Increasing organic C and N fluxes from a northern boreal river basin to the sea

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Abstract Increasing trends in dissolved organic carbon (DOC) concentrations in lakes and streams across Europe and North America have been reported. The widespread occurrence of these phenomena indicates large-scale causes, e.g. enhanced decomposition of organic soils, changes in hydrology or decreased acid deposition. The Simojoki River basin (3160 km²) is located in the Northern Boreal Zone where human impacts are minor. Long-term changes (30–40 years) of organic C and N concentrations and fluxes in the Simojoki River system were studied: both TOC and TON concentrations were increasing, fluctuating between droughts and wet periods. Highest concentrations were detected in 1998–2000 during a period of very high flows, after the drought period of 1994–1997. The average TOC flux increased by 38% during the 1990s compared with the 1980s, while the average TON flux during the same period increased even more, by 42%. Runoff accounts for part but not all of the increase in the TOC and TON outputs. Since 2000, the fluxes have decreased to slightly lower levels but year-to-year variability has remained considerable. Multiple effects are probable, i.e. changes in both hydrology and in catchment soils have impacts on these increasing fluxes.

Key words organic carbon; organic nitrogen; fluxes; climate change; river basin; boreal zone; Finland

INTRODUCTION

Increasing dissolved organic carbon (DOC) concentrations have been reported in lakes and streams in Europe and North America (e.g. Freeman et al., 2001; Vuorenmaa et al., 2006). The widespread occurrence of this phenomenon indicates large-scale causes, and various hypotheses have been proposed to explain them, e.g. changes in temperature, enhanced decomposition of organic soils, changes in hydrology and flow paths, decreased acid deposition, elevated atmospheric CO₂ levels, or land-use changes and disturbances. Climate change is predicted to cause increased temperature, contributing to the enhanced decomposition of peat soils (Freeman et al., 2001). Other possible drivers include changes in hydrological regimes, including increasing flow volumes and consequent changes in flow paths (Tranvik & Jansson, 2002) and the frequency of severe droughts (Worrall et al., 2004). Longer wet or drought periods may significantly contribute to leaching. Wet periods of several years have strong regional effects, e.g. higher groundwater tables, closer-to-surface flow paths, and higher DOC leaching. It may not be changes in the amount of runoff but rather its source, i.e. as flowpaths shift new, richer sources of DOC are accessed (Worrall & Burt, 2007). Consequently, droughts could augment DOC production. Changes in the relationship between flow and DOC were observed after a severe drought that persisted even through more minor droughts (Worrall & Burt, 2004).

Land-use change may also be expected to result in increased decomposition of soil organic matter and release of carbon (C) and nitrogen (N), but land management practices are typically not sufficiently widespread to explain DOC trends at large spatial scales. Decreasing mineral acid deposition may have resulted in an increase in organic acidity, resulting in increased DOC concentrations (e.g. Stoddard et al., 2003; Evans et al., 2005). However, the most important mechanisms behind the increasing DOC trends remain a subject of discussion (e.g. Roulet & Moore, 2006). It is unlikely that one single mechanism would be sufficient to explain changes occurring at large spatial scales (see e.g. Worrall & Burt, 2007).

Globally, the loss of terrestrial organic C to rivers is equivalent to 10% of the net ecosystem production on land (Schlesinger, 1991), and is thus an important part of the ecosystem C budget. Changes in C and N fluxes may have many consequences. For example, these include increased water treatment costs, increased fluxes of heavy metals such as Hg associated with DOC, and increased energy and nutrient supply to surface waters. Changes in fluxes of DOC and dissolved
organic nitrogen (DON) from land to surface water may alter the aquatic food webs and affect lake and coastal water ecology.

DON export is typically related to DOC export within individual watersheds or across regions (e.g. Campbell et al., 2000). In boreal headwater catchments, C and N losses are highly related ($R^2 = 0.95$) to each other, due to the dominance of organic N compounds in N cycling (Kortelainen et al., 2006). A considerable portion of N flux from boreal forest and peatland-dominated river basins may reach the sea in the form of organic N, e.g. 75–80% in the northern Bothnian Bay, where the River Simojoki discharges (Pitkänen, 1994). Most of organic N and C occur as dissolved organic fractions (Mattsson et al., 2005). The dominance of DOC and DON fractions suggests very low retention in fast flowing northern rivers such as the Simojoki, with a major part of the fluxes in the water phase reaching the estuaries (Lepistö et al., 2006).

In this paper, long-term changes (30–40 years) in organic C and N concentrations and fluxes were studied in the northern boreal Simojoki River system, as well as factors behind these changes.

MATERIAL AND METHODS

Site description, hydrological monitoring and water sampling

The River Simojoki (3160 km$^2$) discharges to the Gulf of Bothnia of the Baltic Sea. It is a salmon river in near-natural state, the dominant human impact being forestry, mainly forest drainage and cutting. Peatlands and peatland forests are common and an average of 0.5% of the total forest area of the catchment is cut annually. Agricultural fields cover only 2.7% of the catchment area (Lepistö et al., 2008).

Discharge of the Simojoki River has been monitored daily since 1965. The annual average discharge for 1971–2000 was 40.4 m$^3$ s$^{-1}$, i.e. annual average runoff was 403 mm. A snowmelt-induced spring flood in late April–May dominates the annual hydrological pattern and smaller flow peaks occur in autumn. Water samples were taken at the outlet of the Simojoki River, with four samples annually during 1966–1981, and 10–18 samples annually during 1982–2009, by a regional environment centre. Total N was analysed as NO$_3$-N after oxidation with K$_2$S$_2$O$_8$. NH$_4$-N was analysed by a spectrophotometric method with hypochlorite and phenol, and NO$_3$-N by the cadmium amalgam method beginning in 1982. Since 1982, organic N fractions (TON) were calculated for each sampling occasion as the difference between total nitrogen (N) and total inorganic nitrogen (TIN). Chemical oxygen demand (COD) was analysed by titrimetric determination with KMnO$_4$ during the whole observation period, 1966–2009. Total organic carbon (TOC) was estimated from COD concentrations (Kortelainen, 1993; Lepistö et al., 2008). In the Simojoki River, differences between TOC and DOC, and TON and DON were very small (Mattsson et al., 2005; Mattsson, T., unpublished). Therefore, patterns of TOC and TON analysed herein can be directly compared and discussed with respect to literature values and patterns of DOC and DON.

Annual fluxes were estimated by interpolating observed concentrations linearly to estimate daily concentrations, which were multiplied by daily flow and summed, using the RLOAD software developed in Linköping University, Sweden.

RESULTS AND DISCUSSION

Organic C and N concentrations and fluxes

**TOC and TON time series** As expected, correlation between TOC and TON concentrations was strong ($R^2 = 0.61$). TOC concentrations fluctuated notably over the observation period, but statistically significant increasing trends in 1982–2005 were not detected (Lepistö et al., 2008). Strong fluctuation, towards higher year-to-year variability, was found in TON concentrations during the study period of 1982–2009 (Fig. 1). Typically, the highest concentrations occurred during autumn high flow periods. Periodic fluctuation could be detected: e.g. the dry period of
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The delivery of terrestrial DON to aquatic systems depends on production/decomposition rates, loss from solution and the availability of hydrological transport. Leaching of organic matter, particularly DOC, typically strongly increases with peatland proportion (e.g. Kortelainen et al., 2006), but in the case of DON agricultural land areas may play a more important role in large spatial data sets (Mattsson et al., 2005). Pellerin et al. (2004) found that 79% of the variance in DON concentrations in streams and rivers in the northeastern USA was explained by the percentage of wetlands in a catchment.

**TOC and TON fluxes to the sea** The average TOC flux increased by 38% during the 1990s, from 14 800 t year\(^{-1}\) in the 1980s to 20 500 t year\(^{-1}\) in the 1990s, but decreased somewhat during the 2000s (2001–2009), to 17 200 t year\(^{-1}\) (Fig. 2). The average TON flux during the same period increased slightly more, 42%, from 480 t year\(^{-1}\) in the 1980s to 680 t year\(^{-1}\) in the 1990s, and decreased to a slightly lower level of 610 t year\(^{-1}\) in 2001–2009. The average annual runoff was 27% higher during the 1990s (477 mm) than during the 1980s (375 mm), and therefore runoff accounts for only part of the increase in the TOC and TON outputs. Year-to-year hydrological variability is very high and is an obvious driver for C and N fluxes (Fig. 2). A dry period with low runoff and low regional groundwater table (1994–1997; average runoff 369 mm) was followed by a considerably wetter period (1998–2000; average runoff 618 mm) with high groundwater tables. High water tables contribute more surface runoff from the TOC-rich soil layers, and more runoff from riparian areas to the stream than low groundwater tables.

When annual TON fluxes (Fig. 3(a)) were compared with annual runoff values, highly significant positive correlations were found. TOC and TON is leached simultaneously (Fig. 3(b), \(R^2 = 0.96\)) in this northern, relatively undisturbed ecosystem. We did not find any clear evidence as to whether the relationship is linear or slightly non-linear. However, there is some indication that leaching was less during the most rainy year of 2000, when runoff was 766 mm, i.e. dilution is starting to decrease fluxes of TON (Fig. 3(a)).

![Fig. 1 TON concentration time-series in the River Simojoki during 1982–2010. Single observations are shown together with the 30 point moving average and a trend line.](image)
Fig. 2 TOC and TON flux (tonnes year⁻¹), and annual runoff (mm) in the Simojoki River basin in 1966–2009. Note that TON measurements start in 1982.

Fig. 3 (a) Annual TON fluxes as a function of annual runoff of the Simojoki River basin, and (b) correlation between annual TOC and TON fluxes in 1982–2009.

Possible driving factors contributing to increased TOC and TON fluxes

**Hydrological dynamics and seasonality** Both hydrological transport and production/decomposition rates contribute to the delivery of terrestrial TOC and TON to aquatic systems. Periodic fluctuation between drought and wet periods is strong and these fluctuations cause higher TOC and TON export during the wet period.

Production of both TOC and TON have presumably increased, resulting in higher leaching losses during similar flow situations. One impacting factor is higher soil temperatures during the 1990s relative to those in the 1980s (Lepistö *et al.*, 2008). DOC concentrations in streams draining...
organo-mineral soils typically increase following rainfall, as the dominant flowpath changes from the lower mineral horizons that adsorb DOC, to the organic horizons that produce DOC (McDowell & Likens, 1988). These flowpath changes support increased concentrations during periods of high flow. DOC concentrations are typically highest in surface soil layers and decline sharply in lower soil horizons, because of adsorption/co-precipitation in mineral soils with iron and aluminium (e.g. McDowell & Wood, 1984) and microbial decay. At high flow, near-surface flow paths dominate. Consequently, the high water volumes moving through the organic-rich horizons coupled with the high organic C and N concentrations in the organic horizons result in high leaching losses.

Forestry change In the Simojoki River basin, which is part of the watershed area of the Bothnian Bay, forest management was most intensive in the early 1970s. At that time, annual forestry activities covered 2.0–2.5% of the area, decreasing to 0.8–1.0% annually during the late 1980s–1990s (K. Kenttämies, unpublished data based on the yearbooks of forest statistics). The most evident change has been in the spatial intensity of forest first-time drainages, which have been replaced by supplementary drainage works. Forest fertilization has almost been discontinued. The percentage of cut area varied from year to year with no major long-term change. Cut areas are scattered throughout the river basin, with only minor annual treatment areas (0.2–0.6% in 1968–2000) (Lepistö et al., 2008). Intensive forestry in the 1970s caused an increase in TOC concentration levels at that time, but otherwise changes in land use probably have not played a major role in increased fluxes of TOC or TON.

Changing climate Increasing flow trends during the 30-year period of 1976–2005 have been observed during summer low flow and during late autumn (Lepistö et al., 2008). During summer low flow, river water consists mostly of groundwater, suggesting that the groundwater contribution to the river (and annual water yield) might be increasing. In the Yukon River basin in Alaska, groundwater contribution to streamflow has been shown to be increasing, due to climate warming and permafrost thawing, which enhances infiltration and supports deeper flowpaths (Walvoord & Striegl, 2007). However, compared to the Yukon basin, watersheds in Europe are warmer and have little or no permafrost. Warming can affect DOC export in different ways, depending on whether it is accompanied by increased or decreased precipitation; the variation is related to hydrology as well as to biological productivity, and to how productivity is balanced by decomposition (Tranvik & Jansson, 2002).

Piao et al. (2008) recently discussed the need for a greater understanding of responses of terrestrial ecosystems to climate trends during the transition to (spring) or from (autumn) the growing season. In the Simojoki River, both flow and organic N concentrations have increased significantly in November (Lepistö et al., 2008), and the organic N concentration was considerably higher during autumn floods than during spring floods. Furthermore, increase in precipitation volume and intensity may increase autumn floods in particular, which have a high potential contribution to increase C and N fluxes.

Inter-annual hydrological fluctuations are important. The drought period of 1994–1997 with low concentrations was followed by high TOC and TON concentration peaks and strong leaching flushes during the period 1998–2000. There are several lines of evidence to support the conclusion that droughts can be major drivers of C and N release. These include: (i) change in the relationship between flow and DOC after a severe drought, (ii) soil respiration and DOC production become decoupled after a severe drought, (iii) stepwise changes in the flux of DOC are observed after droughts, and (iv) increased drought frequency in British peatlands since the 1920s. However, direct evidence for a drought effect on DOC concentrations is lacking (Worrall & Burt, 2007).

CONCLUDING REMARKS
The average TOC flux increased by 38% during the 1990s compared with the 1980s, while the average TON flux during the same period increased even more, 42%. The annual runoff was 27%
higher during the 1990s than during the 1980s and therefore runoff accounts for part of, but not all of, the increase in the TOC and TON fluxes. Since 2000, the fluxes have decreased to slightly lower levels but inter-annual flux variability is large.

Hydrology plays an important role in this northern ecosystem. Increasing trends were found in both flow and organic N concentrations. Earlier findings suggest that the autumn season is particularly sensitive to climate change impacts. Hydrological fluctuations are important: the drought during 1994–1997, with low concentrations, was followed by the highest TOC and TON concentrations and strong leaching fluxes during the floods in 1998–2000. In the River Simojoki ecosystem multiple effects are probable, i.e. changes in both hydrological dynamics and in catchment soils, contributing to higher TOC and TON fluxes to the sea.

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REFERENCES


