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Surface Water Quality

Post-drainage stand growth and peat mineralization impair water quality from forested peatlands

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Abstract
Many recent studies have indicated upward trends in carbon and nutrient concentrations from drained peatland forests over time since their initial drainage, but the mechanisms behind these trends are still poorly understood. We gathered data on nitrogen and phosphorus concentrations discharged from 37 drained boreal peatland forests where we also had data on peat and tree stand characteristics. We found that tree stand volume and peat bulk density were positively correlated with the nitrogen and phosphorus concentrations discharged from particularly the deep-peated sites. We interpret these results to indicate that a plausible reason for the reported upward trends in nutrient concentrations is the maturing and growing of the tree stands over time since initial drainage and the consequent increasing evapotranspiration capacity, which results in lowered soil water levels and enhanced aerobic peat mineralization. We discuss how our results should be considered in the management of drained peatland forests.

1 | INTRODUCTION

Internationally, around 15 million ha of peatlands and wetlands have been drained for forestry in the temperate and boreal regions (Paavilainen & Päivänen, 1995). Many studies have indicated upward trends in dissolved carbon (C) and nutrient concentrations in waters discharging from drained peatland forests over the past decades (Asmala et al., 2019; Nieminen et al., 2017; Nieminen, Sarkkola, et al., 2018; Räike et al., 2019).

Although the quality of surface waters discharging from drained peatland forests may already be poor (Marttila et al., 2018; Nieminen et al., 2017; Nieminen, Sarkkola, et al., 2018), these upward trends in nutrient and C concentrations further complicate achieving their "good water status" as targeted by the EU Water Framework Directive (WPD 2000/60/EC). Efficient mitigation options are thus an urgent need to improve water quality discharging from drained peatland forests. Such areas are common in large parts of Scandinavia, the Baltic States, the British Isles, as well as the western parts of the Russian Federation (Paavilainen & Päivänen, 1995).

Mitigating C and nutrient exports from drained peatland forests is significantly complicated by poorly understood

Abbreviations: TN, total nitrogen for water samples; TP, total phosphorus for water samples.

mechanisms behind upward trends in their nutrient concentrations. These mechanisms may include hydrological factors such as changes in water pathways due to drainage (Nieminen, Piirainen, et al., 2018), biotic factors such as enhanced microbial activity resulting in increased release of nutrients and C from peat (Nieminen, Sarkkola, Hasselquist, et al., 2021), as well as abiotic factors such as changes in the chemistry of atmospheric deposition and increasing air and water temperatures due to climate warming (Finstad et al., 2016; Fork et al., 2020; Sarkkola et al., 2009; Wang et al., 2015).

Nieminen, Sarkkola, Hasselquist, et al. (2021) and Nieminen, Sarkkola, Sallantaus, et al. (2021) hypothesized that the primary reason for upward nutrient and C concentration trends would be post-drainage forest succession (i.e., maturing and growing of the tree stands with time since initial drainage and a resulting increase in their evapotranspiration capacity). This would result in lowered soil water levels (Sarkkola et al., 2010) and increased aerobic peat mineralization (Ojanen & Minkkinen, 2019). The nutrients mineralized particularly from the deep peat layers could easily be leached outside the rooting zone of trees and other vegetation. Besides increasing evapotranspiration, maturing of the tree stands could increase nutrient exports, for example, by increasing root exudates and litter input into the soil (Škerlep et al., 2019; Straková et al., 2010, 2012). If this were true, one should find higher nutrient concentrations in waters discharging from old drainage areas with mature forest stands and highly decomposed peats than from recently drained sites with low-volume stands and slightly decomposed peats. However, very shallow-peated areas can behave differently from deep-peated soils because the deep peat layers subjected to aerobic mineralization under dry conditions are absent. A significant research gap is that no studies so far have attempted to assess the relationship between peat and tree stand characteristics and nutrient exports from drained peatland forests.

Thus, our purpose was to assess if nitrogen (N) and phosphorus (P) concentrations in waters discharging from forestry-drained peatlands are higher from mature stands and highly decomposed peats than from sites with low-volume stands and slightly decomposed peats. We analyzed tree stand, peat characteristics, and water quality data from 37 drained peatland catchments in Sweden and Finland. We first analyzed the data by using all catchment areas and then excluded shallow-peated catchments (peat depth <0.5 m), which we expected not to have similar correlations between tree stand and peat characteristics and discharged N and P concentrations as deep-peated sites.

2 | MATERIALS AND METHODS

For the purposes of our study, we compiled data from forestry-drained peatland dominated headwater catchments in Finland and Sweden, where there were already data available on water quality and peat and tree stand characteristics. To limit the influence of land use on our analysis, we focused on relatively small catchments (<50 ha) that were only influenced by peatland and upland forestry. We excluded sites with the impacts of recent forest operations; that is, we excluded sites if forest operations affected >10% of the catchment in <20 yr before the water quality monitoring or during it (see also Nieminen et al., 2017; Nieminen, Sarkkola, et al., 2018). We also did not include sites with considerable groundwater discharge (visible springs) because of the difficulties in determining their catchment area.

We used a combination of previously published data and data collected in ongoing research projects. The average total N (TN) and total P (TP) concentrations of streams or ditch outflow waters were chosen as response variables because these were the most widely available data regarding N and P in published studies. Flow data were available for so few catchments ($n = 6$) that flow-weighted concentrations or average nutrient exports in kg ha^{-1} could not be used as response variables. The duration of monitoring discharge water quality varied from 1 to 19 yr in our catchments; thus, the average TN and TP concentration data represent 1–19 yr of records. A total of 37 catchments for TN and 32 catchments for TP were found that satisfied our selection criteria. The smaller number for TP is because the five Swedish catchments had data only for TN (Table 1).

The compiled catchment data represented typical conifer dominated forest areas, where Norway spruce [*Picea abies* (L.) Karsten] dominates the most fertile sites and Scots pine (*Pinus sylvestris* L.) dominates the low-fertile mineral soils and tree-covered bogs. Silver birch (*Betula pendula* Roth) and downy birch (*Betula pubescens* Ehrh.) were generally found as nondominant species. Peatlands covered 20–100% of the catchment areas, and drained peatlands also covered 20–100%. The catchments were either by double-ditching isolated artificial catchments (e.g., Kaila et al., 2014), topographically delineated catchments, or delineated both

Core Ideas

- Nutrient concentrations discharging from forestry-drained peatlands were correlated with site properties.
- Positive correlations were found between peat bulk density and discharged N and P concentrations.
- Positive correlations were found between tree stand volume and discharged N and P concentrations.
- We emphasize a risk for water quality deterioration over time since drainage.

TABLE 1 Characteristics of the study catchments

Catchment	Location (WGS84 coordinates)	Area	Peatland	Drained	Site	Tsum	Monitoring period
		ha	————%————			dd > +5 ˚C	
Peat depth >1 m							
Ctrl-WTH[a]	6707448 N, 449645 E	7	74	74	0	1,350	2007–2008
T_{PH}[b]	6703986 N, 387521 E	3.1	100	100	1	1,300	2014–2015
Ta_{C}[b]	6726848 N, 333812 E	3.3	100	100	0	1,250	2015–2016
Jylisjärvi[b]	6765327 N, 381359 E	12	30	30	1	1,250	1994–2013
Paroninkorpi1[b]	6766246 N, 378215 E	6	100	100	1	1,250	2,016
Paroninkorpi2[b]	6766433 N, 378266 E	3	100	100	1	1,250	2,016
Ränskälänkorpi[b]	6784419 N, 406583 E	18	100	100	0	1,300	2,019
Vesijako2[b]	6804319 N, 399072 E	7.8	39	39	0	1,250	2018–2019
Control 5[c]	6882532 N, 368615 E	0.9	100	100	1	1,250	2007–2012
C3[d]	6877972 N, 339506 E	18	41	41	1	1,150	2008–2014
$H_{PH1\text{-}3}$[b]	6885540 N, 276338 E	1.5	100	100	1	1,150	2016
BA5[e]	6881471 N, 277511 E	31	50	28	1	1,150	2013–2015
BA6[e]	6881471 N, 277511 E	20	53	45	1	1,150	2013–2015
BA3[e]	6881528 N, 276639 E	30	45	41	1	1,150	2013–2015
BA4[e]	6881528 N, 276639 E	50	46	42	1	1,150	2013–2015
M10[f]	7109720 N, 551437 E	7	51	51	1	1,100	2008
KV13[f]	7097412 N, 538749 E	4.8	56	56	0	1,100	2008–2012
KV14[f]	7097412 N, 538742 E	1.2	100	100	1	1,100	2008
KV22[f]	7105633 N, 544208 E	1.6	31	31	0	1,100	2008
ML09[f]	7128046 N. 555778 E	1.3	100	100	0	1,100	2008–2012
ML10[f]	7128010 N, 558148 E	1	72	72	0	1,100	2008
ML07[f]	7110393 N, 550655 E	1.7	41	41	0	1,100	2008
s24[f]	7097424 N, 544471 E	7	33	33	0	1,100	2008
Utajärvi[b]	7180706 N, 474380 E	6	100	100	1	1,000	2014–2016
Koiraoja[b]	7369578 N, 475878 E	3	100	100	1	900	2015
Peat depth <0.2–0.5 m							
WTH1[a]	6707448 N, 449645 E	9	33	33	0	1,350	2007–2013
WTH2[a]	6707448 N, 449645 E	6	88	88	0	1,350	2007–2008
SOH1[a]	6724116 N, 452612 E	11	55	55	0	1,350	2007–2008
SOH2[a]	6724116 N, 452612 E	9	37	37	0	1,350	2007–2008
Ctrl-SOH[a]	6724116 N, 452612 E	15	20	20	0	1,350	2007–2013
Vesijako1[b]	6804487 N, 398996 E	4.3	58	58	0	1,250	2018–2019
Ruotsinkylä[b]	6692605 N, 391267 E	3.7	38	38	0	1,350	2018–2019
Krycklan[b]	7125351 N, 442249 E	47	51	51	0	870	2019-2020
Trollberget1[b]	7117455 N, 444763 E	6.7	46	46	0	1,050	2019–2020
Trollberget2[b]	7117234 N, 444813 E	4.4	86	86	0	1,050	2019–2020
Trollberget3[b]	7116767 N, 444875 E	8.4	73	73	0	1,050	2019–2020
Trollberget4[b]	7116811 N, 444355 E	10.7	31	31	0	1,050	2019–2020

Note. dd, degree days; Drained%, proportion of drained peatlands in the catchment area; Peatland%, proportion of peatlands in the catchment area; Tsum, temperature sum; Site, fertility of peatlands (0, minerotrophic, 1 = ombrotrophic). Krycklan and Trollberget catchments are from Sweden; other catchments from Finland.

[a]Pre-harvest data and control area data from Kaila et al. (2015).

[b]Unpublished.

[c]Control area data from Kaila et al. (2014).

[d]Control area data from Koskinen et al. (2017).

[e]Pre-restoration data from Nieminen et al. (2020).

[f]Pre-harvest data and control area data from the study areas by Kiikkilä et al. (2014).

topographically and artificially. The stand volume in the drained peatlands varied from 4 to 301 m^3 ha^{-1}. Stand volumes had been estimated by measuring tree attributes in conventional field plots. If no stand volume data were available for the selected site, we estimated stand volumes by utilizing the open database of the Multi-source National Forest Inventory of Finland (Mäkisara et al., 2016) or the Swedish National Lidar estimations (https://www.skogsstyrelsen.se/sjalvservice/karttjanster/geodatatjanster/ftp). Climatic conditions in the study region correspond to those given by Nieminen, Sarkkola, Hasselquist, et al. (2021).

The water samples in our compiled catchment data had generally been collected by focusing on the periods with high flows, which are in Finland and Sweden during spring snowmelt period and the autumn heavy rainfalls. Mid-winter (January–March) and mid-summer (July–August) periods are often missing because of no or minor runoff in small catchments during those seasons. The samples had been collected from an outflow ditch or stream draining each catchment from the overflow of a V-notch weir, from a discharge pipe of a soil embankment, or directly from flowing water in the ditch or stream.

Peat samples had been previously taken from the 0-to-10-cm ($WTH_{1\text{-}2}$, Ctrl-WTH, $SOH_{1\text{-}2}$, Ctrl-SOH) or the 0-to-20-cm peat layer (other sites). Samples had been collected from 3–10 systematically placed sampling locations within the catchment of each drained peatland area. The volume of each peat sample was noted in the field. In the laboratory, the samples from different sampling locations were dried (40 ˚C) and weighed for bulk density. Thereafter, these samples were typically pooled and analyzed for total N and total P, and total potassium (K), calcium (Ca), aluminum (Al), and iron (Fe) content. Other parameters, such as bioavailable or exchangeable forms of nutrients, were not available. Total N in the samples were analyzed with a CHN-1000 analyzer (LECO Corp.), and total P and total K, Ca, Al, and Fe were analyzed using an inductively coupled plasma emission spectrometer (iCAP 6500 Duo, Thermo Fisher Scientific) after digestion in either concentrated nitric acid or hydrochloric acid. Stand volume and peat nutrient characteristics of the sites are given in Table 2.

Concentrations of TP in the water samples had been analyzed colorimetrically after oxidation with $K_2S_2O_8$ (Vesihallinnon analyysimenetelmät, 1981), and TN had been analyzed either using flow injection analysis (Tecaton FIA) and the nonpurgeable organic C method or via the combustion catalytic oxidation method on a TOC VCPH analyzer (Shimadzu).

Spearman rank correlation analysis and ordinary least squares regression analysis were used to identify the factors behind the variation in TN and TP concentrations discharging from the 37 drained peatland sites. The statistical analyses were performed by SPSS Statistics 27 software (IBM).

3 | RESULTS

Average TN concentrations (± SD) in waters discharging from our 37 catchments were 934 ± 506 μg L^{-1}, and average TP concentrations were 33 ± 25 μg L^{-1}. Average TN concentrations were 988 ± 559 μg L^{-1} discharging from the 25 deep-peated sites (>1 m) and 822 ± 367 μg L^{-1} discharging from the 12 shallow-peated sites (0.2–0.5 m) (Table 1). Average TP concentrations in the deep-peated and shallow-peated sites were 30 ± 21 and 48 ± 30 μg L^{-1}, respectively.

Temperature sum, tree stand volume, and peat bulk density were positively correlated with the TN and TP concentrations (Table 3; Figure 1). The proportion of drained area in the catchments was positively correlated with the discharged TN concentrations but not with the TP concentrations (Table 3). Correlations particularly for TN were stronger in the deep-peated data set compared with all data including also shallow-peated sites.

Potassium in peat correlated significantly with the discharged TN concentrations, and K, P, Al, and Fe in peat correlated significantly with the TP concentrations discharging from our sites (Table 3; Figure 1). Peat K contents correlated negatively with the TN and TP concentrations in waters discharging from deep-peated sites, and P, Al, and Fe in peat correlated positively with the TP concentration discharging from all sites.

4 | DISCUSSION

This is the first study to assess the relationship between peat and tree stand characteristics and nutrient concentrations in waters discharging from drained peatland forests. The results supported our hypothesis that nutrient concentrations are higher from sites with mature tree stands and highly decomposed peats than from sites with low-volume tree stands and slightly decomposed peats. The results are in accordance with those by Nieminen et al. (2017); Nieminen, Sarkkola, et al. (2018); and Räike et al. (2019), which indicated that nutrient concentrations from drained peatland forests may be increasing over time since their initial drainage. We interpret these results to indicate that a plausible reason for the reported upward trends in nutrient concentrations is the maturing and growing of the tree stands over time since drainage and the consequent increasing evapotranspiration capacity, which results in lowered soil water levels (Sarkkola et al., 2010) and enhanced aerobic peat mineralization (Ojanen & Minkkinen, 2019).

Our findings also supported our hypothesis that shallow-peated areas may not have as strong relationships between peat and tree stand characteristics and discharged nutrient concentrations as deep-peated sites because of the absence of deep peat that is decomposing under dry conditions and

TABLE 2 Stand volume and peat characteristics at the 37 catchments

Catchment	Stand volume	BD	N	P	K	Ca	Al	Fe
	m^3 ha^{-1}	kg m^{-3}	%	mg kg^{-1}				
Peat depth >1 m								
Ctrl-WTH[a]	171	180	2.3	1,130	600	3,620	2,920	5,490
T_{PH}	140	146	1.2	465	324	1,330	876	1,020
Ta_C	270	150	2.4	786	–	2,001	1,261	6,793
Jylisjärvi	150	95	1.3	462	303	1,660	823	971
Paroninkorpi1	220	175	1.9	755	141	2,370	2,800	2,050
Paroninkorpi2	170	163	1.6	564	141	2,650	1,410	1,390
Ränskälänkorpi	280	154	1.8	630	124	2,360	1,330	2,680
Vesijako2	62	176	2.1	648	–	4,510	1,990	2,500
Control 5	149	93	1.6	617	–	3,180	640	1,080
C3	145	104	1.9	574	162	2,260	1,820	1,680
$H_{PH1\text{-}3}$	147	115	1.6	781	295	1,190	1,460	1,620
BA5	85	114	1.6	777	193	1,730	2,150	2,850
BA6	90	121	1.8	836	290	1,220	1,980	1,550
BA3	95	141	1.9	842	142	2,100	2,330	3,100
BA4	80	93	1.1	511	364	2,100	988	1,800
M10	111	60	1.2	552	694	1,388	531	914
KV13	71	108	1.5	811	838	3,395	618	1,602
KV14	86	75	2.0	650	473	2,106	571	2,535
KV22	109	54	2.8	1,410	338	2,185	6,708	5,623
ML09	70	49	1.5	875	1,189	10,195	5,545	4,543
ML10	169	118	2.6	1,098	244	4,060	1,608	11,040
ML07	169	77	2.3	1,008	775	10,405	2,185	5,030
s24	70	52	1.5	829	661	2,360	812	3,634
Utajärvi	4	92	2.3	680	160	2,010	1,650	2,950
Koiraoja	117	135	2.2	1,047	226	1,975	1,745	8,665
Peat depth 0.2–0.5 m								
WTH1[a]	301	213	2.2	1,590	2,330	2,600	23,600	12,600
WTH2[a]	293	202	1.8	1,380	2,090	4,600	20,500	13,600
SOH1[a]	251	175	2.1	1,580	1,690	3,780	18,400	11,600
SOH2[a]	238	156	1.8	1,590	1,900	4,320	16,100	12,300
Ctrl-SOH	233	156	2.2	1,380	1,290	5,370	13,400	4,507
Vesijako1	75	175	2.0	804	–	8,850	2,190	4,510
Ruotsinkylä	350	175	1.4	624	300	4,250	1,880	2,350
Krycklan	220	172	1.3	1,224	719	2,606	5,597	55,474
Trollberget1	285	113	1.4	1,047	926	2,939	2,209	4,018
Trollberget2	278	155	1.5	927	776	4,245	1,250	2,448
Trollberget3	291	122	1.6	1,008	411	3,353	3,799	24,165
Trollberget4	229	211	1.7	1,073	781	2,594	4,073	7,420

Note. BD, bulk density.

[a]Peat characteristics for the 0-to-10-cm peat layer; 0-to-20-cm peat layer at the other sites.

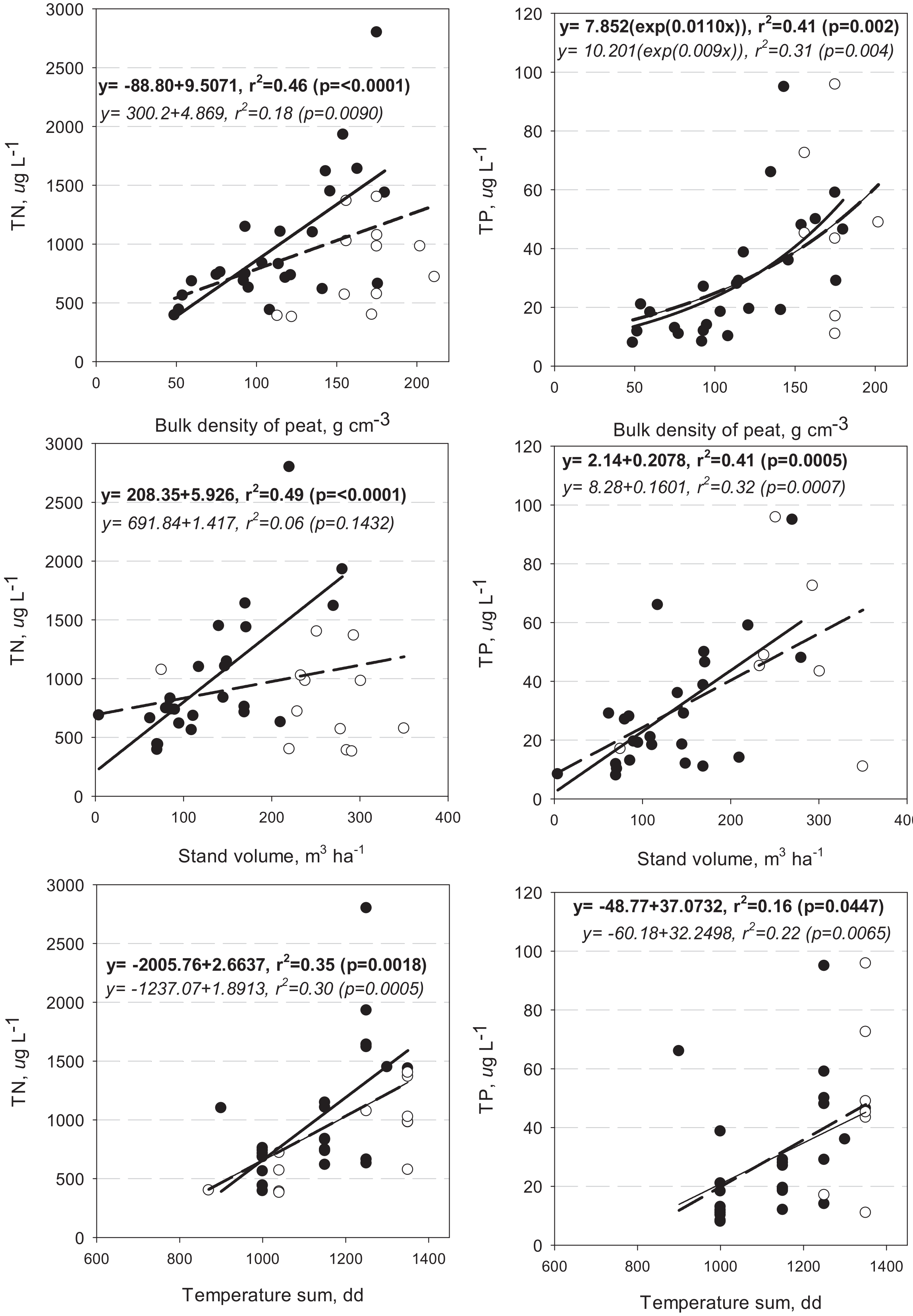

FIGURE 1 Scatter plots showing the relationships between selected catchment characteristics and total N (TN) and total P (TP) concentrations discharging from all drained peatland sites or just deep-peated sites. Open circles designate shallow-peated sites; black circles denote deep-peated sites. The dotted line with corresponding italicized equation describes the relationship among all sites; the straight line whose equation is shown in bold describes the relationship among just deep-peated sites. dd, degree days

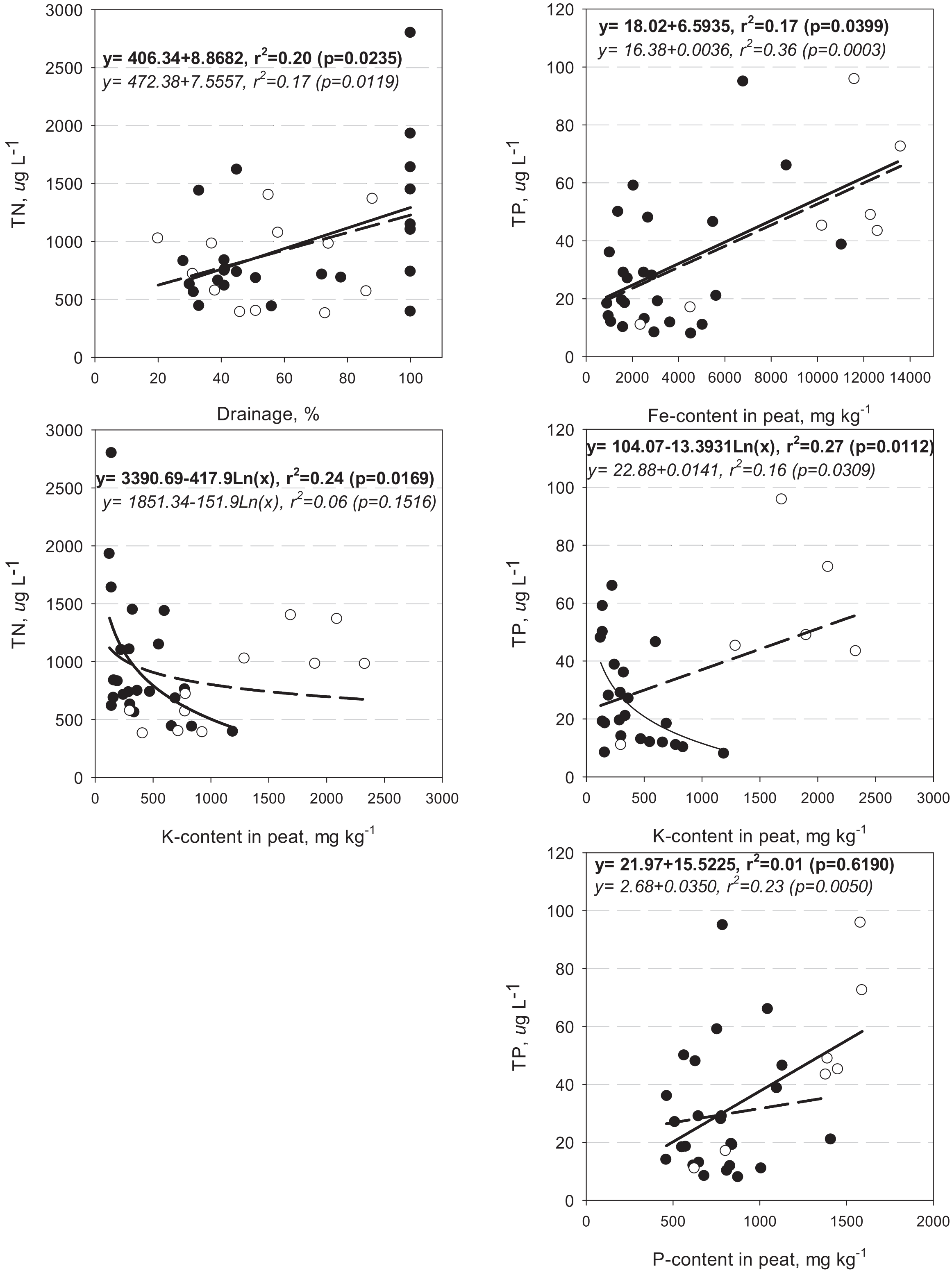

FIGURE 1 Continued

leaching nutrients. One mechanism that plausibly controls nutrient exports from shallow-peated areas is the quality of mineral soil because ditches in shallow-peated sites generally reach the mineral soil below peat. Fine-textured mineral soils in ditch beds can be a significant source of particulate P (Nieminen, Piirainen, et al., 2018). Indeed, the positive correlations in our data between peat P, K, Al, and Fe concentrations and TP concentrations discharging from all sites may

TABLE 3 Spearman correlation coefficients (*p* values in parentheses; $p < .05$ in bold) for the relationship between catchment characteristics and total N and total P concentrations discharging from drained peatland forests

	Total N		**Total P**	
	All data	**Deep-peated**	**All data**	**Deep-peated**
n	37	25	32	25
Tsum, dd > 5°C[a]	**.509 (.003)**	**.567 (.003)**	**.517 (.003)**	**.487 (.018)**
Drained, %	**.441 (.019)**	**.432 (.035)**	.051 (.791)	.078 (.724)
Stand volume, m^3 ha^{-1}	**.556 (.001)**	**.704 (.001)**	**.601 (<.001)**	**.607 (.002)**
BD, kg m^{-3}	**.548 (.001)**	**.619 (<.001)**	**.623 (<.001)**	**.785 (<.001)**
N	.199 (.242)	.154 (.462)	.429 (.018)	.353 (.099)
P	−.004 (.981)	−.259 (.211)	**.381 (.038)**	.077 (.727)
K[a]	−.153 (.429)	**−.501 (.015)**	.081 (.689)	**−.502 (.020)**
Ca	−.030 (.869)	−.117 (.579)	−.050 (.793)	−.115 (.602)
Al	.132 (.473)	−.014 (.948)	**.394 (.031)**	.213 (.330)
Fe	.100 (.586)	−.095 (.653)	**.486 (.006)**	.263 (.225)

Note. BD, bulk density; dd, degree days; Drained, proportion of drained area from the catchment area; Tsum, temperature sum.
[a]$n = 34$ for total N and 29 for total PP in all data; $n = 23$ in deep-peated sites.

not be due to the concentrations of P in the peat but because the sites with high P, K, Al, and Fe contents in peat are usually shallow peated. Thus, those correlations may be more likely related to particulate P release due to ditch erosion than mobilization of P from peat. Further studies should analyze their water samples not only for TP but also for particulate P and different dissolved fractions to get a better understanding of the processes behind P exports from drained peatland forests.

Our results also indicated that low K content in peat may be one factor increasing TN and TP concentrations in waters discharging from drained peatland forests. This may be because K is often a limiting factor for the growth of drained peatland forests (Laurén et al., 2021). Low K content in peat, and thus low K bioavailability, may increase TN and TP exports by resulting in poor utilization of the N and P mineralized from peat by the tree stand and other peatland vegetation. The correlations between peat K content and discharged TN and TP concentrations were relatively poor, however, and further studies are needed on the relationship between peat K contents and nutrient exports from drained peatland forests.

Our results may at first seem to contrast with those by Finér et al. (2021), who did not find upward temporal trends in nutrient concentrations discharging from drained peatland covered catchments. They did not present their data in such a detailed way that the variation with respect to the time elapsed since initial drainage (drainage age) could be estimated. However, because they did not include drainage areas as old as this study or Nieminen et al. (2017) and Nieminen, Sarkkola, et al. (2018), their study most likely involves only relatively young drainage areas with respect to time since drainage. It is very unlikely that upward concentration trends could be observed in such a data set with very limited variation in drainage age and consequently the processes that enhance peat mineralization over time since initial drainage.

Peat N and P concentrations correlated relatively poorly with the variation in TN and TP concentrations discharging from drained peatland forests. This is most likely because they are not as good of a proxy variable for the post-drainage peat mineralization processes in drained peatland forests as tree stand volume and peat bulk density. Tree stand volume is strongly related to the variation in the volume of aerobic peat layer (Sarkkola et al., 2010), and peat bulk density relates directly to the rate of peat mineralization and nutrients released from mineralized peat. High total nutrient concentration in drained peat, on the other hand, may indicate resistance of peat nutrients to mineralization compared with a high rate of peat mineralization and nutrient release.

Nitrogen concentrations discharging from the 37 drained peatland forests in our study also correlated with the temperature sum of the study sites; that is, they were higher in the southern than in the northern boreal regions. Total P concentrations also correlated with the temperature sum, but this correlation was weak compared with TN concentrations. High TN concentrations in southern boreal locations may be because forest-covered areas are efficient in capturing dry deposition and because N deposition is higher in boreal regions in the south than in the north (Lövblad et al., 1992). The effect of temperature sum may also be because temperature is an important factor controlling peat mineralization in drained peatlands (Laurén et al., 2021).

Six of the study sites were analyzed for bulk density and nutrient, Al, and Fe concentrations in the 0-to-10-cm peat layer, whereas the 0-to-20-cm peat layer was sampled in the other sites. This likely introduces some error in the analysis of all data but has minor impact on the relationships between peat characteristics and nutrient concentrations discharging from deep-peated sites because only one of those six sites was deep peated. Phosphorus concentrations at 80 drained Scots pine mires in Finland did not differ much between the 0-to-10-cm and the 10-to-20-cm peat layers; N concentrations and bulk densities were at most 20–30% higher in the lower layer, but K contents in the 10-to-20-cm layer were only about one-third of the concentrations in the 0-to-10-cm layer (Laiho et al., 1999). Excluding those six sites sampled only from the top 0-to-10-cm layer did not have much effect on the relationships between peat K contents and TN and TP concentrations discharging from our sites.

In the interpretation of our results, it should also be noted that we did not purposely collect and analyze data to study the relationships between tree and peat characteristics and nutrient concentrations discharging from drained peatlands but used data that were previously collected for many different purposes. There are therefore factors that likely increase the variation in our soil and water quality data compared with data that would have been purposely collected and analyzed to study nutrient exports and post-drainage succession on peatlands. One such factor is the large variation in the lengths and timing of the water quality monitoring of our catchments (Table 1), which may be a significant source of variation in the nutrient concentration data. Soil bulk density and nutrient concentration data may be significantly influenced by the between-site variations in sampling protocols, particularly the spatial representativeness of the soil samples. However, these factors may strengthen rather than weaken our results and conclusions. Given that our data indicated relatively strong correlations between soil and tree stand characteristics and nutrient exports, even stronger correlations might be found in purposely collected data. Nevertheless, further studies should limit the variation in sampling protocols and analyze the samples in a more versatile way (e.g., easily soluble nutrients in soil, flow-weighted dissolved, and particulate nutrient concentrations) to better understand the relationships between soil and tree characteristics and nutrient exports on drained peatlands.

In conclusion, we studied the dependence of nutrient concentrations in waters discharging from drained peatlands forests on their peat and tree stand characteristics. We found that tree stand volume and peat bulk density, particularly in deep-peated sites, were positively correlated with the discharged N and P concentrations, whereas peat K content showed a slight negative relationship. We conclude that there is a considerable risk that nutrient concentrations in waters discharging from drained peatland forests increase over time since their initial drainage due to the maturing of their tree stands, which, in turn, draws down the water table and enhances the mineralization of their peats and releases nutrients.

We suggest that this risk for increasing nutrient exports should be considered in developing environmentally sound management of peatland forests. Instead of using even-aged (clear-cut) forestry to grow large tree stands with high evapotranspiration capacity, which results in low water levels (Sarkkola et al., 2010) and mineralization of deep peat layers (Ojanen & Minkkinen, 2019), one should manage peatland forest with continuous cover forestry, specifically by harvesting the largest trees and leaving smaller trees with lower evapotranspiration capacity. This type of continuous cover forestry would stabilize relatively shallow groundwater levels as opposed to even-aged forestry, where water levels sink deeper and deeper with maturation of the tree stands. By maintaining shallower water levels than in mature even-aged forests, continuous cover management on drained peatlands could decrease not only nutrient exports but also CO_2 fluxes (Ojanen & Minkkinen, 2019).

DATA AVAILABILITY STATEMENT

Data are available from the corresponding author.

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AUTHOR CONTRIBUTIONS

Mika Nieminen: Conceptualization; Data curation; Funding acquisition; Project administration; Resources; Supervision; Writing – original draft. Eliza Maher Hasselquist: Data curation; Funding acquisition; Investigation; Resources; Writing – review & editing. Virginia Mosquera: Data curation; Formal analysis; Investigation; Methodology; Validation; Writing – review & editing. Liisa Ukonmaanaho: Data curation; Funding acquisition; Resources; Writing – review & editing. Tapani Sallantaus: Conceptualization; Data curation; Writing – review & editing. Sakari Sarkkola: Data curation; Formal analysis; Investigation; Methodology; Visualization; Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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REFERENCES

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. https://doi.org/10.1088/1748-9326/ab4fa9

Finér, L., Lepistö, A., Karlsson, K., Räike, A., Härkönen, L., Huttunen, M., Joensuu, S., Kortelainen, P., Mattsson, T., Piirainen, S., Sallantaus, T., Sarkkola, S., Tattari, S., & Ukonmaanaho, L. (2021). Drainage for forestry increases N, P and TOC export to boreal surface waters. *Science of the Total Environment*, *762*, 144098. https://doi.org/10.1016/j.scitotenv.2020.144098

Finstad, A., Andersen, T., Larsen, S., Tominaga, K., Blumentrath, S., de Wit, H. A., Tømmervik, H., & Hessen, D. O. (2016). From greening to browning: Catchment vegetation development and reduced S-deposition promote organic carbon load on decadal time scales in Nordic lakes. *Scientific Reports*, *6*, 31944. https://doi.org/10.1038/srep31944

Fork, M. L., Sponseller, L. A., & Laudon, H. (2020). Changing source-transport dynamics drive differential browning trends in a boreal stream network. *Water Resources Research*, *56*, e2019WR026336. https://doi.org/10.1029/2019WR026336

Kaila, A., Laurén, A., Sarkkola, S., Koivusalo, H., Ukonmaanaho, L., Xiao, L., Asam, Z., OťDriscoll, 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., OťDriscoll, C., Asam, 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

Kiikkilä, O., Nieminen, T. M., Starr, M., Mäkilä, M., Loukola-Ruskeeniemi, K., & Ukonmaanaho, L. (2014). Leaching of dissolved organic carbon and trace elements after stem-only and whole-tree clear-cut on boreal peatland. *Water, Air, and Soil Pollution*, *225*, 1767. https://doi.org/10.1007/s11270-013-1767-y

Koskinen, M., Tahvanainen, T., Sarkkola, S., Menberu, M. W., Laurén, A., Sallantaus, T., Marttila, H., Ronkanen, A -K., Tolvanen, A., Parviainen, M., Koivusalo, H., & Nieminen, M. (2017). Restoration of fertile peatlands poses a risk for high exports of dissolved organic carbon, nitrogen, and phosphorus. *Science of the Total Environment*, *586*, 858–869. https://doi.org/10.1016/j.scitotenv.2017.02.065

Laiho, R., Sallantaus, T., & Laine, J. (1999). The effect of forestry drainage on vertical distributions of major plant nutrients in peat soils. *Plant and Soil*, *207*, 169–181.

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

Lövblad, G., Amann, M., Andersen, B., Hovmand, M., Joffre, S., & Pedersen, U. (1992). Deposition of sulfur and nitrogen in the Nordic countries: Present and future. *Ambio*, *21*, 339–347.

Mäkisara, K., Katila, M., Peräsaari, J., & Tomppo, E. (2016). *The multi-source national forest inventory of Finland – Methods and results 2013*. Finnish Forest Research Institute.

Marttila, H., Karjalainen, S-M., Kuoppala, M., Nieminen, M. L., Ronkanen, A. -K., Kløve, B., & Hellsten, S. (2018). Elevated nutrient concentrations in headwaters affected by drained peatland. *Science of the Total Environment*, *643*, 1304–1313. https://doi.org/10.1016/j.scitotenv.2018.06.278

Nieminen, M., Piirainen, S., Sikström, U., Löfgren, S., Marttila, H., Sarkkola, S., Laurén, A., & Finér, L. (2018). Ditch network maintenance in peat dominated boreal forests: Review and analysis of water quality management options. *Ambio*, *47*, 535–545. https://doi.org/10.1007/s13280-018-1047-6

Nieminen, M., Sallantaus, T., Ukonmaanaho, L., Nieminen, T. M., & Sarkkola, S. (2017). Nitrogen and phosphorus concentrations in discharge from drained peatland forests are increasing. *Science of the Total Environment*, *609*, 974–981. https://doi.org/10.1016/j.scitotenv.2017.07.210

Nieminen, M., Sarkkola, S., Hasselquist, E. M., & Sallantaus, T. (2021). Long-term nitrogen and phosphorus dynamics in waters discharging from forestry-drained and pristine boreal peatlands. *Water, Air, and Soil Pollution*, *232*, 371. https://doi.org/10.1007/s11270-021-05293-3

Nieminen, M., Sarkkola, S., Hellsten, S., Marttila, H., Piirainen, S., Sallantaus, T., & Lepistö, A. (2018). Increasing and decreasing nitrogen and phosphorus trends in runoff from drained peatland forests: Is there a legacy effect of drainage or not? *Water, Air, and Soil Pollution*, *229*(8), https://doi.org/10.1007/s11270-018-3945-4

Nieminen, M., Sarkkola, S., Sallantaus, T., Hasselquist, E. M., & Laudon, H. (2021). Peatland drainage: A missing link behind increasing TOC concentrations in waters from high latitude forest catchments? *Science of the Total Environment*, *774*(18), 145150. https://doi.org/10.1016/j.scitotenv.2021.145150

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

Ojanen, P., & Minkkinen, K. (2019). The dependence of net soil CO_2 emissions on water table depth in boreal peatlands drained for forestry. *Mires and Peat*, *24*, 27. https://doi.org/10.19189/MaP.2019.OMB.StA.1751

Paavilainen, E., & Päivänen, J. (1995). *Peatland forestry – Ecology and principles*. Springer-Verlag.

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

Sarkkola, S., Hökkä, H., Koivusalo, H., Nieminen, M., Ahti, E., Päivänen, J., & Laine, J. (2010). Role of tree stand evapotranspiration in maintaining satisfactory drainage conditions in drained peatlands. *Canadian Journal of Forest Research*, *40*, 1485–1496. https://doi.org/10.1139/X10-084

Sarkkola, S., Koivusalo, H., Laurén, A., Kortelainen, P., Mattsson, T., Palviainen, M., Piirainen, S., Starr, M., & Finér, L. (2009). Trends in hydrometeorological conditions and stream water organic carbon in boreal forested catchments. *Science of the Total Environment*, *408*(1), 92–101. https://doi.org/10.1016/j.scitotenv.2009.09.008

Škerlep, M., Steiner, E., Axelsson, A. -L., & Kritzberg, E. S. (2019). Afforestation driving long-term surface water browning. *Global Change Biology*, *26*, 1390–1399. https://doi.org/10.1111/gcb.14891

Straková, P., Anttila, J., Spetz, P., Kitunen, V., Tapanila, T., & Laiho, R. (2010). Litter quality and its response to water level drawdown in boreal peatlands at plant species and community level. *Plant and Soil*, *335*, 501–520. https://doi.org/10.1007/s11104-010-0447-6

Straková, P., Penttilä, T., Laine, J., & Laiho, R. (2012). Disentangling direct and indirect effects of water table drawdown on above- and belowground plant litter decomposition: Consequences for accumulation of organic matter in boreal peatlands. *Global Change Biology*, *18*, 322–335. https://doi.org/10.1111/j.1365-2486.2011.02503.x

Vesihallinnon analyysimenetelmät. (1981). *The analyse methods of water samples in Finnish Environment Institute*. Vesihallitus.

Wang, H., Richardson, C., & Ho, M. (2015). Dual controls on carbon loss during drought in peatlands. *Nature Climate Change*, *5*, 584–587. https://doi.org/10.1038/nclimate2643

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