Trends in concentration and load of total organic carbon in forested catchments in Finland

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Summary

Long-term trends in concentration and export of total organic carbon (TOC) were studied in forested headwater catchments within a climatically consistent area in eastern Finland. The material consists of 11 small catchments (29-494 ha), where the proportion of peatland ranged from 8 to 70%. Runoff and TOC concentration were intensively monitored for 15-29 years in each catchment. Seven catchments have been subject to forestry operations with various management intensities and four catchments have been left unmanaged. Significant increasing annual trends in TOC concentrations were found for seven of the catchments. Seasonal Kendall tests revealed the strongest upward trend in TOC concentrations and export occurred in wintertime.

Key index words: forested catchment, organic carbon, time-series, water quality

Introduction

Dissolved organic carbon (DOC) affects numerous physical, chemical and biological processes in aquatic environments (e.g. Hudson *et al.,* 2003). Increasing trends in DOC concentrations over the last 10-15 years have been reported for lakes and rivers across Europe and North America (Monteith *et al.,* 2007). The increase has been explained by various factors, such as changes in climate, atmospheric chemistry, and soil chemistry. Large-scale land-use management, such as agricultural or forestry operations, also result in a release of DOC from soil.

One of the most significant carbon stocks and sources of organic carbon in the boreal zone are mires (peatlands) (Clark *et al.,* 2005). The proportion of peatland cover has been shown to correlate with DOC concentrations in the stream water (Kortelainen, 1993; Laudon *et al.,* 2004). However, mires can also have a decreasing effect on the DOC concentration during spring time, when snowmelt runoff is flowing on the frozen mire surface without a contact with peat. Climate change can alter the seasonal variation and timing of the amount of runoff and change the dynamics of DOC export (Holmberg *et al.*, 2006). In boreal forested areas, it is poorly known how forest management together with changes in climatic conditions affects the DOC leaching to watercourses.

The aim of this study was to investigate long-term changes in the total organic carbon (TOC) concentrations and exports in stream water discharged from forest and peat dominated headwater catchments in the boreal zone.

Materials and methods

The study material were collected from 11 forested catchment located in eastern Finland (Table 1) having similar climate conditions and terrain characteristics (e.g. Finer *et al.,* 1997). The annual precipitation in the areas is about 600 mm and the temperature sum (>5 °C) of the growing season is 1100 degree days.

Catchment area varies from 29 to 494 ha and proportion of peatland from 8 to 70%. The forests are mainly Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* L. (Karst.)) dominated with an average stand volume varying from 26 to 187 m^3 ha^{-1}. Seven of the catchments have been subject to forestry operations (clear-cuttings and/or drainage) with various management intensities while four of the catchments have been left intact for at least three decades before the start of the monitoring period.

Runoff and water quality have been monitored for 29 years at six of the catchments and for 15 years at five of the catchments. Water samples have been taken 1-2 times a month and TOC concentrations determined using UV-persulphate oxidation followed by IR gas measurements or a high-temperature oxidation. Missing TOC values were estimated based on available measurements of chemical oxygen demand (CODMn).

Mean TOC concentrations and exports were calculated both annually and seasonally (winter: December-February; spring: March-May; summer: June-August and autumn: September-November). The linear trends in annual and seasonal data over the monitoring period were calculated using the non-parametric Seasonal Kendall test.

Table 1. General information about the studied catchments. Site preparation with ploughing, mounding and harrowing has been conducted within 3 years after clear cutting.

Catchment	Location coordinates	Area ha	Elev. m	Mire% / Drained%	Treatment methods and years	Clear cuttings %
Monitored for 28 years						
Murtopuro	(63.46 N;28.28 E)		494	225	50/40 Drainage 1983	Clear cutting 1983
Liuhapuro	(63.47 N;28.29 E)	165	225	48/0	No management	0
Kivipuro	(63.52 N;28.65 E)	54	200	32/0	Clear cutting 1983	56
Suopuro	(63.53 N;28.40 E)	113	200	70/13	Drainage 1983	0
Välipuro	(63.52 N;28.65 E)	86	200	56/0	Clear cutting 2001	9
Koivupuro	(63.53 N:28.45 E)	118	200	57/27	Clear cutting 1983, 1996 Clear cutting 2000, 2005 Drainage 1983	5, 16. 11, 4
Monitored for 15 years						
Iso-Kauhea	(63.53 N:28.30 E)	176	200	50/36	Drainage 1983 Clear cutting 1996	 13
Korsukorpi	(63.53 N;28.40 E)	69	198	56/0	Clear cutting 2000	6
Porkkavaara	(63.52 N;29.10 E)	72	182	16/0	No management	0
Kangasvaara	(63.51 N;28.58 E)	56	187	8/0	Clear cutting 1996	34
Kangaslampi	(63.52 N;28.57 E)	29	184	9/0	No management	0

Daily meteorological data were obtained from two and the atmospheric deposition data from one nearby meteorological station.

Results

Concentrations

Significant increasing annual trends in TOC concentrations were found for seven of the catchments (Table 2, Fig. 1). The largest increase in concentrations occurred after the middle of 1990s. The trend in the concentration was clearest in winter, but significant increasing trends were also found for summer and autumn seasons (data not shown). The trends were most distinctive for the catchments that were pristine (Liuhapuro, Porkkasalo, Kangaslampi) or only slightly managed (Välipuro). For the intensively managed Murtopuro area, the annual trend was negative because the TOC concentration was decreasing after the peak caused by former forest management (Fig. 1)

Exports

With the exception of the Murtopuro and Liuhapuro areas, which showed significant negative trends in exports, annual trends in TOC exports were non-significant (Table 2). Negative trends were explained by a significant decreasing trend in runoff (not shown). During years 1996-2006 the average TOC exports ranged from 24 to 117 kg ha^{-1} yr^{-1}. In unmanaged areas the average TOC export was 60 kg ha^{-1} yr^{-1}.

Table 2. Trends (correlation coefficients) in the mean annual TOC concentration (mg l^{-1}a^{-1}) and export (kg ha^{-1}) and their significance in different catchments. The trends are tested with the Seasonal-Kendall test.

	Concentration		Exports	
Catchment	Corr.	*P-value*	Corr.	*P-value*
Suopuro	0.08	*0.5748*	-0.15	*0.2679*
Liuhapuro	0.31	*0.0249*	-0.3	*0.0284*
Välipuro	0.52	*0.0001*	0.11	*0.4406*
Kivipuro	0.51	*0.0001*	-0.09	*0.5017*
Koivupuro	0.20	*0.1526*	-0.08	*0.5732*
Murtopuro	-0.16	*0.2336*	-0.28	*0.0408*
Iso-Kauhea	0.58	*0.0040*	-0.03	*0.9128*
Korsukorpi	0.45	*0.0217*	-0.3	*0.1367*
Porkkasalo	0.49	*0.0112*	-0.19	*0.3465*
Kangasvaara	0.22	*0.2512*	-0.11	*0.5823*
Kangaslampi	0.53	*0.0056*	-0.28	*0.1648*

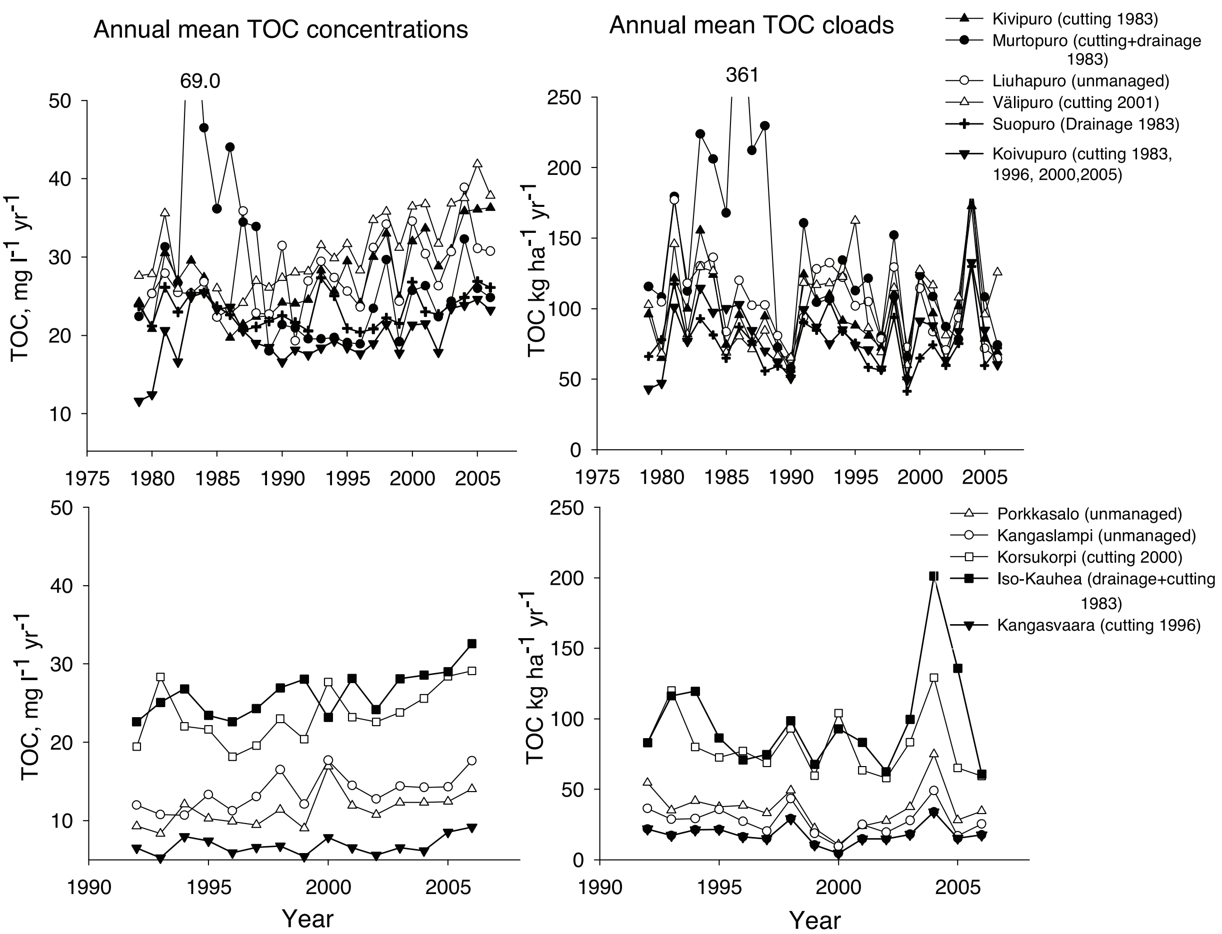

Figure 1. The time-series of the annual TOC concentration in stream water and export from the intensively monitored forested catchments. Statistical significance of the trends is presented in Table 2.

Discussion

The positive trends in the annual and seasonal TOC concentrations, particularly during latest 10 years, are in accordance with the earlier observations from the boreal and temperate rivers and lakes (e.g. Vuorenmaa *et al.,* 2006; Monteith *et al.,* 2007). Since 1995, the annual dynamics of the TOC concentrations (Fig. 1) were very similar for all catchments, in spite of having had different treatments. This indicates that forest management only had a short term effect on TOC fluxes. The significant increases in TOC concentrations from the pristine areas indicates that environmental factors other than forest management are involved.

Worrall *et al.* (2004) found that only part of the increasing TOC trends in British rivers was explained by changes in climate variables. One of the most discussed indirect reasons explaining the increasing DOC trends in European water courses is the drastic decrease in the acidic deposition, which has destabilized soil organic matter (e.g. Monteith *et al.,* 2007). In our study sites, the amount of acid deposition has low and the change in the deposition did not explain the trend of TOC concentration. Most of the temporal trends of the TOC exports were masked by the annual and seasonal variation in the runoff (see Holmberg *et al.*, 2006). Increased trends of the concentrations largely coincided with decreased runoff (concentration effect), particularly in the autumn.

Although there are large seasonal variations in the trends and dynamics of carbon leaching, our results indicate that TOC concentrations in surface waters in Finland have indeed increased over the last fifteen years. The causes behind this phenomenon as well as the future trends, however, remain poorly known and need further study.

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