://doi.org/10.1002/jeq2.20412

Nieminen, M., Sarkkola, S., Tolvanen, A., Tervahauta, A., Saarimaa, M. &; Sallantaus, T. 2020. Water quality management dilemma: Increased nutrient, carbon, and heavy metal exports from forestry-drained peatlands restored for use as wetland buffer areas. Forest Ecology and Management 465: 118089. https://doi.org/10.1016/j.foreco.2020.118089

Nieminen, M., Koskinen, M., Sarkkola, S., Laurén, A., Kaila, A., Kiikkilä, O., Nieminen, T.M. &; Ukonmaanaho, L. 2015. Dissolved organic carbon export from harvested peatland forests with differing site characteristics. Water, Air, and Soil Pollution 226: 181. https://doi.org/10.1007/s11270-015-2444-0

Nieminen, M., Hökkä, H., Laiho, R., Juutinen, A., Ahtikoski, A., Pearson, M., Kojola, S., Sarkkola, S., Launiainen, S., Valkonen, S., Penttilä, T., Lohila, A., Saarinen, M., Haahti, K., Mäkipää, R., Miettinen, J. &; Ollikainen, M. 2018. Could continuous cover forestry be an economically and environmentally feasible management option on drained boreal peatlands? Forest Ecology and Management 424: 78–84. https://doi.org/10.1016/j.foreco.2018.04.046

Paavilainen, E. &; Päivänen, J. 1995. Peatland Forestry: Ecology and Principles. Ecological studies 111. Springer-Verlag, Berlin Heidelberg.

Päivänen, J. 1973. Hydraulic conductivity and water retention in peat soils. Acta Forestalia Fennica 129: 1–70. https://doi.org/10.14214/aff.7563

Palviainen, M., Peltomaa, E., Laurén, A., Kinnunen, N., Ojala, A., Berninger, F., Zhu, X. &; Pumpanen, J. 2021. Water quality and the biodegradability of dissolved organic carbon in drained boreal peatland under different forest harvesting intensities. Science of the Total Environment 806: 150919. https://doi.org/10.1016/j.scitotenv.2021.150919.

Pirinen, P., Simola, H., Aalto, J., Kaukoranta, J-P., Karsson, P. &; Ruuhela, R. 2012. Tilastoja Suomen ilmastosta 1981–2010. Climatological statistics of Finland 1981–2010. Raportteja, reporter, reports 2012:1. Ilmatieteen laitos, Finnish Meteorological Institute.

Postila, H., Ronkanen, A.-K. &; Kløve, B. 2015. Wintertime purification efficiency of constructed wetlands treating runoff from peat extraction in a cold climate. Ecological Engineering 85: 13–25. https://doi.org/10.1016/j.ecoleng.2015.09.066.

Postila, H., Saukkoriipi, J., Heikkinen, K., Karjalainen, S.M., Marttila, H. &; Kløve, B. 2014. Can treatment wetlands be constructed on drained peatlands for efficient purification of peat extraction runoff? Geoderma 228–229: 33–43. https://doi.org/10.1016/j.geoderma.2013.12.008

Räike, A., Taskinen, A. &; Knuuttila, S. 2019. Nutrient export from Finnish rivers into the Baltic Sea has not decreased despite water protection measures. Ambio 49: 460–474. https://doi.org/10.1007/s13280-019-01217-7

Rodgers, M., O'Connor, M., Healy, M. G., O'Driscoll, C., Asam, Z-u-Z., Nieminen, M., Poole, R., Muller, M. &; Xiao, L. 2010. Phosphorus release from forest harvesting on an upland blanket peat catchment. Forest Ecology and Management 260(12): 2241–2248. https://doi.org/10.1016/j.foreco.2010.09.037

Saarinen M., Valkonen S., Sarkkola S., Nieminen M., Penttilä T. &; Laiho R. 2020. Jatkuvapeitteisen metsänkasvatuksen mahdollisuudet ojitetuilla turvemailla. Metsätieteen aikakauskirja 2020: 10372. https://doi.org/10.14214/ma.10372 (in Finnish).

Sarkkola, S., Nieminen, M., Koivusalo, H., Laurén, A., Ahti, E., Launiainen, S., Nikinmaa, E., Marttila, H., Laine, J. &; Hökkä, H. 2013. Domination of growing-season evapotranspiration over runoff makes ditch network maintenance in mature peatland forests questionable. Mires and Peat 11: 02. http://www.mires-and-peat.net/map11/map_11_02.htm

Stenberg, L., Haahti, K., Hökkä, H., Launiainen, S., Nieminen, M., Laurén, A. &; Koivusalo, H. 2018. Hydrology of drained peatland forest: Numerical experiment on the role of tree stand heterogeneity and management. Forests 9(10): 645. https://doi.org/10.3390/f9100645

Stenberg, L., Leppä, K., Launiainen, S., Laurén, A., Hökkä, H., Sarkkola, S., Saarinen, M. &; Nieminen, M. 2022. Measuring and modeling the effect of strip cutting on the water table in boreal drained peatland pine forests. Forests 13(7): 1134. https://doi.org/10.3390/f13071134

Urzainki, I., Laurén, A., Palviainen, M., Haahti, K., Budiman, A., Basuki, I., Netzer, M. &; Hökkä, H. 2020. Canal blocking optimization in restoration of drained peatlands, Biogeosciences 17: 4769–4784. https://doi.org/10.5194/bg-17-4769-2020

Väänänen, R., Nieminen, M., Vuollekoski, M., Nousiainen, H., Sallantaus, T., Tuittila, E.-S. &; Ilvesniemi, H. 2008. Retention of phosphorus in peatland buffer zones at six forested catchments in southern Finland. Silva Fennica 42: 211–231. https://doi.org/10.14214/sf.253

Vesihallinnon analyysimenetelmät, 1981. (The analysis methods of water samples in Finnish Environment Institute). Vesihallitus 1981, 136 p. (in Finnish with English abstract).

Vikman, A., Sarkkola, S., Koivusalo, H., Sallantaus, T., Laine, J., Silvan, S., Nousiainen, H. &; Nieminen, M. 2010. Nitrogen retention by peatland buffer areas at six forested catchments in southern and central Finland. Hydrobiologia 641: 171–183. https://doi.org/10.1007/s10750-009-0079-0.