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The effect of climate and landuse on TOC concentrations and loads in Finnish rivers

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The variability of the concentration and export of the total organic carbon (TOC) was analysed in 16 rivers in Finland (northern Europe). The river basins were categorized by major landuse settings, and their geographical location ranged from the southern boreal to sub-arctic. In the long-run (1975–2000), the concentration of the TOC had a statistically significant ($p < 0.05$) decreasing trend in nine rivers at least once during March, May, August and October. The estimated annual load of the TOC was statistically significantly higher ($p < 0.03$) in the basins characterized by peatlands than in those dominated by fields, being on average 5.4 and 4.1 g C m^{-2} a^{-1}, respectively. The winter (January–March) North Atlantic Oscillation (NAO) index predicted rather well (mean of $r^2 = 0.48$ and $p = 0.04125$) the TOC load in March in the eight northernmost rivers.

Introduction

In northern Europe, and especially in Finland and NW Russia, both climate and topography favour the formation and accumulation of organic matter in the soil. There are areas where peatlands cover more than half of the total land area. However, in Finland ditching and fertilization of peatlands have been very intensive since the early 1960s (*see* Kortelainen *et al*. 1997), and today more than half of the original peatlands have been ditched. In the southern and central part of the country the proportion of drained peatlands is much higher than in the north, where the large, mostly minerotrophic mires are situated. In the south, most peatlands (mainly ombrotrophic mires) are currently used for forestry or agricultural purposes.

Although there is a close relationship between the export of the organic matter (OM) and water runoff from the drainage basin (e.g. Kortelainen and Saukkonen 1998, Arvola 1999), the OM leaching may differ greatly between the different ecosystems and basins. For example, Mulholland and Kuenzler (1979) found a linear relationship between the export of the organic carbon (OC) and the annual runoff in five watersheds in North Carolina, where more OC per unit runoff was exported from the drainage basins dominated by wetland forests than from the upland areas. In the Precambrian Canadian Shield, the dissolved organic matter (DOM) production of wetlands was offset by the flushing which decreased the concentrations of the dissolved organic carbon (DOC) with the increasing flow (Schiff *et al*. 1998). However, in the upland catchments the DOC concentrations in the soil increased with antecedent soil moisture conditions in the developed B horizon resulting in the increased DOC concentrations with

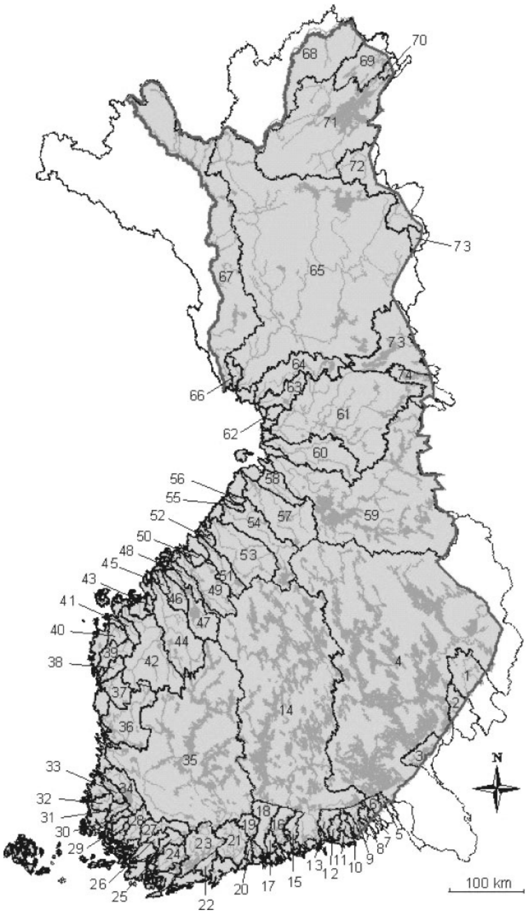

Fig. 1. River basins in Finland.

higher stream flows (Schiff *et al.* 1998). Thus it is evident that besides the catchment characteristics, hydrological processes, landuse, extreme hydrological and weather conditions, such as storms (e.g. Manny and Wetzel 1973, Buffam *et al.* 2001) and rising temperature (Freeman *et al.* 2001), may influence DOM/DOC concentrations in rivers and their fluxes from the drainage basins. Because meteorological forcing is one of the key factors influencing organic carbon leaching and transportation out of the drainage basin, long-term changes in precipitation and air temperature, although small in quantity, may cause drastic shifts in the TOC load. With this respect it is important to note that the annual precipitation has increased in some areas of the northern Baltic Sea area during the recent years (Bergström 2003).

In this paper, we analyse the long-term hydrological and total organic carbon (TOC) time-series from 16 rivers of variable sizes and having different drainage basin landuse characteristics. We expected that (i) the TOC concentrations in the rivers are strongly related to the proportion of peatlands in the drainage basins throughout the study region, and that (ii) the TOC load varies between the years with varying climatic conditions.

Material and methods

The rivers are located in northern Europe (Fig. 1), and all of them are draining from the Finnish (and one partly from the Swedish and one from the Russian) territory into the northern part of the Baltic Sea, the Gulf of Finland, the Bothnian Sea or the Bothnian Bay. The vegetation in the drainage basins covers a range from the southern boreal taiga to the sub-arctic vegetation. The northernmost areas — Rivers Tornio, Kemi, Ii and Kiiminki drainage basins — are very sparsely populated and not heavily impacted by agriculture or other intensive landuse practices (Table 1). The other drainage basins are impacted more by agriculture and other anthropogenic factors. Within the data set we have three large (mean annual discharge, MAD, > 100 $m^3 s^{-1}$) rivers (Ii, Kemi and Tornio), five medium sized (MAD > 20 but < 100 $m^3 s^{-1}$) rivers (Lapua, Perho, Kala, Pyhä, Kiiminki), and eight smaller (MAD < 20 $m^3 s^{-1}$) rivers. Rivers Tornio and Kiiminki are both non-regulated and without any power stations or dams, while the other rivers have power stations and/or upstream water reservoirs for the purpose of energy production or flood regulation.

For all river basins monthly mean discharge values based on continuous measurements by the Finnish Environment Institute (FEI) were used. The reason was that the sampling frequency for the TOC was once a month. Furthermore a focus was on four months, i.e. March, May, August and October, which had the most complete data sets for the TOC covering the period between 1975 and 2000. The discharge and/or the TOC data set for the following five rivers: Lapväärti (1980–2000), Lapua (1986–2000), Perho (1984–

2000), Lesti (1980–2000) and Pyhä (1984–2000) did not cover the entire period, however. The TOC samples were collected and analysed by the regional environment centres and/or by the FEI. The TOC were analysed by oxidation to CO_2 followed by IR-measurement, and the estimated annual average TOC concentrations are based on the TOC values in March, May, August and October. The landuse statistics are based on the information from FEI and represent the current situation.

The North Atlantic Oscillation (NAO) index, which was used as the index of regional climate variability (Hurrell 1995), was acquired from the following address: http://www.cgd.ucar.edu/~jhurrell/ nao.html. The statistical analyses were carried out with the SigmaStat3.0 and CANOCO (Ter Braak 1987) for Windows 4.5. For trends, the seasonal Kendall time series analysis was applied. The data were $\log_{10}$-transformed prior to statistical analysis.

Results

The long-term data showed that the TOC concentrations decreased statistically significantly (Seasonal Kendall: $p < 0.05$) in nine rivers at least once during the four periods (March, May, August and October; Table 2) of investigation. In the TOC load, however, a significant ($p = 0.0389$, $n = 11$) increasing trend was found in River Lapväärti in March. There was a weak relationship between the discharge and the TOC concentration in March, May and August, but in October the discharge explained ≥ 50% of the variation in the TOC concentration in 11 rivers, i.e. in 58% of the sites (Table 3). During the wet years the TOC concentration was statistically significantly higher than during the dry years in four rivers, the difference being on average 10% for the whole data set (Table 4).

The estimated load of the TOC was statistically significantly higher ($p < 0.03$) in the basins characterized by peatlands than in those dominated by fields, being on average 5.4 and 4.1 g C m^{-2} a^{-1}, respectively. The linear multiple regression analyses revealed that the amount (as a percentage of the drainage area) of peatlands and fields were the two most important landuse characteristics which explained the TOC concentrations in the rivers (Table 5). The percentage of peatlands and fields of the drainage basin explained 60% to 91% of the variation

Table 1. The landuse settings in the river basins (source data from the Finnish Environment Institute); the landuse characteristics represent the current situation.

River	No of drainage basin*	Area (km^2)	Landuse (%)				
			Forest	Water	Field	Peatland	Other
Porvoo	18	1128	61.1	2.1	31.6	3.1	2.1
Musti	19	780	61.1	2.3	29.8	6.1	0.7
Vantaa	21	1680	59.5	3.1	25	6	6.5
Kisko	24	560	62.8	6.7	23.7	6.6	0.2
Paimio	27	954	50.6	2.7	42.1	4	0.7
Aura	28	874	43.5	1.5	35	9	2.6
Lapväärti	37	976	54.2	0.5	14.5	30.5	0.2
Lapua	44	976	52.3	2.8	22.7	21.5	0.6
Perho	49	2460	43.4	3.3	10.3	42.7	0.3
Lesti	51	1283	46	6.1	10	37.6	0.4
Kala	53	4147	52	1.8	15.6	30	0.5
Pyhä	54	3712	52	5	9.6	32.9	0.4
Kiiminki	60	3812	42.5	4.1	3.4	49.9	0.1
Ii	61	14191	51.2	6.6	1.9	40.1	0.1
Kemi	65	50683	60.2	4.6	1	34.2	0.1
Tornio	67	40131	66.1	5	1.2	27.4	0.1

* *See* Fig. 1.

Table 2. The significance of long-term trends of the concentration of the TOC in the studied rivers in 1975–2000. Significance was estimated with the seasonal Kendall time series analysis; $p < 0.1$ are only shown. The trends were negative ($p < 0.1$) in all cases.

	Porvoo	Musti	Vantaa	Kisko	Paimio	Aura	Lapväärti	Lapua
March	–	–	–	–	0.023	0.024	–	–
May	–	–	–	0.006	–	–	0.050	–
August	0.063	0.032	0.001	0.015	–	–	–	–
October	–	–	–	0.027	–	–	–	–
Median	–	0.021	–	–	–	–	–	–
	Perho	Lesti	Kala	Pyhä	Kiiminki	Ii	Kemi	Tornio
March	–	–	–	–	–	–	0.010	–
May	–	–	–	–	–	0.076	–	–
August	–	–	–	–	–	–	–	–
October	–	–	–	–	–	0.034	–	0.018
Median	–	–	–	–	–	–	–	–

Table 3. The relationship between the discharge and TOC concentration during four seasons in the studied rivers. R^2 values represent averages for all rivers. Number of rivers where the discharge explained ≥ 50% of the variation of the TOC is also given.

Period	Mean R^2 (%)	*N* of rivers $R^2 \geq 50\%$
March	16.6	1
May	16.7	1
August	31.0	3
October	47.7	11

in the TOC concentration in different periods while the inclusion of other two major landuse variables, water and forest, did not significantly improve the regressions. The canonical correspondence analyses (CCA) distinguished the rivers on the base of the TOC concentrations and the two major landuse practices (vectors) into three groups (Fig. 2). The rivers with the largest drainage basins (Tornio and Kemi), and relatively low concentration of the TOC, form one group of sites, the second one is formed by the seven rivers with the highest TOC and extended peatland coverage (> 30%) in the upper left of the diagram, and the third one is formed by the rest of the rivers characterized by the relatively low TOC and high amount of fields (> 20% of the drainage basin) in the lower right of the diagram. The first axis explained 99.5% of the variation of the TOC — land-use relation, and it was statistically significant (Monte Carlo permutation test; $p = 0.0240$, $F = 5.381$).

Table 4. The ratio of average TOC concentrations of the river basins between dry and wet years. The annual average TOC concentrations are based on the TOC values in March, May, August and October. Wet and dry years are those belonging to the 75% and 25% quartiles of the mean annual discharge. Significance values are based on *t*-test, and only $p < 0.1$ are shown.

River basin	Wet/Dry	*p*	*N*
Porvoo	0.99	–	6
Musti	1.20	0.007	6
Vantaa	1.08	–	6
Kisko	0.97	–	5
Paimio	0.92	–	6
Aura	1.00	–	6
Lapväärti	1.25	–	5
Lapua	1.16	0.067	3
Perho	1.21	0.047	4
Lesti	1.02	–	5
Kala	1.20	0.045	5
Pyhä	1.09	–	4
Kiiminki	1.23	0.035	6
Ii	1.10	–	5
Kemi	1.02	–	6
Tornio	1.25	0.070	4
Average	1.10	–	

There was a statistically significant positive relationship between the North Atlantic Oscillation (NAO) index in winter (January–March) and the load of the TOC in March in five rivers (Table 6).

Discussion

The strongest relationship between the water discharge and TOC was recorded in autumn in two small drainage basins in southern Finland (L. Arvola *et al.* unpubl. data). Such close pairing between the TOC and the discharge indicates that higher TOC concentrations are found during the wet seasons and years rather than during the dry ones. The results support earlier observations that organic matter transport from boreal drainage basins is closely related to the hydrological conditions (Wartiovaara 1978, Mulholland and Kuenzler 1979, Arvola *et al.* 1990, Ivarsson and Jansson 1994, Arvola 1999). Precipitation and air temperature are, therefore, the key meteorological variables which modify the seasonal and inter-annual pattern of the TOC transport. Buffam *et al.* (2001) showed that in boreal peatlands and organic forest soils, which make a vast deposit of organic carbon in the northern hemisphere and particularly in Finland (Ilvesniemi *et al.* 2002), storms with high flow may enhance the leaching of the DOC and nutrients into river channels. In fact, storms can be seen as a primary mechanism of the OC export from drainage basins because they produce increases in both OC and discharge as has been demonstrated by Manny and Wetzel (1973).

Besides precipitation and hydrology, landuse generally has an important effect on the TOC load from river basins in the boreal area (e.g. Kortelainen and Saukkonen 1998). In our data set the coverage of peatlands was the most important landuse variable determining the mean annual TOC load, a result which was consistent with our earlier observations from a number of Finnish drainage basins (Kortelainen *et al.* 1997, Arvola 1999). However, the explanation power of the multiple linear regression model with two explanatory landuse variables (peatlands and fields) varied substantially between the different periods, being highest in October and lowest in March. The long-term trends in the TOC load in the studied rivers were not always similar, however, and in one case (River Lapväärti) even contradictory. We expect that possible reasons for these differences and also partly for the

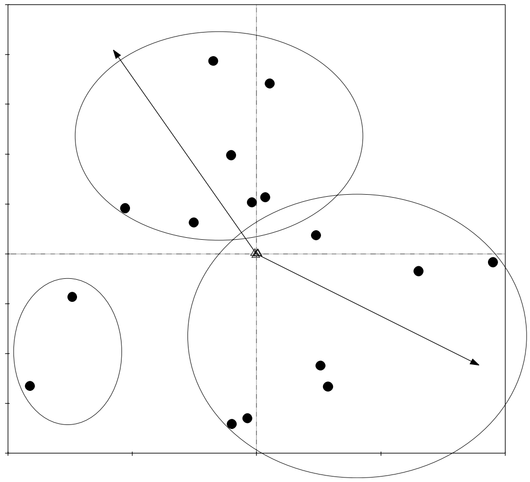

Fig. 2. CCA ordination of the river sites based on the two major landuse variables. The first, horizontal axis explained 99.5% of the variation of the TOC–landuse relation, and which was statistically significant (Monte Carlo permutation test: $p = 0.024$, $F = 5.381$).

Table 5. Multiple linear regressions between the TOC and the most important landuse practices for four periods. The original data (average monthly value for each river) were $\log_{10}$-transformed before the analysis.

Period	*N*	*r*	Adjusted r^2	*p* fields	*p* peatlands	Equation
March	16	0.806	0.595	< 0.001	= 0.001	TOC = 0.332 + (0.301 × Field) + (0.330 × Peatland)
May	16	0.911	0.804	< 0.001	< 0.001	TOC = 0.305 + (0.324 × Field) + (0.395 × Peatland)
August	16	0.928	0.839	< 0.001	< 0.001	TOC = 0.254 + (0.381 × Field) + (0.391 × Peatland)
October	16	0.962	0.913	< 0.001	< 0.001	TOC = 0.277 + (0.383 × Field) + (0.393 × Peatland)
Mean	16	0.958	0.906	< 0.001	< 0.001	TOC = 0.296 + (0.346 × Field) + (0.379 × Peatland)

long-term trends could be changes e.g. in point-loadings and landuse. Obviously many of the rivers were in the past rather strongly loaded by waste waters, and those presumably affected both the TOC concentrations and loads particularly during the periods of low flow, i.e. in winter before the spring flood and in summer after the spring flood.

McDowell and Likens (1988) hypothesized that in the Hubbard Brook Valley, New Hampshire, the leaching of organic carbon seems to be derived from the large standing stock of organic matter in the forest floor rather than from the recent primary production. This is supported by the observation of Raymond and Bauer (2001) that a major fraction of carbon, especially in northern rivers, can be very old (> 10^3 years). We assume this might be the situation also in many Finnish river basins of this study.

The annual loads were within the range given in the literature for boreal rivers (e.g. Heikkinen 1989, Arvola *et al.* 1990, Ivarsson and Jansson 1994, Kortelainen *et al.* 1997, Arvola 1999), although the sparse seasonal sampling for the TOC probably slightly underestimated the TOC load particularly in the smallest rivers. A noteworthy observation was that the TOC load was, on average, 31% higher from the peatland-dominated drainage basins to the Bothnian Sea and the Bothnian Bay than from the agriculturally characterised drainage basins to the Gulf of Finland, a phenomenon which was earlier observed by Laaksonen (1970) and Wartiovaara (1978). This clearly emphasizes the fact that in terms of the TOC load the key difference seems to be the amount of peatlands in the drainage basin. This became particularly evident because in our data set there were no catchments with high percentage of water area (*see* Table 1).

Table 6. The relationship between the load of TOC in March and the NAO index in January–March. Only values $p < 0.1$ are shown.

River	*R*	*P*	*N*
Porvoo	0.022	–	25
Musti	0.600	0.002	24
Vantaa	–0.068	–	26
Kisko	–0.017	–	26
Paimio	–0.130	–	26
Aura	–0.058	–	26
Lapväärti	0.140	–	21
Lapua	0.209	–	15
Perho	–0.433	0.083	17
Lesti	0.383	0.087	21
Kala	0.355	0.075	26
Pyhä	0.586	0.013	17
Kiiminki	0.581	0.002	26
Ii	0.379	0.062	25
Kemi	0.522	0.006	26
Tornio	0.628	0.002	22

During the last decade on both sides of the Bothnian Sea and the Bothnian Bay, the precipitation values slightly increased (Bergström 2003). In this respect it is interesting that the TOC load relative to the North Atlantic Oscillation, NAO, was rather dissimilar in the two river groups, southern and northern, because in the north the linkage was evident while in the south it was lacking. The relationship between the NAO index and the spring TOC load corresponds to the North Atlantic circulation patterns strongly influencing weather conditions and freshwaters in northern Europe (e.g. Straile *et al.* 2003). Such a positive correlation between the TOC load and the NAO makes sense, because during warm winters more water is coming from the drainage basins to the rivers in late winter–early spring than during cold winters (Gottschalk and Krasovskaia 1997, Vehviläinen and Huttunen 1997).

The results indicate that the carbon outflow from the terrestrial ecosystems in northern Europe is highly dependent on the basin hydrology and the landuse properties, and in particular on the amount of peatlands in the drainage basin. However, the geographical position may influence the transportation and the TOC load, and this should be taken into account when regional estimates of the carbon loads are constructed. If the summer and winter air temperatures as well as precipitation increase in future as the recent regional climate scenarios (Carter *et al.* 2002) suggest, an increase in the annual TOC load will be expected.

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