Transport of organic carbon from the Mogot Experimental Watershed in the southern mountainous taiga of eastern Siberia

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Abstract More than 60% of river runoff from the Lena River basin originates in the southern mountainous region of eastern Siberia within the permafrost zone. We studied the transport of dissolved organic carbon (DOC) and particulate organic carbon (POC) within the Mogot Experimental Watershed, which is close to the drainage divide between the Lena and Amur River basins in the southern mountainous taiga region, from 1 August 2000 to 12 November 2001. DOC concentration was strongly related to thawing depth at the bottom of the main valley when thawing depth was less than 20 cm during snowmelt runoff. When thawing depth was equal to or greater than 20 cm, DOC concentration was more closely related to the rate of river discharge in summer runoff. On the basis of our observations, we extrapolated the annual transport of DOC and POC to be 4.75 g C m^{-2} yr^{-1} and 0.03 C kg C m^{-2} yr^{-1}, respectively. Transport of organic carbon from the catchment was about 4.78 g C m^{-2} yr^{-1} during 2001. DOC is the main form of organic carbon flux in the study area.

Keywords Dissolved organic carbon; particulate organic carbon; small watershed; thawing depth

Abbreviations

DOC	dissolved organic carbon
POC	particulate organic carbon
FORSGC	Frontier Observational Research System for Global Change
SWE	snow water equivalent
RMSE	root mean square error
DIC	dissolved inorganic carbon
TOC	total organic carbon

Introduction

Valentini *et al.* (2000) reported that carbon exchange between atmosphere and forest varied from 100 g C m^{-2} yr^{-1} at a source to 700 g C m^{-2} yr^{-1} at a sink. Carbon transport in streams and rivers is one of the pathways of the carbon cycle in terrestrial ecosystems. Hope *et al.* (1994) reviewed published data on carbon transport in rivers, mostly from sites in North America and northern Europe, and found the average dissolved organic carbon (DOC) flux to

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be approximately 4.7 g C m^{-2} yr^{-1}, with particulate organic carbon (POC) flux equal to approximately 10% of the DOC flux. Values of POC flux differed among river basins.

Dolman *et al.* (2004) estimated that the annual sequestration of carbon within a larch forest in Yakutsk, far eastern Siberia, was 160 g C m^{-2} yr^{-1} during 2001. The average riverborne carbon transport detailed above therefore corresponds to about 2.9% of net ecosystem production. While this is not a large figure, it is important to understand details of the carbon cycle in terrestrial ecosystems such as those in eastern Siberia. Transport of carbon in streams and rivers of the southern mountainous taiga region has been rarely documented.

In this study, therefore, we quantified the transport of organic carbon in streams of the Mogot Experimental Watershed, eastern Siberia, focusing on the thawing soil process.

Methods

Site description

The Mogot Experimental Watershed is located in the Nelka River basin, within the southern mountainous region of eastern Siberia (55.5°N, 124.7°E), approximately 60 km north of Tynda, Russia. The Nelka River basin lies within the Amur River basin, close to the drainage divide between the Lena and Amur River basins. The Nelka River basin is 12 km long and 2.5 km wide, with a total area of 30.8 km^2. Slopes within the Nelka River basin face northeast and southwest, and elevations range from 580 m to 1130 m. Hydrometeorological observations were carried out in this area from August 2000 until 12 November 2001 during a joint project between the Frontier Observational Research System for Global Change (FORSGC) of Japan and the State Hydrological Institute of Russia.

The location of the study site is shown in Figure 1. The dominant land cover is larch forest (*Larix cajanderii*), although ridges are partially covered by birch and pine forests. Nearly 90% of the watershed is covered in forest, and the remaining area is grassland. The study site comprises mostly natural conditions of primary forest with some secondary growth where forest fires have occurred. The upper 20 cm of soil is organic, with a porosity of 85% in most of the watershed. The soils are covered by a 10- to 15-cm-thick layer of moss. Deeper layers consist of a loamy soil.

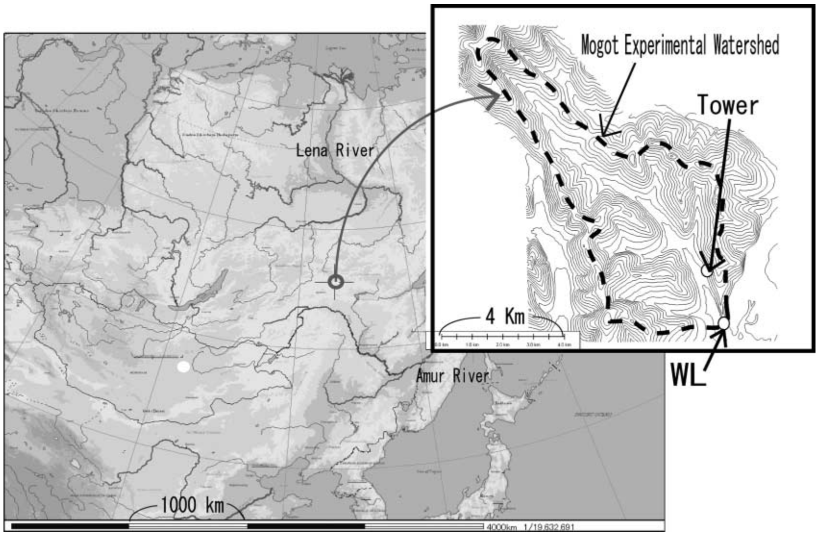

Figure 1 Location of the Mogot Experimental Watershed. "WL" and "Tower" denote the water-level measurement and meteorological observational sites, respectively

Measurement

We made meteorological and hydrological measurements at sites both above and below the larch forest canopy. Precipitation was measured using a Tretyakov gauge at 0800 h and 2000 h each day. From 1 August 2000 until 12 November 2001, river discharge measurements and water sampling were carried out at location "WL", at the mouth of the watershed, and meteorological observations were carried out at the "Tower", about 3 km above the mouth of the watershed (Figure 1). The snow water equivalent (SWE) was measured by a snow survey every ten days when snow was present during the study period. The thaw depth within the surface soil was measured using a cryopedometer at two sites near the Tower.

River water samples were collected weekly for DOC and POC analysis. Samples were collected at the WL site from 10 August 2000 to 24 October 2001, except between 3 November 2000 and the end of April 2001, when the river was frozen. Following field measurement of each water sample for temperature, electrical conductivity, and pH, a 1 L sample of water was filtered through glass fiber filter paper (Whatman GF/F), with the filtrate retained as the POC sample; 15 mL of filtered water was poured into a brown glass bottle with 25 μL of 6 N HCl. POC concentrations were analyzed using an elemental analyzer (Thermoquest NA2500), while DOC concentrations were analyzed *via* the high temperature catalyst oxidizing method (Shimadzu TOC5000A). Water samples were analyzed for stable isotopes using a MAT252 or DeltaS apparatus with a $CO_2-H_2-H_2O$ equilibration device (Thermoquest, USA, manufactured in Germany). The isotope ratio of oxygen was expressed as the $\delta^{18}O$ value:

$$\delta^{18}O‰ = (R_{sample}/R_{st} - 1) \times 1000 \quad (1)$$

where R_{sample} and R_{st} are the isotope ratios ($H_2^{18}O/H_2^{16}O$) of the sample and of Vienna standard mean ocean water, respectively.

Organic carbon flux was determined using DOC and POC concentrations as described below:

$$F_{OC} = F_{DOC} + F_{POC} = C_{DOC}D + C_{POC}D \quad (2)$$

where F_{OC}, F_{DOC}, and F_{POC} are organic carbon and DOC and POC fluxes from the watershed (mg C m^{-2} d^{-1}), respectively; C_{DOC} and C_{POC} are DOC and POC concentrations (mg L^{-1}), respectively; and D is river discharge from the watershed (mm d^{-1}).

Results and discussion

Hydrological characteristics

Figures 2(a–e) show temporal variations in air and river water temperatures; $\delta^{18}O$; pH; SWE and precipitation; and river discharge within the watershed, respectively. River discharge was observed from 26 April 2001 to 12 November 2001, with a total measured river discharge during this period of 204.6 mm. $\delta^{18}O$ values initially increased from early May to mid-June (which we defined as the period of snowmelt runoff), and stabilized at around −15‰ from mid-September to the end of October. This indicated that snowmelt water contributed to runoff generation because snow had lower $\delta^{18}O$ values than rainwater. Snowmelt river discharge totaled 23.7 mm, about 10% of the annual river discharge in 2001. Most of the river discharge was associated with summer rain; we defined the summer runoff period to be from mid-June until the river froze in late November. pH values were relatively constant at 6 to 7 for overall period. Although daily air temperature in 2001 varied considerably, from −40°C to about 20°C, river water temperature varied only slightly, from 0°C to about 10°C.

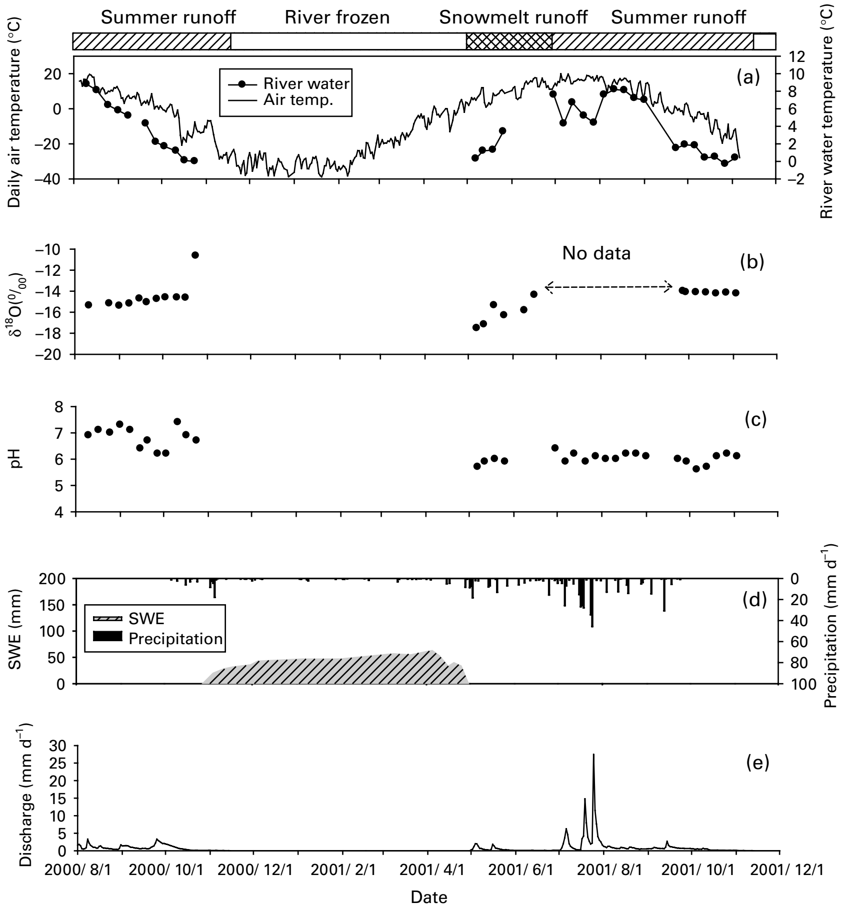

Figure 2 Temporal variations of hydrological and meteorological variables measured from August 2000 until 12 November 2001. (a) Daily air and river temperature. (b) $\delta^{18}O$. (c) pH. (d) Snow water equivalent (SWE) and precipitation. (e) River discharge

Variations in DOC and POC concentrations

Figures 3(a, b) show temporal variations in DOC and POC concentrations, river discharge, and thawing depth, respectively. POC concentrations varied from 0.1 mg L^{-1} to 0.2 mg L^{-1}, while DOC concentrations ranged from 8.9 mg L^{-1} to 44.7 mg L^{-1}. DOC was therefore the main form of organic carbon in streams in the studied watershed. High DOC concentrations occurred during periods of snowmelt runoff, indicating that snowmelt water contained elevated DOC concentrations. During the summer runoff period in 2000, DOC concentrations were correlated with river discharge. Previous studies have documented a relationship between elevated DOC concentrations and periods of increased river discharge (e.g. Sakamoto *et al.* 1999; Carey 2003). Figures 4(a, b) show the relationships between DOC and POC concentrations and river discharge measured in the present study. POC concentrations were only about 1.0% of DOC concentrations, and did not show a clear correlation with river discharge. DOC concentrations during the snowmelt runoff period were very high, and were not clearly related to river discharge. However, for summer runoff periods, the linear regression line between DOC and river discharge has a high determination coefficient of 0.72. During the snowmelt runoff period, water flow from the surface organic soil resulted in an increased DOC concentration.

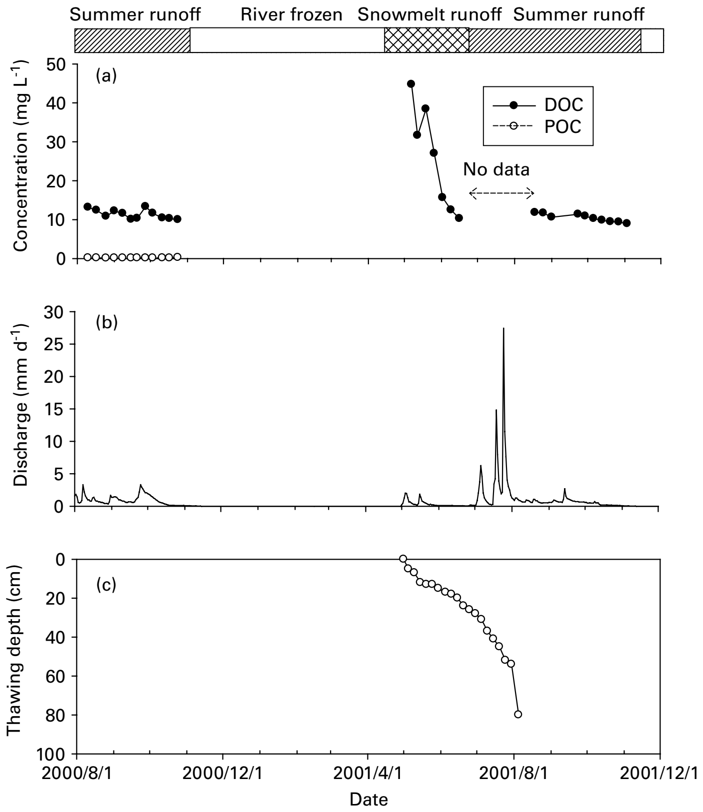

Figure 3 (a) Temporal variations in measured DOC and POC concentrations. (b) Temporal variation in measured river discharge. (c) Temporal variation in thawing depth

The following paragraph discusses the relationship between DOC concentration and thawing depth. Yamazaki *et al.* (2006) demonstrated that runoff processes within the Mogot Experimental Watershed are strongly influenced by thawing depth; a decreasing thawing depth corresponds to an increasingly rapid surface runoff. During the snowmelt runoff period, there is a clear relationship between DOC concentration and thawing depth (Figure 5), because the thawing depth limits the infiltration of surface water into the ground. Suzuki *et al.* (2006a) demonstrated that 23–74 mm of snowmelt water infiltrated the frozen

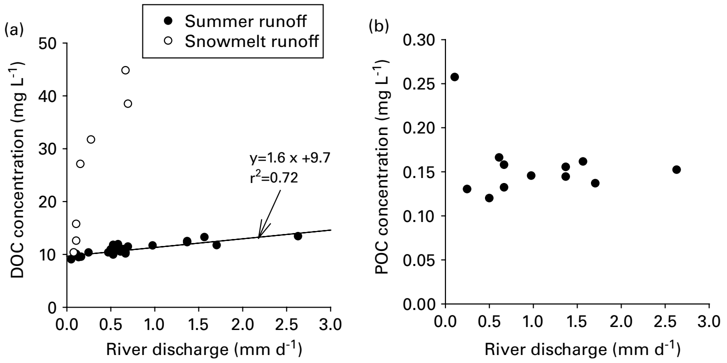

Figure 4 (a) Relationship between DOC concentration and river discharge. (b) Relationship between POC concentration and river discharge

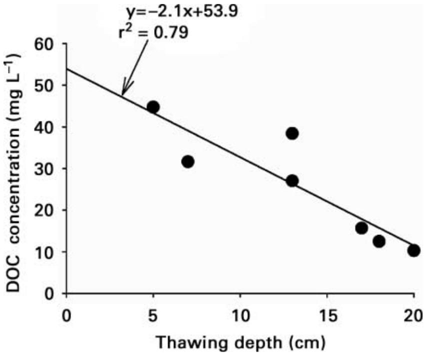

Figure 5 Relationship between DOC concentration and thawing depth during spring snowmelt runoff

upper 20 cm of the surface organic soil. Once thawing depth increased to 20 cm, snowmelt water with high DOC concentrations was released from the soil, because snowmelt water refrozen in the frozen organic soil layer became a source of DOC flux to the river when river discharge began.

In summary, DOC concentrations are determined by thawing depth and the amount of river discharge within the watershed.

Organic carbon flux

To estimate DOC concentration, we used the following empirical equations based on the relationships among DOC concentration, river discharge, and thawing depth.

DOC concentration in snowmelt runoff (when thawing depth at the bottom of the valley was less than 20 cm) was calculated as

$$C_{\mathrm{DOC}} = -2.1TD + 53.9 \tag{3}$$

and *DOC concentration in summer runoff* (when thawing depth at the bottom of the valley was equal to or greater than 20 cm when the river froze) was calculated as

$$C_{\mathrm{DOC}} = 4.0D + 10.0 \tag{4}$$

where TD is thawing depth (cm) and D is river runoff (mm d^{-1}).

Root mean square error (RMSE) values for Equations (3) and (4) were 6.64 mg L^{-1} and 0.64 mg L^{-1}, respectively. Using the DOC concentration thus calculated, the DOC flux can be estimated from runoff data (Figure 6). Consequently, the extrapolated annual DOC flux was 4.75 g C $\mathrm{m}^{-2}\,\mathrm{yr}^{-1}$ in 2001, slightly less than the value estimated for boreal forest by Hope *et al.* (1994), even though the estimated DOC concentration in the present study was higher than that of Hope *et al*. We estimated the DOC flux in snowmelt runoff to be 0.82 g C $\mathrm{m}^{-2}\,\mathrm{yr}^{-1}$, approximately 17% of the annual DOC flux (Table 1). As mentioned above, snowmelt river discharge represents about 10% of annual river discharge; therefore, snowmelt runoff makes a small contribution to DOC flux within this watershed. Carey (2003) reported a larger contribution of DOC flux in snowmelt runoff, comprising 69% of annual DOC flux in the Granger Basin, in the discontinuous permafrost zone of subarctic Canada. Sakamoto *et al.* (1999) also found a high contribution of DOC flux in snowmelt runoff, comprising 65% of annual DOC flux, in the Jyozankei watershed in a cool-temperate region of Japan. We assumed that these differences in snowmelt runoff contribution to annual DOC flux resulted from differences in SWE, because SWE in the present study was about half that of the Granger Basin and about one-quarter that of the Jyozankei watershed. However, the annual DOC flux at the Mogot Experimental

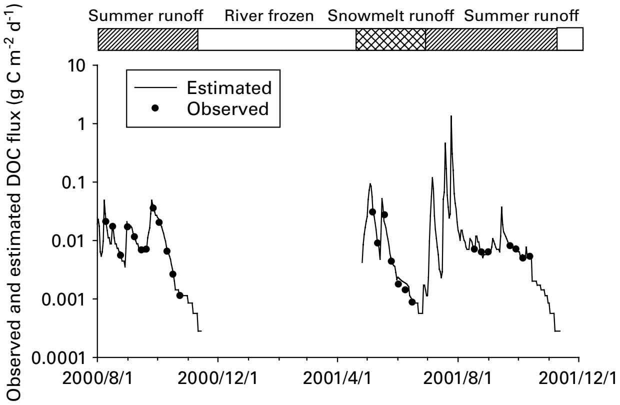

Figure 6 Temporal variations in estimated and observed DOC flux from 1 August 2000 until 12 November 2001

Watershed was the highest among the four examples shown in Table 1. Annual DOC flux in the present study was nearly three times that found in the Granger Basin by Carey (2003).

Because POC concentration varied little with river discharge, we extrapolated annual POC flux as 0.03 g C m^{-2} yr^{-1}, based on runoff data and assuming a constant POC concentration. At the study site, larch forest covers most of the watershed. The deciduous larch trees drop their needles during late autumn. However, annual POC flux in this study site was lowest among the examples shown in Table 1. Suzuki *et al.* (2006b) showed that the thick, understory moss layer played an important role in the water and energy cycles at the study site. We assumed that the thick moss layer caught and filtered leaf litter, allowing pure water to flow to the river. Thus, if the surface soil and moss layer had become saturated, then surface flow might have caused increased POC concentrations in the river. However, we were unable to test this hypothesis because we did not have data for high runoff events during summertime. Future studies should focus on investigating POC concentrations during a summer storm runoff period.

Based on the extrapolated annual DOC and POC fluxes described above, transport of organic carbon at the study site was about 4.78 g C m^{-2} yr^{-1}. This value was larger than the average annual total organic carbon flux in northern Europe reported by Hope *et al.* (1994). Dolman *et al.* (2004) estimated net ecosystem production in a far eastern Siberian larch forest to be 160 g C m^{-2} yr^{-1}, with total transport of organic carbon representing about 3% of this figure.

Our results show that transport of organic carbon can be correlated with thawing depth and river discharge. Recent studies have investigated the change of surface air temperature and river discharge in arctic basins (e.g. Peterson *et al.* 2002), which is likely to change the organic carbon flux into the Arctic Ocean.

In this study, we did not observe the inorganic carbon flux. Dissolved inorganic carbon (DIC) consists mainly of heavy carbonic acid ion, and the amount of this ion is related to the water pH. During 2001, the water pH was low, about 6.0. We therefore assume that there was only minor outflow of DIC within the watershed.

Error analysis for extrapolated annual DOC and POC fluxes

This section addresses the estimation error for extrapolated annual DOC and POC fluxes. In order to evaluate the estimation error for these fluxes, we used RMSE for each least-squares linear regression line of Equations (3) and (4). According to these values, we estimated the

Table 1 Comparison of organic carbon fluxes at different watersheds

Site	Annual DOC flux (g C m^{-2} yr^{-1})	Annual POC flux (g C m^{-2} yr^{-1})	Annual TOC flux (g C m^{-2} yr^{-1})	Contribution of DOC flux in snowmelt runoff to annual DOC flux	Reference
Mogot Experimental Watershed, eastern Siberia	4.75	0.03	4.78	17%	Present study
Granger Basin, Canada	1.64	NA	NA	69%	Carey (2003)
Jyozankei Watershed, Japan	3.3	2.1	5.4	65%	Sakamoto *et al.* (1999)
Northern Europe	3.76	0.45	4.0	NA	Hope *et al.* (1994)

Note: “NA” denotes that data are not available error for DOC flux during snowmelt and summer runoff periods, respectively. The estimated error in DOC flux for snowmelt runoff was 0.15 g C m^{-2} in 2001. On the other hand, the estimated error in DOC flux for summer runoff was 0.12 g C m^{-2} in 2001. Thus, the estimated error for annual DOC fluxes was 0.27 g C m^{-2} yr^{-1} in 2001.

To estimate the error in annual POC flux, we assumed that POC concentration did not change with river runoff. The observed maximum and minimum POC concentrations (0.26 mg L^{-1} and 0.12 mg L^{-1}, respectively) were useful for estimating the range of potential error in annual POC flux. Therefore, annual POC flux ranged from 0.02 g C m^{-2} yr^{-1} to 0.05 g C m^{-2} yr^{-1} in 2001.

Taking into account the above estimation error, the adjusted range of annual total organic carbon flux in 2001 was 4.50 g C m^{-2} yr^{-1} to 5.07 g C m^{-2} yr^{-1}.

Finally, we observed DOC and POC concentrations when river runoff was less than 3 mm d^{-1}; however, the maximum river runoff in summer 2001 was about 25 mm d^{-1}. Thus, we estimated DOC concentration from the relationships among river runoff, thawing depth, and DOC concentration when river runoff was less than 3 mm d^{-1}. We assumed that the extrapolation of the above relationships to high runoff events was valid, based on the high correlation coefficient between DOC concentration and river runoff or thawing depth and no correlation between POC concentration and river runoff. Future studies should focus on the relationship between high summer runoff events and DOC and POC concentrations.

Conclusions

We observed DOC and POC concentrations in the southern mountainous taiga region of eastern Siberia and extrapolated annual DOC and POC fluxes in rivers in the study area. Our results can be summarized as follows:

(1) DOC concentration is correlated with river discharge and thawing depth.
(2) Snowmelt runoff contains high DOC concentrations, comprising 17% of the annual DOC flux.
(3) POC concentrations are 2.5% or less of the DOC concentrations. DOC is the main form of carbon in rivers in the study area.
(4) Extrapolated DOC and POC fluxes during 2001 were 4.75 g C m^{-2} and 0.03 g C m^{-2}, respectively. The total transport of organic carbon in streams was 4.78 g C m^{-2} during 2001, slightly less than the value estimated for boreal forest by Hope *et al.* (1994). According to the error analysis, the estimation error on annual DOC fluxes during 2001 was 0.27 g C m^{-2}.

In summary, future studies should focus on the relationship between high summer runoff events and DOC and POC concentrations.

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