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Export of Suspended Solids and Dissolved Elements from Peatland Areas after Ditch Network Maintenance in South-Central Finland

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In Finland nearly 6 million hectares of peatlands are drained for forestry purposes. Ditch network maintenance in the drained peatlands, i.e. cleaning old ditches or digging complementary ditches, deteriorates surface water quality by increasing the export of dissolved elements and suspended solids (SS). Effect of ditch network maintenance on the export of SS, dissolved organic carbon (DOC), and dissolved nitrogen (N), phosphorous (P), iron (Fe), aluminum (Al) and manganese (Mn) was studied in nine pairs of treated and control (no maintenance) catchments located in southern and central Finland. In this study we extended the paired catchment approach by combining data from several catchments and identifying the treatment effect on SS and element loads from the entire dataset. Following the method of Laurén et al. (2009) we identified how uncertainty in correlation between treatment and control catchments during pre-treatment period is reflected in the estimated treatment effect on SS and element loads. In the experiment, the export of SS increased significantly for the four year study period following the ditch network maintenance and Al export increased for one year. The export of N, P and Fe was not significantly changed and DOC and Mn export decreased after the ditch maintenance operation.

Keywords ditching, drained peatlands, forestry, hydrochemistry, nutrient export, suspended solids

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1 Introduction

The total area of peatlands and paludified mineral soils in Finland is about 10 million hectares or one third of the total land area. Between 1930 and 1990, nearly 6 million hectares of these soils were drained with open ditches for forestry purposes. While pristine peatlands are no longer drained, maintenance of old ditch networks has become important for maintaining the growth of the stands in drained areas. In the 1990s, 70–80 000 ha of drained peatland forests were annually subject to ditch network maintenance, such as ditch cleaning or complementary ditching. From the viewpoint of water quality, ditch network maintenance is currently considered to be the most harmful practice in Finnish forestry (Nieminen et al. 2005).

Total runoff after initial, first-time ditching is found to increase in many studies (Braekke 1970, Bergquist et al. 1984, Prévost et al. 1999), whereas the impact of ditch network maintenance on runoff is reported to be negligible (Manninen 1998, Joensuu et al. 2002). The model experiment by Koivusalo et al. (2008) demonstrated that annual runoff was not much affected by ditch cleaning as long as the initial soil water level was not very close to soil surface and the highly conductive surface layer of peat was not very thin. The lowering of the water table after ditch network maintenance is generally 5–10 cm (Ahti and Päivänen 1997), which corresponds to a decrease of 15–30 mm in the soil water storage. Joensuu et al. (2002) estimated the impact of ditch network maintenance on runoff to be negligible compared with its effect on element concentrations. The changes in export (concentration multiplied with runoff) due to ditch network maintenance were accordingly calculated by assuming no maintenance impact on runoff. The studies by Åström et al. (2001a, 2002) on two experimental sites in mid-western Finland also suggested negligible changes in runoff pattern following ditch network maintenance.

The most pronounced impacts of initial ditching and ditch network maintenance on runoff quality is the increase in the suspended solids (SS) concentrations (Joensuu et al. 1999, Prévost et al. 1999). The magnitude of this increase is related to soil type at the bottom of the ditches. High and long-term sediment export generally occurs from areas where the ditches reach down into the mineral subsoil beneath the peat surface. In areas with peat layer thicker than the depth of ditches, undecomposed organic material at the bottom of ditches is not particularly liable to erosion. Because of peat subsidence, the thickness of the peat layer in drained areas decreases with time and the ditches reach deeper layers after ditch network maintenance than after initial, first-time ditching. Once the maintained ditches extend to the mineral soil the risk for high sediment loads markedly increases. The risk of erosion is highest in the main outlet ditches which are deeper than the feeder ditches, collect large amounts of water, and are often located at areas covered with a shallow peat layer.

Compared with the relative increases in SS export, the changes in the export of dissolved elements following ditch network maintenance are typically lower. Joensuu et al. (2002) studied the export of dissolved nutrients in 40 catchment pairs one year before and 2–3 years after ditch network maintenance and found that the loads of total dissolved N and P decreased slightly. Export of mineral N fractions, especially ammonium, increased but the increase was compensated by the decrease in the load of organic N, which was sufficiently large to cause a decrease of dissolved total N export. Similarly, Ahti et al. (2007) found that ditch network maintenance did not significantly increase the export of dissolved heavy metals, such as cadmium or lead. These results may at first seem contradictory to the studies where high increases in nutrient or metal export has been reported after ditching operations (Manninen 1998, Ahtiainen and Huttunen 1999, Åström et al. 2001a). The differences in reported element exports are due to the selected pretreatment method of the water samples. When the water samples are filtered prior to analysis, the elements in the solids are removed from the analysis solution, and when the samples are not filtered, the element concentrations in the solids strongly affect the results of water analysis. Since ditching operations are likely to increase the export of solids, the impact of ditch network maintenance appears greater when unfiltered samples are used in water analyses. The type and pore size of the filter also affects the results of water quality studies (Tarapchack et al. 1982, Broberg and Persson

1988). Filters with a pore size of 0.45–0.50 μm are generally used by aquatic chemists to separate particulate matter from dissolved elements, but in ditching studies, somewhat coarser filters (1.0 μm porosity) are commonly used (Joensuu et al. 1999, 2002). On the other hand, colloids can be sorped onto the filters and the effective pore size can become lower than the nominal size due to the clogging of the filter (Tarapchack et al. 1982, Broberg and Persson 1988). The clogging effect may be a factor in the analysis of the peatland drainage waters, which are typically rich in fine-fractioned organic material.

According to Åström et al. (2005) both advantages and disadvantages are involved in the use of unfiltered samples. An advantage is that there is no artificial cut-off of particles at a predetermined filter pore size. The disadvantages are that the distribution of nutrients in soluble and solid forms remains unknown and the quality and quantity of particulate material strongly affects the results. Generally, unfiltered water samples are used in earlier studies focusing on both water quality impacts of initial, first-time ditching (Kenttämies 1981, Hynninen and Sepponen 1983, Tossavainen 1991, Ahtiainen and Huttunen 1999), and impacts of ditch network maintenance (Ahti et al. 1995, Manninen 1998, Åström et al. 2001a,b, 2002, 2005). The ditch maintenance-induced export of dissolved elements (using filtered samples) has received less attention (Joensuu et al. 2001, 2002).

The aim of this study was to quantify the impact of ditch network maintenance on the export of SS and dissolved elements from drained peatlands. The principal hypothesis was that the export of elements in a dissolved form is minor compared with the export of SS and the elements adhered to solids.

2 Material and Methods

2.1 Study Areas and Sampling

The study was conducted at 8 locations in south-central Finland (Fig. 1) and is based on the paired catchment approach (also called the calibration period–control area method) (e.g. Laurén et al. 2009). In the paired catchment approach, two similar catchments are monitored during a pre-treatment period. Thereafter, one of the catchments is treated and monitoring is continued during a post-treatment period. The relationship between the catchments during the pre-treatment period is used to predict the behavior of the treated catchment during 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 values. In this study, there was a pair of treated and control catchments at 7 locations and two treated catchments and one control catchment at one location (Table 1). The areas of the treated catchments varied from 21 to 172 ha and the areas of the control catchments from 21 to 168 ha. The

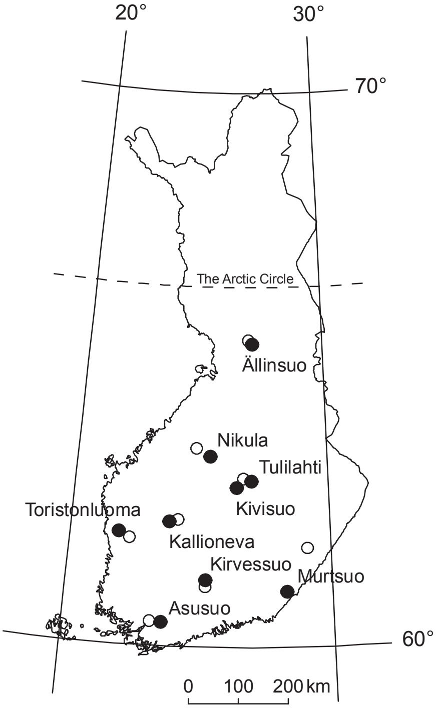

Fig. 1. Location of the study sites (dots) in southern and central Finland, and location of the nearby small catchments (circles) of the Finnish Environment Institute used as reference data for daily runoff. For more information about the network of the small catchment areas, see Hyvärinen & Korhonen (2003).

Table 1. Background information about the study sites.

Experiment	Climate a)				T/C b)	Location	Area, ha	Treated area, ha/ Proportion of the treated area, ha ha^{-1}
	Precip.	Air temperature						
		Annual	February	July				
1 Asusuo	663	5.2	–5.7	17.0	T	60°26´ N, 23°38´ E	83	21/0.25
					C	60°24´ N, 23°29´ E	48	
2 Murtsuo	626	3.9	–8.1	17.2	T	61°01´ N, 28°19´ E	110	18/0.16
					C	61°00´ N, 28°19´ E	89	
3 Kirvessuo	562	4.1	–7.9	16.8	T	61°14´ N, 25°15´ E	134	52/0.39
					C	61°10´ N, 25°15´ E	78	
4 Toristonluoma	668	3.7	–6.9	15.9	T	62°02´ N, 21°52´ E	28	16/0.57
					C	62°14´ N, 21°54´ E	168	
5 Kallioneva	681	3.2	–7.7	15.5	T	62°16´ N, 23°48´ E	21	6/0.29
					C	62°17´ N, 23°48´ E	56	
6 Kivisuo	637	2.4	–9.5	15.7	T	62°54´ N, 26°23´ E	172	54/0.31
7 Tulilahti	637	2.4	–9.5	15.7	T	63°01´ N, 26°59´ E	47	15/0.32
					C	62°56´ N, 26°22´ E	76	
8 Nikula	561	2.4	–9.2	15.8	T	63°27´ N, 25°20´ E	43	22/0.51
					C	63°29´ N, 25°17´ E	21	
9 Ällinsuo	589	1.2	–10.6	15.5	T	65°29´ N, 27°00´ E	102	77/0.75
					C	65°32´ N, 26°58´ E	95	

a) Longterm (1971–2000) mean values of annual precipitation (mm) and air temperature (°C) at the nearby weather stations operated by the Finnish Meteorological Institute (Drebs et al. 2002)

b) T = Treated catchment, C = Control catchment

catchments were forested areas, where peat was the dominant soil type at the lower elevations and mineral soils at the surrounding uplands. The peatland and upland forests were dominated by either Norway spruce (*Picea abies* Karst.) or Scots pine (*Pinus sylvestris* L.). The catchment boundaries and ditch networks for the Asusuo, Murtsuo, Kirvessuo, Tulilahti, and Kallioneva treatment catchments are presented in Nieminen et al. (2005). The proportion of the ditch network maintenance area from the total catchment area varied from 16 to 75%. No major fertilization or harvesting was applied in the catchments during the last 15 years.

Annual climatic cycle in the region includes four distinct seasons. Winter period (December–March) is characterized by freezing temperatures and a snow cover with depths ranging in midwinter from about 20 to 120 cm. Snowmelt period typically starts in late April or early May and after two or three weeks the snowpack and the frozen ground have melted. Summer (June–August) is characterized by high biological activity and the daily mean air temperature in July is about 17 °C in the southern part and 15 °C in the northernmost part of the region. During autumn (September–November) the daily air temperatures gradually decrease from a range of 10–15 °C to values below zero and late autumn the ground and surface water bodies start to freeze. The mean annual precipitation is 560–680 mm, about 200 mm of which falls as snow.

Monitoring for the pre-treatment period started in 1995 in three catchment pairs, in 1996 in five pairs, and in 1998 in one pair. Ditch network maintenance was performed after the pre-treatment period of three years at Kirvessuo and two years at Asusuo and Nikula, and one year at the remaining six catchments. The length of the post-treatment period was two (Kirvessuo, Kallioneva, Nikula), three (Toristonluoma, Tulilahti) or four (Asusuo, Murtsuo, Kivisuo, Ällinsuo) years. The ditch spacing in the drainage areas was sufficiently low (<40 m) for a satisfactory drainage effect and there was no need to dig supplementary ditches between the old ditches. Ditch network maintenance operations were therefore conducted by only cleaning the existing old ditch network.

Water samples were taken from the discharge of each area once or twice a week during the snowmelt period and weekly or biweekly during the other seasons. The sampling was started along with snowmelt in spring and it continued till the freezing of waters in late autumn. The samples were taken either from the overflow of a V-notched weir or directly from flowing water in the outlet ditch. Stirring of the sediment deposited in the ditch bottom was carefully avoided when pushing the 0.5 l PVC bottles below the water level in the ditch. When there was a sedimentation pond or buffer zone constructed below the treatment catchment, the water samples were taken from their inlet, right at the point where waters discharged from the ditch maintenance area. Before laboratory analysis, the samples were stored at +5 °C for a maximum period of one week. Runoff from the catchments was not monitored, but reference data of discharge were available from the small catchments operated by the Finnish Environment Institute (Fig. 1).

2.2 Chemical Analysis

Water samples were analysed in the Central Laboratory of the Finnish Forest Research Institute according to procedures described by Jarva and Tervahauta (1993). The samples were first filtered and then the fibre-glass filters (pore size 1.0 μm) were dried (+60°C) and weighed for the amount of suspended solids (SS). Concentrations of total dissolved P, Al, Fe, and Mn were determined from the filtrates using an inductively coupled plasma emission spectrophotometer (ICP/AES, ARL 3580). The concentrations below the determination level of ICP/AES were set equal to zero. The concentrations of total dissolved N were analysed with a Tecaton FIA analyser and the concentrations of dissolved organic carbon (DOC) with a Shimadsu carbon analyzer.

2.3 Data Analysis

The impact of ditch network maintenance on the export of SS and dissolved elements in runoff was estimated using the paired catchment approach. Traditionally the analysis of paired catchment data is conducted without considering uncertainty in the estimated treatment effect (Joensuu et al. 2002, Nieminen 2004). Laurén et al. (2009) extended the analysis to account for uncertainty in the estimate of treatment effect on element export in annual time scale. In this study the treatment effect on concentration levels is presented without uncertainty quantification, whereas the method of Laurén et al. (2009) is applied for analysing the annual element export data.

On the basis of concentration measurements during the pre-treatment period, the average ratio of concentration values in the treated catchment to the respective values in the control catchment was calculated. After ditch network maintenance, concentration values were predicted for the ditch maintenance area as if it had not been treated using this ratio and the measured values from the control catchment. The effect of ditch network maintenance on SS and dissolved element concentrations was derived as the difference between measured values in the treated catchment and the predicted values.

The annual element export was computed in the following way. First, available concentration measurements were used to produce monthly mean concentration for each catchment. Concentration values for months with no observations were interpolated from the closest available monthly values. Second, the monthly concentration was multiplied with monthly runoff, which was obtained from the nearby research catchment of the Finnish Environment Institute (Fig. 1). Finally, the monthly exports were summed up to yield the annual export. In the computation of export it was assumed that the change in runoff due to ditch network maintenance is negligible compared with its impact on element concentrations (Joensuu et al. 2002).

In the analysis of the export data all nine catchment pairs were combined in the same analysis. This allows a wider generalization of the results than in individual catchment studies. When all catchments are analysed together, one must consider that the proportion of the treated area varies between the treatment catchments. In the studied catchments this proportion ranged from 0.16 to 0.75 (Table 1). To consider the different proportions of treated area, the treatment effect is expressed as *specific export*. When ditch network maintenance is applied to only a fraction of a treatment catchment, the export from the untreated area is assumed to be at the background level and all the detected change from the background level is caused by the ditch network maintenance. *Specific export* is defined as the detected change from the background level divided by the proportional area of the ditch network maintenance.

Annual export of an element from treatment catchment was calculated using the following linear mixed model:

$$f_j^{-1} T_{ij} = a_0 + a_j + a_1 C_{ij} f_j^{-1} + b_1 I_1 + b_2 I_2 + b_3 I_3 + b_4 I_4 + e_{ij},\ i=1,2,3,4 \tag{1}$$

where T_{ij} is the annual export from the treatment catchment (kg ha^{-1} a^{-1}), i is the year index, j is the catchment pair, a_0 is the intercept (kg ha^{-1} a^{-1}), f_j is the proportion of the treated area from the treatment catchment area (see Table 1), a_j is the catchment specific deviation in a_0 (kg ha^{-1} a^{-1}), a_1 is the slope coefficient, C_{ij} is the annual export from the control catchment (kg ha^{-1} a^{-1}), $b_1,\ldots,b_4$ are the parameters determining specific export for the post-treatment years from 1 to 4 (kg ha^{-1} a^{-1}), $I_1,\ldots,I_4$ are the dummy variables for post-treatment years, and e_{ij} is the error term. The dummy variable I_k is assigned with a value of 1, when the year index i is equal to n_c+k, else I_k is equal to zero (n_c is the number of pre-treatment years, k is the index of post-treatment years).

According to the principles of the paired catchment setup, the export from the treatment catchment under the assumption that the treatment has not occurred ("background export") is calculated as $f_j(a_0+a_j+a_1C_{ij}f_j^{-1})$. For each year in the post-treatment period, the deviation of the export from the background level is represented by b_k (Laurén et al. 2009), which is a measure of specific export for year k after the treatment. When the linear model (Eq. 1) is fitted to data, the uncertainty of specific export parameters $b_1,\ldots,b_4$ are defined with 95% confidence intervals. Data from all catchment pairs are used simultaneously, when the parameters a_l and b_k are identified in Eq. 1.

In the analysis of N, DOC, Al, Fe, Mn and P, no filtering of the data was necessary, but in the analysis of skewed SS data, natural logarithm of the measured SS export both from the control and treatment catchments was applied.

3 Results

3.1 Concentration of Suspended Solids and Dissolved Elements

The concentration of SS in runoff during the pre-treatment period varied between 0.3 and 9.9 mg l^{-1} in the control and treatment catchments (Table 2). The corresponding variation was between 11.2 and 47.6 mg l^{-1} for DOC, 0.28 and 1.40 mg l^{-1} for N, 0.27 and 2.80 mg l^{-1} for Fe, and 0.06 and 0.90 mg l^{-1} for Al. The variation was between 12 and 54 μg l^{-1} for P, and 3 and 60 μg l^{-1} for Mn.

Concentration of SS in runoff increased in eight of the nine treated catchments during the first year following the ditch maintenance operations (Fig. 2). The variation in SS concentration after ditch network maintenance was considerable, and increase in SS concentration was substantially higher in catchments 7 (Tulilahti) and 8 (Nikula) than in the remaining catchments. Concentration of Al increased in eight catchments during the first year after the ditch maintenance.

DOC concentration in runoff decreased after the ditch network maintenance in eight catchments (Fig. 2). The decrease in DOC concentration was substantial at catchments 6 (Kivisuo), 5 (Kallioneva), and 4 (Toristonluoma). The data on the change in dissolved N, P, Fe and Mn concentration following the ditch network maintenance show considerable variation between the studied catchments and no clear treatment effect can be seen.

3.2 Specific Export

The paired catchment analysis combining data from the nine catchment pairs indicated that ditch network maintenance increased export of SS and Al, decreased export of DOC and Mn and had no effect on export of N, P, and Fe (Table 3). For

Table 2. Element concentrations (± SEM) in the treatment (T) and control (C) catchments during the pre-treatment period.

Experiment		SS	DOC	N	Fe	Al	P	Mn
		$\mathrm{mg\ l^{-1}}$					$\mathrm{\mu g\ l^{-1}}$	
1 Asusuo	T	0.3 ± 0.1	29.0 ± 1.5	0.58 ± 0.07	0.37 ± 0.02	0.45 ± 0.03	27 ± 4	14 ± 1
	C	0.4 ± 0.1	26.0 ± 0.8	0.56 ± 0.02	0.53 ± 0.06	0.66 ± 0.02	31 ± 6	11 ± 8
2 Murtsuo	T	4.5 ± 0.7	22.7 ± 0.9	0.69 ± 0.07	0.75 ± 0.10	0.56 ± 0.03	32 ± 5	39 ± 3
	C	2.2 ± 0.6	20.2 ± 1.3	0.64 ± 0.01	0.34 ± 0.02	0.10 ± 0.01	22 ± 5	7 ± 2
3 Kirvessuo	T	3.7 ± 0.4	26.9 ± 1.4	0.56 ± 0.02	1.12 ± 0.06	0.12 ± 0.01	37 ± 3	15 ± 2
	C	6.3 ± 0.7	22.9 ± 1.3	0.67 ± 0.03	0.99 ± 0.07	0.06 ± 0.01	16 ± 3	8 ± 3
4 Toristonluoma	T	2.4 ± 0.6	35.3 ± 1.3	0.86 ± 0.02	0.67 ± 0.05	0.65 ± 0.03	54 ± 10	16 ± 5
	C	0.9 ± 0.1	18.4 ± 1.3	0.41 ± 0.03	0.27 ± 0.06	0.76 ± 0.06	36 ± 12	7 ± 1
5 Kallioneva	T	2.2 ± 0.5	45.4 ± 1.8	0.74 ± 0.03	0.74 ± 0.07	0.78 ± 0.03	35 ± 6	60 ± 2
	C	1.8 ± 0.4	24.4 ± 1.7	0.53 ± 0.04	0.59 ± 0.04	0.29 ± 0.03	27 ± 5	32 ± 10
6 Kivisuo	T	9.9 ± 1.3	33.3 ± 1.1	1.40 ± 0.09	2.80 ± 0.29	0.42 ± 0.02	32 ± 6	50 ± 18
7 Tulilahti	T	2.2 ± 0.4	47.6 ± 2.0	0.81 ± 0.03	1.02 ± 0.08	0.51 ± 0.03	35 ± 7	27 ± 2
	C	5.9 ± 0.7	23.4 ± 0.6	0.64 ± 0.03	0.91 ± 0.04	0.34 ± 0.02	21 ± 3	13 ± 2
8 Nikula	T	1.9 ± 0.6	30.2 ± 1.7	0.56 ± 0.03	0.55 ± 0.05	0.81 ± 0.06	14 ± 8	31 ± 2
	C	0.6 ± 0.2	27.1 ± 1.3	0.53 ± 0.03	0.41 ± 0.03	0.90 ± 0.06	12 ± 6	25 ± 2
9 Ällinsuo	T	0.9 ± 0.1	17.3 ± 2.0	0.39 ± 0.04	0.46 ± 0.05	0.14 ± 0.02	34 ± 7	5 ± 1
	C	3.0 ± 0.6	11.2 ± 0.8	0.28 ± 0.02	0.49 ± 0.02	0.14 ± 0.02	16 ± 5	3 ± 1

Table 3. Parameter estimates and their 95% confidence intervals for annual export of elements and suspended solids (Eq. 1) from the research catchments. Parameter estimates $b_1 \ldots b_4$ represent annual specific exports i.e. treatment-induced excess export above the background level is divided by the proportion of the treated area from treatment catchment area. Parameter estimates printed in bold face are statistically significant ($P < 0.05$).

	a_0	a_1	b_1	b_2	b_3	b_4	var(a_1)	var(e_1)
N	1.286 ±1.298	**0.825** ±0.196	0.458 ±0.915	0.785 ±0.897	0.700 ±1.101	1.021 ±1.254	1.471	1.029
DOC	36.157 ±57.446	**1.080** ±0.185	**–57.410** ±37.440	–29.895 ±36.029	–43.780 ±44.316	–12.581 ±49.081	3729.734	1551.426
Al	1.275 ±2.117	**1.075** ±0.393	**2.002** ±1.646	–0.659 ±1.648	–0.047 ±1.913	–1.293 ±2.196	3.067	5.118
Fe	2.217 ±2.303	**0.833** ±0.309	0.560 ±1.623	–1.052 ±1.556	–0.358 ±1.862	–0.526 ±2.073	5.839	2.837
Mn	**0.129** ±0.106	**1.008** ±0.439	–0.002 ±0.099	**–0.096** ±0.095	–0.073 ±0.113	**–0.161** ±0.131	0.009	0.012
P	**0.093** ±0.084	**0.772** ±0.369	0.046 ±0.086	0.039 ±0.087	0.047 ±0.108	–0.067 ±0.165	0.003	0.010
ln(SS)	**1.455** ±1.046	**0.380** ±0.347	**2.864** ±0.709	**1.860** ±0.720	**1.729** ±0.896	**1.239** ±0.999	0.594	0.638

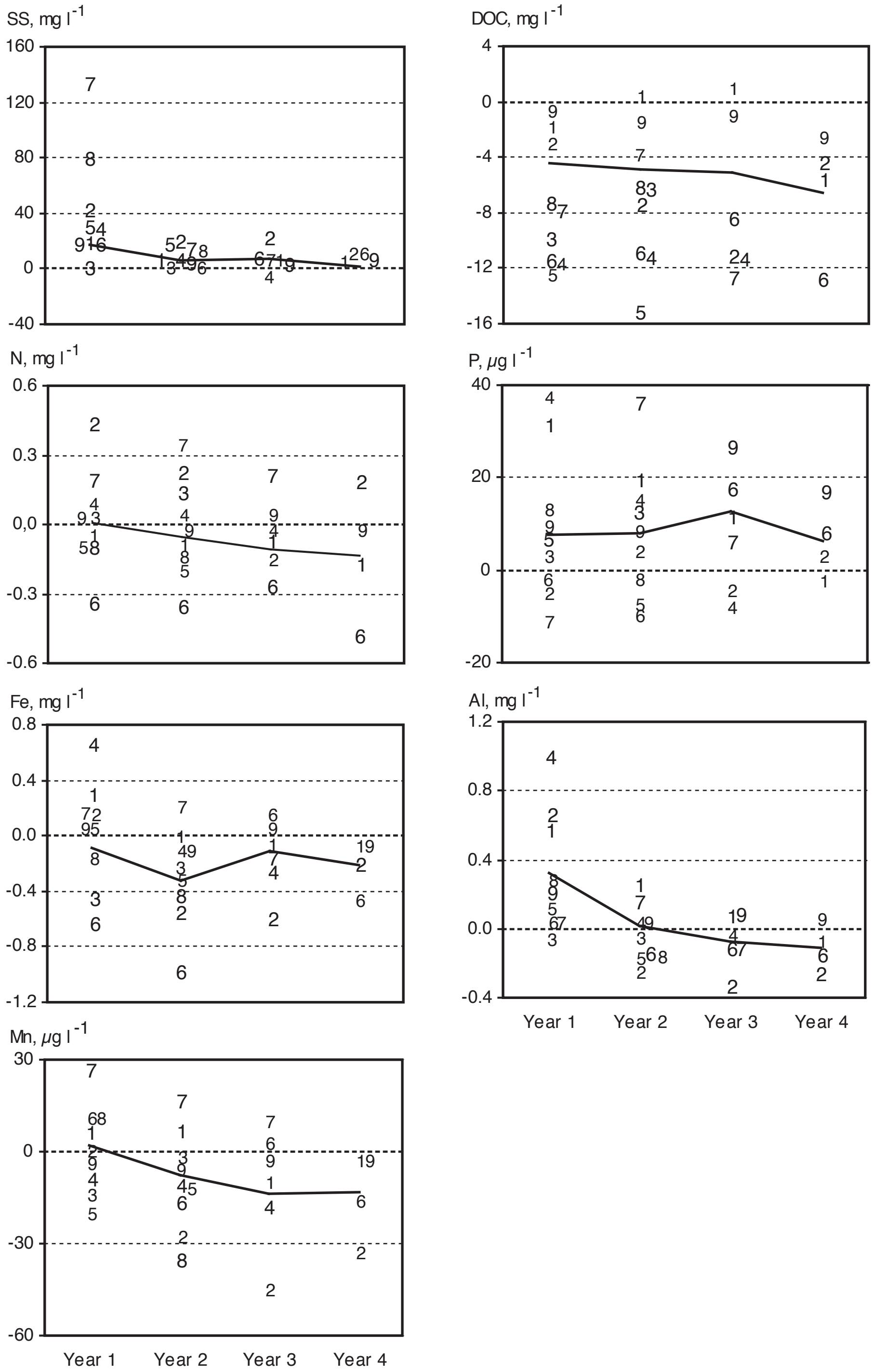

Fig. 2. Changes in average annual concentrations of SS, DOC, N, P, Fe, Al and Mn in runoff due to ditch network maintenance at the nine paired catchment experiments. The numbering of sites is as in Table 1 and the line indicates the average change over all experimental sites.

Al the specific export estimate b_1 (Table 3) indicates that ditch network maintenance increases Al export with 2.0 kg a^{-1} per treated hectare with 95% confidence limits extending from 0.36 to 3.65 kg a^{-1} per treated hectare. The specific export estimates of Al for the following three years were not significant.

The analysis of SS export was conducted with logarithmic data, and therefore special care is required in the interpretation of the results. When transformed to the linear scale, the background export ($C_{ij}f_j^{-1}$) is multiplied with e^{bi} to obtain the specific export affected by the ditch maintenance. For the first year after the ditch maintenance b_1 was equal to 2.864, which means that export of SS increases by $e^{2.864}$ or 17.5 fold compared with the background export. For all the measured four years the increase in SS export was significant; the fourth year the export was $e^{1.239}$ or 3.45 times higher than the estimate of the background export.

Ditch network maintenance decreased the export of DOC. According to the analysis, the decrease in the DOC export was about 57 kg a^{-1} per treated hectare for the first year after the ditch maintenance. Also the export of Mn decreased during the second and fourth year after the ditch network maintenance.

4 Discussion

In this study we conducted for the first time a paired catchment analysis with combined data from several catchment pairs by extending the method of Laurén et al. (2009). This enables quantification of ditch network maintenance effects in a more general level than in individual case studies. Combining data is a clear methodological advance compared with the previous studies. The significance of the specific export estimates depends on both the magnitude of the change in export following the ditch network maintenance and the quality of the pre-treatment dataset (Laurén et al. 2009). The pre-treatment dataset identifies the relationship between the exports from the control and treatment catchment and this relationship is used to quantify the background export from the treatment area. The weaker is the identification of the background export, more uncertainty is included in the specific export estimate, and more likely the specific export estimate becomes insignificant. Finally, the shorter is the pre-treatment period the more conservative is the test of significance.

Ditch network maintenance was shown to clearly increase sediment export and decrease organic carbon export, which is in accordance with the results of Joensuu et al. (2002) and Åström et al. (2001a,b). The present results also confirmed earlier findings that enhanced export of soluble Al only occurred shortly after ditch network maintenance operations (Joensuu et al. 2002). The finding that P and N concentrations in runoff were not increased by the ditch maintenance operations was also observed in earlier studies (Joensuu et al. 2001, Åström et al. 2002).

The results showed that the changes in element and SS concentration occurring after ditch network maintenance considerably varied between the study sites. The number of experimental catchment pairs in the present study is not sufficient to fully analyze and explain this variation and further investigations concerning the role of catchment characteristics in explaining the variation of the treatment effect are therefore needed. Based on earlier studies, possible mechanisms behind the variation can be discussed. The variation in SS loads depends on the type and texture of the bottom soil below the peat and whether the ditches extend down to the mineral soil or remain in the peat layer (Joensuu et al. 2001). The variation in DOC may be related to the extent of the lowering of the water table following ditch network maintenance. After water table lowering less water flows in contact with the surface organic soil layers and the concentration of DOC in runoff may decrease (Åström et al. 2001a). A lower water table and improved aeration can also accelerate the decomposition of organic matter and result in increased loss of carbon as CO_2 into the atmosphere. However, if the water table is not lowered due to ditch network maintenance, the concentration of DOC does not change. In the case when the functioning of the ditches was satisfactory before ditch network maintenance (regardless of their visual condition) or the water uptake by the tree stand was sufficient to keep the water level down, the water table is not likely to be affected by the maintenance (Ahti and Päivänen 1997).

The increase in Al export occurred during and shortly after ditching operations and concurrently with high SS loads. The increase was likely due to elevated transport of those fine sediment fractions that passed through the 1.0 μm filters used in the present study. In contrast to our results, Prévost et al. (1999) did not find increased export of dissolved Al concurrently with high SS loads. Their water samples were filtered through 0.45 μm filters and the contents of fine sediment fractions and adherent metals in the analysis solutions were probably lower than for our samples filtered through coarser filters.

The decrease in Mn export was probably due to oxidation and consequent lower mobility of Mn, which results from the lowering of water table. In the present study, the ditch network maintenance had no effect on the average annual P export. This is in contradiction to earlier studies (Lundin and Bergquist 1990, Joensuu et al. 2002) where dissolved total P and molybdate reactive phosphate export was occasionally found to decrease following ditch network maintenance. It should be noted here that the analysis results for Mn and P were generally below or only slightly above the detection limit of ICP/AES, which may be an additional reason for high variation between the catchments and years.

5 Conclusions

We conducted a paired catchment analysis by combining data from several catchments and extending the recently presented method of Laurén et al. (2009) that accounts for uncertainty involved in the paired catchment analysis. Ditch network maintenance in drained peatland forests was found to significantly increase sediment export and decrease dissolved organic carbon export, which agrees with the results of earlier studies. Significant increase in dissolved Al export was observed only during the first year after the ditching operations. Dissolved N, P, and Fe export were not changed significantly, but the export of Mn was decreased by the ditch network maintenance. There was a considerable variation in the treatment effects between the study sites and years and further investigations about the role of catchment characteristics in explaining the variation are needed.

From the viewpoint of water quality protection, the observed high increase of SS export is regarded as the most harmful environmental effect of ditch network maintenance. In order to understand the impact of ditching operations on functioning of recipient aquatic habitats, future research should be focused on chemical, physical and bioavailability characteristics of sediments eroding from the ditch maintenance areas.

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