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Dissolved Organic Carbon Export from Harvested Peatland Forests with Differing Site Characteristics

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Abstract Calibration period and control area method were used to study the impact of forest tree harvesting on the dissolved organic carbon (DOC) export from drained peatland forests using data from 17 harvested and five control catchments. The results indicated highly increased DOC exports; during the first 3 years following harvesting, the average extra export ranged from over 200 kg ha^{-1} in nutrient-poor ombrotrophic to over 400 kg ha^{-1} in fertile minerotrophic peatland forest sites. The results indicated that a high iron (Fe) content in peat, as well as a high nitrogen (N) content and a low carbon (C)N ratio, are the site characteristics that contribute to large harvest-induced DOC exports. The effect of Fe is probably caused by the reduction of Fe in previously aerobic peat layers that have undergone harvest-induced water level rise and thus enhanced the DOC export, and the effects of the peat N and CN ratio indicate that the impacts of harvesting on DOC are the greatest from the sites with a high overall microbial activity. The calibration period/control area analysis revealed a high uncertainty in our data, the 95 % confidence intervals for average DOC exports overlapping between the groups with differing site characteristics. Given the uncertainties involved in our data, we conclude that significant changes in water colour and other water characteristics associated with large DOC inputs may be expected, where harvested forests on peatlands cover large proportions of catchments of small lakes and rivers.

Keywords C/N ratio · Dissolved organic carbon · Iron · Peatland forestry · Reduction reactions · Water quality

1 Introduction

Dissolved organic carbon (DOC) plays a major role in the quality of boreal surface waters through its implications on water acidity (Laudon and Buffam 2008), complexation and transport of heavy metals (Tipping et al. 1991), the structure of aquatic food webs (Jansson et al. 2007), and because it functions as a microbial substrate (Sigee 2004) and enhances water discoloration (Kortelainen et al. 1986). During the last 15–20 years, DOC concentrations have been observed to increase in lakes and rivers across northern Europe and North America (Vuorenmaa et al. 2006; Monteith et al. 2007; Worrall and Burt 2007; Sarkkola et al. 2009). Several studies have been carried out to elucidate whether cause of this widespread phenomenon is the global climatic warming (Eikebrokk et al. 2004; Erlandsson et al. 2008; Sarkkola et al. 2009) or the decrease in acidic

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atmospheric deposition (Vuorenmaa et al. 2006; Monteith et al. 2007). Assuming that forestry is the most wide-spread land-use throughout the boreal region, its influence on DOC concentrations and exports has received little attention (Laudon et al. 2009).

One of the inherent features of forestry in the boreal zone is that peatlands and wetlands cover a significant proportion of the landscapes and that large areas of them have been drained for forestry (Paavilainen and Päivänen 1995). Internationally, around 15-million hectares of peatlands and wetlands were drained for forestry in the temperate and boreal regions, particularly between the 1960s and the late 1990s. Large areas of these forests are now mature and are being or are about to be harvested in the near future. While the water quality effects of harvesting on mineral soil forests have long been of concern (Nieminen 2004), the effects of harvesting of drained peatlands on nutrient and DOC export have received minor attention (Lundin 1999; Cummins and Farrell 2003a, b; Nieminen 2003, 2004; Rodgers et al. 2010; Kiikkilä et al. 2014). However, the studies thus far have already raised concerns of the impact of harvesting on DOC from drained peatland forests. Nieminen (2004) estimated that with 40 % of the catchment area treated with harvesting, the DOC exports during the growing season (May–October) increased from the background level of 12–22 kg DOC ha^{-1} year^{-1} to 38–62 kg DOC ha^{-1} year^{-1} during the first 2 years after harvesting. This gives an annual increase of 65–100 kg ha^{-1} from the harvested 40 % proportion of the catchment during the growing season, assuming that all the detected increase compared to the background level of the catchment area was caused by harvesting. The other catchment studied by Nieminen (2004) with a harvested area covering 72 % of the catchment area indicated an extra annual load of 47–72 kg DOC ha^{-1} during the growing season during the first 2 years, also giving an extra growing season load of 65–100 kg DOC ha^{-1} year^{-1} from the forest tree harvested part of the catchment area. In a study by Lundin (1999) where 15–19 % of the catchment areas had been harvested, the annual extra DOC exports from the three drained peatland areas varied from 18 to 23 kg DOC ha^{-1} and the extra annual exports from the harvested part of the catchment from 120 to 168 kg ha^{-1}, respectively, assuming again that all the detected increases above the background levels of the catchment areas were caused by harvesting. In contrast, Palviainen et al. (2013) in their study on three mineral soil dominated catchments did not detect any increase in DOC exports that would have been caused by harvesting, and the DOC concentrations even decreased from the area with the greatest harvest area proportion (34 %). Other studies from mineral soil forests (Lamontagne et al. 2000; Laudon et al. 2009) also indicated lower DOC exports following harvesting than reported for peat soils by Lundin (1999) and Nieminen (2004). The results by Cummins and Farrell (2003b) from blanket peat bog catchments in western Ireland also indicated that the increases in DOC following harvesting may be greater from peat soils than for mineral soils. Mineral soil dominated catchments with mineral soil on their slopes but with an extensive organic riparian zone may, however, be significant sources of DOC when the forest on the slopes are harvested. In the study by Schelker et al. (2012) on mineral soil dominated catchments in northern Sweden, the increase in lateral flow of saturated water from forest harvested mineral soil slopes through surface peats of riparian wetlands was interpreted to be the key-driver for a large increase in riverine DOC export.

In the interpretation of the results of previous studies on the impact of forest harvesting on DOC exports from boreal peat soils, it should be noted that the data is only from minerotrophic and fertile fen types (Lundin 1999; Nieminen 2004), and there is thus far no data from less fertile ombro-oligotrophic sites. Owing to the major differences in peat and tree stand characteristics between nutrient-poor and fertile sites at their clear-felling phase, the DOC exports from the latter may be significantly larger. The peat is more decomposed with larger amounts of recently dead organic material at the clear-felling phase in the nutrient-rich sites with higher microbial activity than in less fertile sites. Also, the tree stands and their transpiration demand in boreal peatlands are significantly larger at the clear-felling phase in the fertile sites (Sarkkola et al. 2013), resulting in that the water levels before harvesting are lower in fertile sites and the postharvest rise of water levels greater than for nutrient-poor sites. Owing to the larger amounts of easily degradable organic material in peat in fertile sites and the greater postharvest change in water levels, the expanded anoxic peat profile feeding DOC into discharge waters (Zak and Gelbrecht 2007; Grybos et al. 2009) is both larger and richer in labile carbon in harvested fertile than nutrient-poor sites. If an important mechanism behind increased DOC is the release of carbon from soil upon oxygen depletion and reduction of iron oxohydroxides after harvest (Grybos et al. 2009), then the release of DOC will also be larger from nutrient-rich fen types than from less fertile types because the oxohydroxide contents are higher in fertile sites (Nieminen and Penttilä 2004). Thus, the DOC export from drained peatland sites following harvesting may correlate significantly with the overall fertility and tree production capacity of the site, but this has thus far not been assessed for boreal peatlands.

The aim of the study was to quantify the DOC exports from drained boreal peatland sites following final harvesting using clear-felling, with the main hypotheses that the stand biomass removal increases the DOC exports from drained peatland forests and that there are significant differences in the overall harvest-induced exports between sites with differing site characteristics.

2 Material and Methods

2.1 Study Sites

The study was conducted on altogether 22 catchment areas at three locations in Finland, in the southern coastal area at Lapinjärvi (60° 38′ N, 26° 12′ E), at Vilppula south-central Finland (62° 04′ N, 24° 34′ E) and at Sotkamo eastern Finland (64° 12′ N, 28° 30′E). The catchments have been presented in previous studies, the Sotkamo catchments in the study by Kiikkilä et al. (2014), the Vilppula catchments by Kaila et al. (2014) and the Lapinjärvi catchments in the study by Kaila et al. (2015). Thus, only a brief description of the study catchments is given here.

The Sotkamo catchment M10 (Kiikkilä et al. 2014) was excluded from this study in the early phases of the data examination because of the concern that the recently harvested peatland area of 2.4 ha still contributed to almost twice the pre-harvest DOC loads than from the other catchments. In the remaining data, there were two unharvest control catchments and four harvested catchments at Lapinjärvi, one control and eight harvested catchments at Vilppula, and two control catchments and five harvested catchments at Sotkamo (Table 1). The Vilppula catchments were artificial catchment areas established by isolating the areas hydrologically from the surroundings by double-ditching, while the other catchments were topographically delineated catchments. The Vilppula catchments and the Sotkamo S_{WTHS3} catchment were pure peatlands, while on the other catchments, peatland forests covered the lowest part of the catchments and mineral soil forests the surrounding uplands. The long-term (1981–2010) annual precipitation in the Lapinjärvi region averages about 670, 600 and 620 mm in the Vilppula and Sotkamo regions, respectively (Pirinen et al. 2012). The long-term mean annual temperature at Lapinjärvi is about +5.5 °C, + 3.5 °C at Vilppula, and +1.5 °C Sotkamo. The mean temperatures for July and February are, respectively, about +14.5 and −7.0 °C at Lapinjärvi and +17.0 and −8.5 °C at Vilppula, and +16.0 and −10.5 °C at Sotkamo.

The drained peatlands of the Lapinjärvi catchments were of the very fertile herb-rich type (Rhtkg) with Norway spruce as the dominant tree species, while the Vilppula catchments represented pure Scots pine stands and the nutrient-poor *Ledum-Empetrum* type (Table 1). The Sotkamo catchments represented all drained peatland site types in the classification system by Heikurainen and Pakarinen (1982), apart from the most fertile herb-rich type. Norway spruce or Scots pine was the dominant tree species at Sotkamo. The average thickness of the peat layer was >1 m at all the 16 Vilppula and Sotkamo catchments. Except for the $L_{WTH\text{-}C}$ catchment (peat thickness 40–60 cm), the Lapinjärvi catchments were thin-peated, the thickness of the peat layer varying mostly between 10 and 25 cm. At the clear-felling phase, the tree stands at Lapinjärvi were significantly larger (tree stand volume; 171–301 m^3 ha^{-1}) than at the less fertile and more northern Vilppula (100–200 m^3 ha^{-1}) and Sotkamo areas (70–170 m^3 ha^{-1}).

To characterise the peats of the catchments, pooled samples from 10 (Vilppula), 3 (Sotkamo) or 6–7 (Lapinjärvi) systematically located sampling positions 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 either concentrated nitric acid (Sotkamo) or chloric acid (Vilppula, Lapinjärvi). The peat analysis revealed that particularly the Fe and Al content and bulk density in the surface peat were significantly greater at Lapinjärvi than in the Sotkamo and Vilppula catchments (Table 2). For further details of peat sampling and analyses, see Kaila et al. (2014, 2015) and Kiikkilä et al. (2014).

Table 1 Catchment characteristics

	Area, ha	Harvested area, ha	Tree stand volume, m^3 ha^{-1}	Dominant tree species	Site type
L_{WTH1}	11.0	6.0	301	Norway spruce	Rhtkg
L_{WTH2}	9.3	3.4	293	Norway spruce	Rhtkg
L_{WTH-C}	15.3		171	Norway spruce	Rhtkg
L_{SOH1}	6.0	5.3	251	Norway spruce	Rhtkg
L_{SOH2}	6.6	4.9	238	Norway spruce	Rhtkg
L_{SOH-C}	9.2		233	Norway spruce	Rhtkg
S_{WTHS1}	0.7	0.5	169	Norway spruce	Mtkg
S_{WTHS2}	1.7	0.7	170	Norway spruce	Mtkg
S_{C1}	1.3		70	Scots pine	Mtkg/Vatkg
S_{WTHS3}	1.2	1.2	86	Scots pine	Vatkg
S_{WTHS4}	1.6	0.5	110	Norway spruce	Mtkg
S_{SOH}	6.9	1.6	70	Scots pine	Ptkg
S_{C2}	4.8		71	Scots pine	Ptkg
V_{WTH1}	0.8	0.8	200	Scots pine	Vatkg
V_{WTH2}	1.1	1.1	100	Scots pine	Vatkg
V_{WTHS1}	1.1	1.1	139	Scots pine	Vatkg
V_{WTHS2}	1.1	1.1	105	Scots pine	Vatkg
V_{SOH1}	1.1	1.1	156	Scots pine	Vatkg
V_{SOH2}	0.90	0.90	187	Scots pine	Vatkg
V_{SOH3}	1.0	1.0	110	Scots pine	Vatkg
V_{SOH4}	1.0	1.0	113	Scots pine	Vatkg
V_C	0.9		149	Scots pine	Vatkg

Rhtkg herb-rich type, *Mtkg Vaccinium Myrtillus* type, *Ptkg Vaccinium vitis-idaea* type, *Vatkg Ledum-Empetrum* type, *L* Lapinjärvi, *S* Sotkamo, *V* Vilppula, *WTH* whole-tree harvesting, *SOH* stem-only harvesting, *WHTS* whole-tree and stump harvesting, *WHT-C* control for WHT treatment, *SOH-C* control for SOH treatment

In Sotkamo, S_{C1} acted as control for S_{WTHS1} and S_{WTHS2}, and S_{C2} for S_{WTHS3}, S_{WTHS4} and S_{SOH}. In Vilppula, VC was the control for all harvest treatments. The tree stand volume is for the harvested proportion of the catchment in the harvested catchments and the whole catchment in the control catchments. For characterization of site types, see Heikurainen and Pakarinen (1982)

The tree stands were harvested in February–March 2009 or 2010 (L_{SOH2}). The catchments were clear-felled using either stem-only harvesting (SOH, including only stems down to a diameter of 7 cm) or whole-tree harvesting (WTH, including stems, branches, twigs, needles) or WTH and stump harvesting (WTHS, including stems, twigs, branches and stumps). The treatments were either SOH or WTH at Lapinjärvi, SOH or WTHS at Sotkamo, and SOH or WTH or WTHS at Vilppula. The stumps at the Sotkamo WTHS sites were lifted during the autumn following the clear-felling using an excavator and hauled from the sites during the next summer. At the Vilppula WTHS catchments, the lifting of stumps occurred during the summer following the clear-felling, and their hauling was done during the next winter. No regeneration operations were carried out at Lapinjärvi and Vilppula, but the Sotkamo catchments were mounded and sown with Scots pine or Norway spruce seeds in spring 2011.

For the monitoring of the discharge DOC concentrations, an earth embankment with an outflow pipe was built in the outlet ditch of each catchment area. Water samples were taken from the outflow pipe or right upstream of it (Sotkamo) once or twice a month (sometimes more often during runoff peaks) during 2007–2012 (Lapinjärvi), 2007–2011 (Vilppula) or 2008–2012 (Sotkamo), i.e. 1–2 years before harvesting and 3–4 years after harvesting. During each sampling occasion, the runoff was also measured from the outflow pipe manually by using a stop watch and a bucket or a larger 40-L container during high flows. The non-harvested Vilppula control catchment was also equipped

Table 2 Bulk density and chemical characteristics of the surface peat (0–10 cm) in each catchment area

	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}
L_{WTH1}	213	36.6	1.8	1590	2330	2600	540	23600	12600
L_{WTH2}	202	42.9	2.2	1380	2090	4600	1490	20500	13600
$L_{WTH\text{-}C}$	180	53.0	2.2	1130	600	3620	1560	2920	5490
L_{SOH1}	175	40.0	2.1	1580	1690	3780	1780	18400	11600
L_{SOH2}	156	43.0	2.1	1390	1900	4320	1890	16100	12300
$L_{SOH\text{-}C}$	156	46.1	2.2	1450	1290	5370	1560	13400	10200
S_{WTHS1}	117	54.2	2.5	1190	330	3560	490	1620	10040
S_{WTHS2}	68	51.7	2.2	920	950	8410	1890	1790	4940
S_{C1}	85	47.0	1.5	900	1230	9790	1810	3240	4910
S_{WTHS3}	82	54.1	2.1	690	720	1890	430	520	2400
S_{WTHS4}	48	51.9	2.7	1560	470	1740	460	6240	6040
S_{SOH}	48	51.2	1.3	870	1030	2270	760	730	4750
S_{C2}	146	52.2	1.3	790	1330	2960	630	530	1130
V_{WTH1}	92	54.6	1.6	550	550	3680	400	1170	1240
V_{WTH2}	103	52.9	1.5	620	400	3050	460	660	1090
V_{WTHS1}	114	52.9	1.5	560	550	5080	470	540	1020
V_{WTHS2}	104	54.3	1.5	600	450	2980	360	670	910
V_{SOH1}	117	53.0	1.9	720	510	4700	470	556	2730
V_{SOH2}	91	55.1	1.6	570	470	3650	390	740	940
V_{SOH3}	94	54.0	1.5	580	420	3270	390	600	880
V_{SOH4}	97	54.1	1.6	600	480	3470	410	620	1140
V_C	93	54.2	1.6	620	550	3180	430	640	1080

For the explanation of different catchment areas and their treatments, see Table 1

with an insulated runoff well, where the runoff was monitored automatically in a V-notch weir with a water height probe (TruTrack WT-HR500). The DOC concentrations were analysed using a TOC-VCPH/N Total Organic Carbon analyzer after filtering the water samples through a glass fiber filter (Whatman GF/B, nominal pore size 1.0 μm).

2.2 Calculation

The runoff data from the Lapinjärvi and Vilppula catchments has been analysed in earlier studies (Kaila et al. 2014, 2015), and the Sotkamo data was analysed in the same manner as the Lapinjärvi data (Ukonmaanaho, pers. comm.). To produce the annual DOC exports (kg ha^{-1} year^{-1}) as the product of runoff and the DOC concentration in runoff water, this study utilized the results of those earlier runoff analyses. The analysis of the Lapinjärvi and Sotkamo runoff data was briefly as such that the instantaneous manual runoff measurements were transformed to continuous daily runoffs (mm day^{-1}) by simulating runoff with the FEMMA ecohydrological model (Koivusalo et al. 2008), and then studying the correspondence between the simulated and manually measured runoffs. The principles and practical execution of the model simulations, as well as the correspondence between simulated and manually measured runoffs in the Lapinjärvi data was as shown in Kaila et al. (2015). The correspondence for the Sotkamo catchments was as good as for the Lapinjärvi catchments (Ukonmaanaho pers. comm.), the Nash-Sutcliffe efficiency coefficient (ENS) values indicating a satisfactory or good model fit according to Moriasi et al. (2007). The daily runoff from the harvested Vilppula catchments was calculated utilizing the automatic continuous runoff data from the control catchment and the relationship between manually measured runoffs in the control and the harvest catchments as shown in Kaila et al.

(2014). The analysis of runoff data indicated that the increase in the annual runoff during the 4 years after harvesting was between 150 and 260 mm from the harvested part of the catchment at Lapinjärvi (Kaila et al. 2015), and between 15 and 100 mm at the Sotkamo catchments S_{WTHS1}, S_{WTHS2}, S_{WTHS3} and S_{WTHS4} (Ukonmaanaho, pers. comm). At the Vilppula V_{SOH} catchments and the Vilppula V_{WTHS1} catchment, the increase in runoff during the first 3 years after harvesting was between 30 and 190 mm (Kaila et al. 2014). In contrast, the analysis of runoff data did not indicate increased runoff from the catchment areas V_{WTH1}, V_{WTH2}, V_{WTHS2} and S_{SOH}.

The annual DOC exports (kg ha^{-1} year^{-1}) from the different catchment areas were then calculated by first summing up to daily runoffs to produce monthly runoffs. The monthly runoffs were multiplied with the monthly mean DOC concentrations to produce the monthly DOC exports. Finally, the monthly DOC exports were summed up to produce the annual DOC exports. The effect of harvesting on the annual DOC exports was studied with the calibration period—control area method (also called the paired catchment approach) (e.g. Laurén et al. 2009). In the calibration period—control area method similar catchments are monitored during a pre-treatment period. Thereafter, during a post-treatment period, one of the catchments is left as an untreated control while the other catchments are treated. Monitoring is continued at all areas. The relationship during the calibration period between the control area and the areas to be treated is then used to predict the behaviour of the treated catchment during the post-treatment period as if it had not been treated. The treatment effect can then be determined as the difference between the actual measured values and the predicted background values during the post-treatment period. The length of calibration period was either 1.5 (L_{SOH2}) or 2 years for the Lapinjärvi and Vilppula catchments, and about 1 year for the Sotkamo catchments.

With the calibration period/control area method, the uncertainty in the relationship between the data series of the control catchments and the treatment catchments during the pre-treatment period introduces an error in the post-treatment estimations of treatment effects, but this uncertainty is typically ignored (Laurén et al. 2009). To account for this uncertainty, we used the approach by Laurén et al. (2009), combined more than one catchment pair in the same analysis as in Nieminen et al. (2010) and calculated the harvest-induced DOC loads using the following formula:

$$f_j^{-1}E_{ij} = a_1 \mathrm{C}_{ij} f_j^{-1} + b_1 \mathrm{I}_1 + b_2 \mathrm{I}_2 + b_3 \mathrm{I}_3 + b_4 \mathrm{I}_4 + \mathrm{u}_{0\mathrm{j}} + \mathrm{e}_{ij} \qquad I = 1, 2, 3, 4 \tag{1}$$

where E_{ij} is the annual DOC export (kg ha^{-1} a^{-1}) from the treatment catchment, i is the year, j is the treatment catchment, f_j is the proportion of the treated area (Table 1) of the catchment, a_1 is the slope coefficient, C_{ij} is the annual export from the control catchment, $b_1,\ldots,b_4$ are the regression coefficients for the harvest induced increase in export for each post-harvest year (kg ha^{-1} a^{-1}), $I_1,\ldots,I_4$ are the dummy variables for the post-harvest years, u_{0j} is the random error of the catchments j, and e_{ij} is the random error that accounts for the variation among the years i within the catchments j. In the model, the dummy variable $I_{1\ldots4}$ was one at a time assigned with a value of 1 to separately indicate each of the post-harvest years, else $I_{1\ldots4}$ was 0 (i.e. if the first post-harvest year I_1 was 1, the other post-harvest years I_2–I_4 were assigned with value 0). The harvest impact on annual DOC export (kg ha^{-1}year^{-1}) are $b1,\ldots,b4$. The inclusion of f_j^{-1} in the equation denotes that the impacts of harvesting on the annual export are expressed as kg per harvested area, not the whole catchment area. The constant was excluded from the model following the theoretical essence in the paired catchment approach that the control catchment and the treatment catchments should behave similarly during the pre-treatment period (Laurén et al. 2009), i.e. whenever the DOC exports from treatment catchments during the calibration period decreased and approached zero export, the exports from the control catchments also approached zero. The goodness of fit of the model was assessed in terms of the log-likelihood value and the Chi-square test.

In order to take into account the uncertainty related to calibration period control area method and to simultaneously study the impacts of catchment characteristics on DOC exports, we divided the data into two contrasting groups with respect to catchment characteristics or treatment (SOH, WTH + WTHS), analysed the harvest-induced DOC exports separately for these two groups using Eq. 1, and studied if the 95 % confidence intervals overlapped or not between these two groups. We performed several analysis with several different groupings in such a way that there were eight catchments, at least, in each group using the following grouping criteria: site type = ombrotrophic (Vatkg sites) *versus* minerotrophic (Ptkg, Mtkg and Rhtkg) site, treatment = SOH vs WHT + WHTS, tree stand volume; > or <150 m^3 ha^{-1}, peat bulk density; > or <100 kg m^{-3}, C; > or <52 %, N; > or <1.7 %, P; > or <800 mg kg^{-1}, K; > or <900 mg kg^{-1}, Ca; > or <3500 mg kg^{-1}, Mg > or <500 mg kg^{-1}, Al; > or <1500 mg kg^{-1}, Fe, > or <4000 mg kg^{-1}, and CN ratio; > or <30. With these criteria, we ended up in 9 different groupings, the 13 grouping factors notwithstanding, as the site type, Fe content, and P content criteria resulted in exactly the same two groups, as also did the peat N content and CN ratio criteria.

3 Results

The concentrations of DOC from Sotkamo and Lapinjärvi were higher from all 9 harvested catchments after than before harvesting (Table 3). The average pre-harvest concentrations were 38.8, 20.2, 34.1 and 26.6 mg l^{-1} from the L_{WTH1}, L_{WTH2}, L_{SOH1} and L_{SOH2} catchment, respectively, and the post-harvest concentrations were 53.4, 36.9, 45.8 and 46.5 mg l^{-1}, respectively. The DOC concentrations from the harvested Sotkamo catchments before and after harvesting were 25.7 and 50.5 mg l^{-1}, respectively, for S_{WTHS1}, 17.8 and 23.0 mg l^{-1} for S_{WTHS2}, 40.8 and 49.5 mg l^{-1} for S_{WTHS3}, 21.7 and 32.2 mg l^{-1} for S_{WTHS4} and 25.2 and 34.4 mg l^{-1} for S_{SOH}. The concentrations of DOC from the Sotkamo control catchments were not significantly different between between pre- and post-harvest periods, but increased from 21.7 to 32.2 mg l^{-1} at the Lapinjärvi control catchment $L_{SOH\text{-}C}$ and from 25.4 to 36.6 mg l^{-1} at $L_{WTH\text{-}C}$. Relative to pre-harvest concentrations, the increase in harvested catchments was the highest at S_{WTHS1} (97 %), followed by L_{WTH2} (83 %), L_{SOH2} (75 %) and S_{WTHS4} (49 %). The increase in the other harvested areas was between 21 and 44 % at Lapinjärvi and Sotkamo (Table 3).

The DOC concentrations from all Vilppula treatment catchments were also higher after than before harvesting. The DOC concentrations from the Vilppula treatment catchments were high particularly during the third year (2011) after harvesting, but the concentrations from the control catchment also peaked during the third year. Compared with the pre-harvest concentrations, the increase in concentrations was highest from V_{WTH2} and V_{WTHS2} (37 %), followed by V_{SOH1} (21 %) and V_{SOH3} (14 %).

In the analysis of the harvest impact on annual DOC exports (kg ha^{-1} $year^{-1}$) using Eq. 1, harvesting increased the DOC exports by >200 to >400 kg ha^{-1} during 3 years (Fig. 1, Table 4). The DOC exports did not decrease with time, indicating that the effect of harvesting on DOC lasts longer than 3 to 4 years. When grouping the data into two contrasting groups on the basis of site characteristics, the between-group difference in average harvest-induced DOC exports was the greatest for the two groups that differed with respect to their site type (minerotrophic vs ombrotrophic), Fe content (>4000 vs <4000 mg kg^{-1}), as well as P content (>800 vs <800 mg kg^{-1}) (Fig. 1a), and the two groups with different C/N ratio and N content (Fig. 1b). Grouping the data on the basis of the other site characteristics or treatment resulted in very similar DOC exports in the contrasting two groups. Although the average harvest-induced DOC exports differed between the group "minerotrophic, Fe>4000 mg kg^{-1}, *P*>800 mg kg^{-1}" vs the group "ombrotrophic, Fe< 4000 mg kg^{-1}, *P*<800 mg kg^{-1}", as well as the groups "C/N<30, N>1.7 %" vs "C/N>30, N<1.7 %", the 95 % confidence intervals overlapped between the two groups, indicating a non-significant difference at 5 % risk.

4 Discussion

The results of this calibration period and control area experiment supported our hypothesis that harvesting with clear-felling increases the DOC export from drained peatland forests. Multiplying the harvest-induced exports with the catchment area/harvest area ratio, the extra annual exports in the fertile peatland catchments studied by Lundin varied between 120 and 168 kg ha^{-1} $year^{-1}$ during the first 3 years after harvesting, which is of the same magnitude as the average exports from the minerotrophic sites in the present study. Similarly, taking into account the catchment area/harvest area ratio and the fact that the exports are only from the frost-free period, the harvest-induced exports by Nieminen (2004) for Norway spruce dominated peatland catchments are of the same magnitude as here. The results of the present study supported earlier studies (Lundin 1999; Nieminen 2004) also in that the enhanced DOC export caused by harvesting of peatland forests may not be a short-term phenomenon, but may

Table 3 Mean annual DOC concentrations (mg l^{-1})±standard error of mean from the Lapinjärvi, Sotkamo and Vilppula catchments before and during the first 3 or 4 years (Y) after harvesting

	Y-2	Y-1	Y+1	Y+2	Y+3	Y+4
L_{WTH1}	34.7±1.6	42.9±4.8	57.9±2.3	42.1±1.9	55.5±4.5	58.3±4.6
L_{WTH2}	19.2±1.5	21.1±3.4	43.7±3.4	28.8±3.1	38.5±5.2	36.7±6.6
$L_{WTH\text{-}C}$	24.9±1.2	25.8±3.1	31.4±1.5	30.8±1.8	39.9±2.6	44.2±3.8
L_{SOH1}	32.2±1.9	36.1±2.0	44.6±2.1	35.7±2.6	46.3±3.2	56.6±4.3
L_{SOH2}	28.8±2.2	28.0±1.5	37.1±2.3	46.9±3.9	55.6±6.0	
$L_{SOH\text{-}C}$	26.0±1.3	29.7±1.7	30.1±1.2	28.0±1.4	30.9±1.7	35.1±2.3
S_{WTHS1}		25.7±2.7	45.5±4.6	53.7±3.3	50.8±4.6	51.4±4.5
S_{WTHS2}		17.8±1.4	30.1±4.2	23.9±2.0	20.6±1.9	19.2±2.2
S_{C1}		20.9±2.6	18.4±2.8	16.5±1.3	15.8±1.4	19.0±2.7
S_{WTHS3}		40.8±2.7	49.5±3.1	47.6±1.9	51.7±2.9	49.6±2.8
S_{WTHS4}		21.7±1.2	35.1±2.8	36.9±1.9	30.8±1.7	26.4±2.0
S_{SOH}		25.2±2.6	37.6±6.0	37.2±2.6	32.4±2.7	30.4±2.7
S_{C2}		20.7±2.1	17.0±3.2	18.7±1.8	21.5±1.4	23.0±2.0
V_{WTH1}	65.1±2.2	63.1±1.9	67.3±3.0	69.5±3.6	87.1±3.1	
V_{WTH2}	85.3±3.6	60.3±3.3	92.9±4.8	97.3±8.0	109.6±10.9	
V_{WTHS1}	64.3±2.4	68.1±2.3	64.6±1.9	67.2±6.3	86.7±9.4	
V_{WTHS2}	68.7±3.2	66.0±3.4	85.6±6.9	89.6±11.3	102.4±10.1	
V_{SOH1}	69.8±2.3	85.5±3.6	93.6±5.3	90.1±8.1	99.4±9.8	
V_{SOH2}	66.3±2.0	71.0±2.5	70.6±3.0	68.3±3.0	85.6±8.0	
V_{SOH3}	69.9±3.7	71.7±4.0	75.7±3.9	75.4±6.8	91.2±12.7	
V_{SOH4}	55.6±3.1	57.2±3.4	61.1±4.6	63.0±9.1	76.9±10-8	
V_{C}	68.5±2.6	72.2±2.6	65.0±2.3	63.7±5.6	82.4±8.9	

Y-2 to +Y4 are from 2007 to 2012, but Y-2 to Y+3 are from 2008 to 2012 for L_{SOH2}. For the explanation of different catchment areas and their treatments, see Table 1

continue over 3–4 years. Should the effect of harvesting on DOC last for as long as for P and N in the study by Ahtiainen and Huttunen (1999), i.e. >10 years, the overall export caused by harvesting may amount to well over 1000 kg ha^{-1}. Thus, where harvested peatlands comprise large proportions of catchments of small lakes and rivers, changes in water colour and other water characteristics associated with high DOC inputs are to be expected.

The results also supported our hypothesis (although not statistically with 5 % risk) that the effects of harvesting on DOC export are different for peat sites with differing site characteristics. The results indicated that the harvest-induced DOC exports are, on average, greater from minerotrophic than ombrotrophic sites, and greater from sites with high Fe, P, and N contents, as well as low CN ratios. There are no previous harvesting experiments on drained peatlands dealing with the impacts of site characteristics on DOC, but many restoration studies and simulated restorations with re-wetted peat matrices indicate that harvest-induced water level rise may result in differing DOC exports from sites with differing characteristics. Koskinen et al. (2011) found greater DOC export following restoration and re-wetting from a nutrient-rich minerotrophic spruce mire than from an ombrotrophic nutrient-poor fen-pine bog site. Similarly, Urbanova et al. (2011) and Kaila et al. (2012) found greater DOC release from re-wetted peat matrices containing minerotrophic, Fe- and N-rich fen peat than ombrotrophic Fe- and N-poor bog peat. In addition, Zak and Gelbrecht (2007) reported higher DOC release from rewetted peat matrices with highly decomposed, Fe-rich peat than from slightly decomposed Fe-poor peat.

The effect of peat Fe on the DOC export is probably caused by the reduction of Fe under harvest-induced water level rise that enhances organic matter mobilization. Grybos et al. (2009) argue that the release of

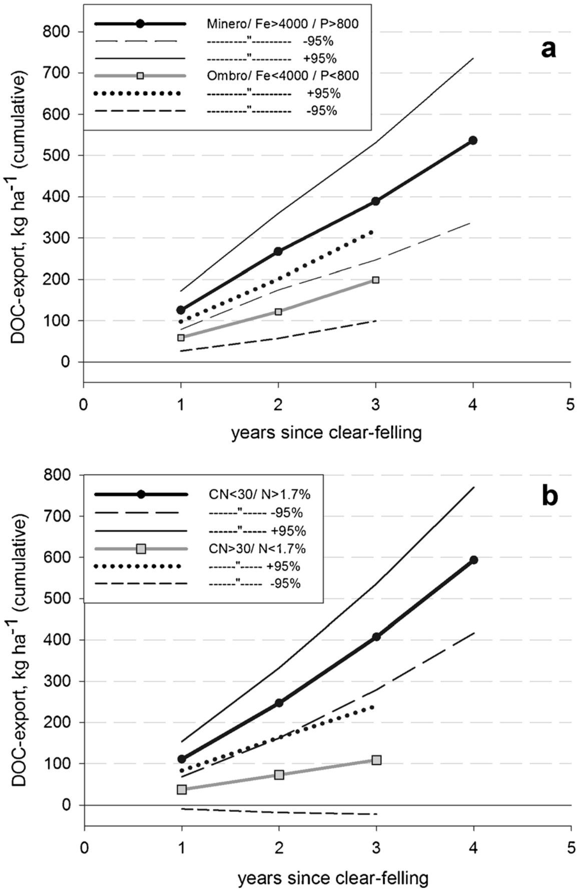

Fig. 1 Cumulative harvest-induced DOC exports and 95 % confidence intervals calculated using Eq. 1. Data grouped by site type and peat Fe and P content (minerotrophic sites, Fe>4000 mg kg^{-1}, P>800 mg kg^{-1} vs ombrotrophic sites, Fe<4000 mg kg^{-1}, P<-800 mg kg^{-1}), and **b** by peat CN ratio and N content

organic matter from Fe-oxohydroxides that undergo reductive dissolution or the production of organic metabolites by microbes during soil reduction are not the key-drivers behind DOC mobilization from re-wetted wetland soils, but the organic matter release occurs in response to pH change. Reduction reactions consume protons, which increases soil solution pH. At low pH, protonated hydroxyl groups are positively charged, which promotes adsorption and surface complex formation with the negatively charged organic molecules. Along with increasing pH, the deprotonation of the hydroxyl groups decreases the soil positive net surface charge and the organic molecules become more negatively charged, inducing that soil mineral surfaces and organic matter start to repel each other. Correlation of DOC release with peat P content (Fig. 1) may not be because P in itself would affect the DOC release, but

Table 4 Parameter estimates and their 95 % confidence intervals for the annual DOC exports (Eq. 1) from the research catchments grouped by site type (minerotrophic vs ombrotrophic type) and peat Fe and P content, and by peat N content and CN ratio

E_{ij}	C_{ij}	b_1	b_2	b_3	b_4	u_{ij}	e_i
Minero/Fe>4000 mg kg^{-1}/P>800 mg kg^{-1}	**2.230**±0.56	**125.369**±46.57	**141.623**±46.09	**122.059**±49.65	**147.602**±56.04	4892.4	**2820.5**
Ombro/Fe<4000 mg kg^{-1}/P<800 mg kg^{-1}	**0.990**±0,092	**58.926**±32.58	**63.146**±32.63	**76.73**±34.20		569.1	**1858.1**
CN<30/N>1.7 %	**1.389**±0.341	**110.823**±42.84	**136.364**±42.30	**160.529**±43.35	**185.75**±48.34	4805.6	**2625.2**
CN>30/N<1.7 %	**0.942**±0.172	36.948±46.24	35.811±44.35	36.268±40.49		11836.3	**2054.8**

Parameter estimates b_1…b_4 represent the annual extra DOC exports (kg ha^{-1}) from the treatment area caused by harvesting. Statistically significant parameter estimates (p<0.05) have been printed in bold most probably because of the high correlation between peat P and Fe (Table 1).

The correlation of peat N content and CN ratio with DOC export probably indicates that the DOC release upon harvest-induced re-wetting is higher from sites with a higher overall microbial activity. There may be considerable microbial activity and organic matter mineralization in fertile minerotrophic sites with high N contents and low CN ratios before harvesting and thus a large organic matter (OM) supply into the soil solution. After harvesting the water-consuming tree stand and subsequent re-wetting of the previously aerobic peat, the OM exchange between the solid and aqueous phases, cleavage of particulate OM by hydrolytic and fermentation processes, as well as microbial catalyzed reactions dependent on the availability of OM are possible processes for a greater DOC release from sites with a larger OM supply (Zak and Gelbrecht 2007).

Although the average DOC exports indicated that there occurred differences in DOC release from sites with different trophic status, as well as different Fe and N content, and CN ratio, it should be noted that the 95 % confidence intervals overlapped between the sites with differing site characteristics, when the DOC exports were calculated using the approach by Laurén et al. (2009) that accounts for the uncertainty in calibration period/control area method (Eq. 1). The uncertainty related to calibration period/control area method is high in our data set probably because all the prerequisites underlying a solid calibration/control area analysis were not met sufficiently well (Laurén et al. 2009). The calibration periods were relatively short in all areas (1–2 years) and the calibration year 2008 was hydrologically exceptional with 100–300-mm higher precipitation, e.g. in the Vilppula region than during the 3 years after harvesting.

The reliability of the results is also affected by how accurate the DOC export estimates calculated as a product of monthly runoff and monthly mean DOC concentration are. The sampling of waters for the DOC analysis was more intensive in Lapinjärvi and Vilppula than in the Sotkamo catchments; thus, the estimates for Lapinjärvi and Vilppula may be more reliable. According to Koivusalo et al. (2008), however, hydrological isolation of catchments with double-ditching may result in leaking catchments, which may affect the DOC estimates particularly from Vilppula (all catchments artificially isolated). Catchment leaking or difficulties in catchment area boundary delineation may be one reason why Kaila et al. (2014) found no increase in runoff in many of our Vilppula catchments following harvesting of the water-consuming tree stand, although the runoff changes may have been relatively small in catchments with a relatively small tree stand volume and consequent low transpiration demand, such as was the case in many of the Vilppula and Sotkamo catchments (Table 1). However, the factor that had the greatest influence on the reliability of the DOC export estimates was probably that the runoffs from the study catchments were not monitored with in situ high-frequency runoff sensors, but the runoffs were produced either by calibrating the hydrological model FEMMA with the instantaneous 1–4-week interval manual runoff measurements (Lapinjärvi and Sotkamo) or predicting the runoffs for the harvest catchments on the basis of manual runoff measurements in all the catchments and the automatic runoff monitoring station in the control catchment (Vilppula). Although the correspondence between simulated and manual runoff measurements was relatively good (e.g. Kaila et al. 2015), future research should utilize high-frequency in situ devices to monitor runoff. As important as that would be the use of automated in situ DOC sensors (Ryder et al. 2014) to improve the understanding of the mechanisms behind variable DOC exports from harvested peat soils. However, equipping as many catchments as here (22) with automatic runoff and DOC sensors would bring about considerable costs, particularly in areas with a distinct winter period, such as Finland, where all sensors need to be assembled within properly insulated wells. Studies with fully automated monitoring systems generally involve only one or a few catchments and the effect of catchment characteristics on exports remain unknown.

In conclusion, our study showed high DOC exports from drained peatlands following harvesting and higher average exports from minerotrophic sites with high Fe and N content and low CN ratio than for nutrient-poor ombrotrophic sites. Given the uncertainties involved in our DOC export estimates and the calculation of harvest-induced DOC exports, we conclude that significant changes in water colour and other water characteristics associated with increased DOC inputs may be expected, where harvested peatlands comprise large proportions of catchments of small lakes and rivers. Current mitigation methods (sedimentation ponds, wetland buffer areas) are not efficient in reducing DOC exports (Ahti et al. 2005; Klöve et al. 2012); thus, development of new water protection methods or less intensive harvesting options than clear-felling are needed to manage DOC exports from forestry-drained peatlands.

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