DOC in streams and soils in forested watershed underlain by continuous permafrost: a seasonal pattern

Anatoly S. Prokushkin[1,*], Satoru Hobara[2], Irina V. Tokareva [1],
Stanislav G. Prokushkin [1], and Anatoly P. Abaimov[1]

[1]*V.N. Sukachev Institute of Forest SB RAS, Akademgorodok, Krasnoyarsk, Russia*
[2]*Department of Environment Systems, Rakuno Gakuen University, Japan*

[*]*Corresponding author: prokushkin@ksc.krasn.ru*

1. INTRODUCTION

Dissolved organic matter has significant contribution to carbon and nitrogen cycling in terrestrial ecosystems and link terrestrial and aquatic environment (McDowell and Likens 1988; Neff and Asner 2001; Dittmar and Kattner 2003; Sondergaard, Stedmon et al. 2003). Permafrost-affected ecosystems which hold 25-33% of the world's soil organic carbon store significant part of this carbon temporarily in ice (Hobbie, Schimel et al. 2000). It is expected that after climate-induced melting of the permafrost this carbon will be partially decomposed and large amounts of carbon will be transported to the oceans (Neff and Hooper 2002). Therefore the transport of DOM from landscapes to riverine systems, its chemical composition and origin are receive growing attention in permafrost-dominated landscapes (Hansell et al., 2004).

Production and release of dissolved DOM in non-permafrost forest ecosystems are well documented (Kalbitz, Solinger et al. 2000; McDowell 2003; Michalzik, Tipping et al. 2003). In general, observed DOM concentrations and fluxes are the result from processes that release, such as leaching and desorption (Guggenberger, Zech et al. 1994; Qualls and Richardson 2003), and remove DOM, such as adsorption and biodegradation (Kaiser et al. 1996). Local carbon stocks (Aitkenhead and McDowell 2000), properties of soils (Currie 1999; Cory, Green et al. 2004), temperature and moisture (Christ and David 1996) are modulating the DOM flux within a particular watershed. In permafrost-affected ecosystems the sources and mechanisms of DOM export from watersheds are still under debate. On the one hand topography modulates heat flux to soils and exerts strong control on spatial variability in permafrost thawing rates and consequently on the decomposition rates of soil organic matter (Prokushkin et al. 2005). Distinct terrigenic signatures for different DOM sources in streams of Interior Alaska underline the importance of topography in driving spatial variability in the chemical structure of DOM reaching streams (White et al., 2002). Moreover, the exact date during the frost-free period on which dydrologic conditions allow the export of DOM from forest ecosystems to surface waters is believed to depend on the active layer depth in permafrost soils (Woo and Winter, 1993, MacLean et al. 1999) and microbial activity in these soils (Guggenberger et al., 1994, Christ and David, 1996, Michalzik et al. 2003). Therefore, it is believed that progressive melting of frozen ground during frost-free period determines specific seasonal combination of soil temperature and moisture (Prokushkin et al., 2005). However, so far no results exist on the importance of these processes and mechanisms for DOM export from permafrost-affected ecosystems of Siberia.

In current study we have attempted to quantify seasonal changes in DOC concentrations in forest floor seepage waters, soil solutions and stream induced by changes in temperature and moisture. Our main objectives were to investigate 1) spatial variability of DOC concentrations

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in terrestrial compartments and 2) seasonal trends of DOC concentrations in forest floor, soil and stream.

2. MATERIALS AND METHODS

2.1 Site description

Kulingdakan watershed (64^{o}17-19'N, 100^{o}11-13'E) encompasses about 4,100 ha. It consists of forested hills with table-like tops and boggy valley bottoms. The watershed area (elevation from 132 m to 630 m, slope 12-15^o) is typical for the Syverma plateau. The stream has approximately 8 km in length (Fig. 1). The mainstem channel near the mouth is ~6 m wide and is characterized by step-pools with large pebbles and boulders. The region has a cold continental climate. For Tura the average temperature in January (the coldest month) is -36^{o}C, and that for July (the warmest month) is 16^{o}C. Average annual temperature is –9.5^{o}C. The watershed is located on the western edge of continuous permafrost distribution. Depth of the active soil layer typically reaches a maximum in September (Pozdnyakov, 1963). Average annual precipitation for the region is 300-350 mm. About 30-40 % of annual precipitation falls as a snow (Gerasimov, 1964). Snowmelt starts in mid-May and continues for about two weeks depending on the year's hydrologic and climatic conditions. Drought periods are usual for mid-summer (July). Rainstorms generate storm runoff with high discharge throughout the whole frost-free period.

Fig. 1. Location of experimental site. Kuligdakan watershed is taken into the circle.

Because of high latitude and low sun angles, north-facing slopes receive less solar radiation than south-facing slopes (MacLean et al., 1999). Study sites (10 m x 10 m each) were selected on the north- and south-facing slopes (hereafter referred to as N- and S-slope, respectively) separated by a stream valley. Slope angle in both locations was 12-13^o. Plots were almost similar in ground vegetation. The dominant species in the moss layer was *Pleurozium schreberi*. Dwarf shrubs were represented by *Vaccinium vitis-idea*, *Empetrum niger* and *Ledum palustre* on S-slope and *Vaccinium uliginosum*, *Vaccinium vitis-idaea* and *Ledum palustre* on N-slope. Soils are pale-yellow soils (Yershov, 1995, Histic Cryosol, and Gelic Cambisol (FAO, 1998)), characterized by a large portion of gravel, shallow (20-40 cm) depths and medium clay contents. Depending on the year and micro-scale topography, active layer depth (measured from the surface of moss cover) on the S-slope reached 80-110 cm, and on N-slope it was 40-80 cm. Tree canopy was dominated by larch (*Larix gmelinii*), with rare birch (*Betula pubescence*) and spruce (*Picea obovata*) on the south-facing slopes (Abaimov et al., 2002). Stand density of the S-slope site was 1500 trees/ha with a mean height of 12.1±2.7 m, and on N-slope density was 1700 trees ha^{-1} with a mean heightof 7.9±1.8 m.

2.2 Water sampling

Collection of water samples for DOC analyses was conducted in 2004 and 2005 during the major part of frost-free period (May 25 – September 15).

Forest floor seepage water. Solutes were collected beneath forest floor (depths of 6.4±1.5 cm on S-slope and 13.0±3.5 cm on N-slope) by zero-tension lysimeters (n=6, area 80 cm^2) similar to those used by Hongve (1999) and connected to 1 dm^3 PET bottle (flushed first with 0.1 M HCl, then with distilled water and finally with leachate). Sample collection was performed after every rain event.

Soil solution. Soil water was sampled by suction cup lysimeters installed at the depths of 1 cm, 5 cm and 20 cm at 4 day interval.

Stream water. Stream water sampling and discharge measurement were made daily using previously published methods (Prokushkin et al., 2001).

2.3 DOC analysis

Organic carbon content in subsamples of 2-10 ml (depending on DOC concentration) was determined by oxidation with a sulfochromic mixture (4.9 g dm^{-3} $K_2Cr_2O_7$ and conc. H_2SO_4, 1:1 w/w) with colorimetric detection of the reduced Cr^{3+} (Kaurichev et al., 1977; Khomutova, et al., 2000). Color of solutions was measured using a colorimeter at wavelength of 590 nm (Prokushkin et al., 2001) against a blank solution. For calibration standard sucrose solutions (n=10, 1.0-0.1 mgC, 3 replicates) were used. Sucrose was chosed as the standard because its O:C ratio (0.92) was close to the DOM O:C ratio (0.98) found in an earlier study (Kracht and Gleixner, 2000). The standard deviation of the organic carbon analysis was 0-1.6% (R^2=0.9984, $p<0.001$).

3. RESULTS AND DISCUSSION

Most intensive thaw rate of active soil layer was found in earlier frost-free period (from mid-May to mid-June). Our observation demonstrated the similar trend for north- and south-facing slopes with the daily increase of thawing depth on about 1 cm (Fig. 2). Meanwhile, active layer of the S-slope was 15 cm thicker and difference was enlarged up to 25-30 cm in later seasons. In general, thawing rate on N-slope was gradually decreased up to 0.2 cm in the autumn. Additional fact is important that there is significant difference in thickness of organic horizon between slopes. In particular, tthickness of the litter layer was 4-9 cm (3.6±0.8 cm, n=10) on the S-slope and 7-15 cm (9.4±1.2 cm, n=10) on the N-slope. It means that mineral soil on the N-slope starts melting 2 weeks later than on the S-slope. Soil temperature curve for the N-slope (Fig. 3) demonstrates that positive values for the 5 cm depth appears only on 14.06.05, and 20 cm layer was thawed on 22.06.05. Even so, monthly average temperatures in depth of 5 cm and deeper on the N-slope already does not exceed 5°C during whole frost-free period (Table 1). At the S-slope the temperature of 5 cm soil layer achieves 10°C in mid-summer season, and temperature of 5°C was monitored at 50 cm depth.

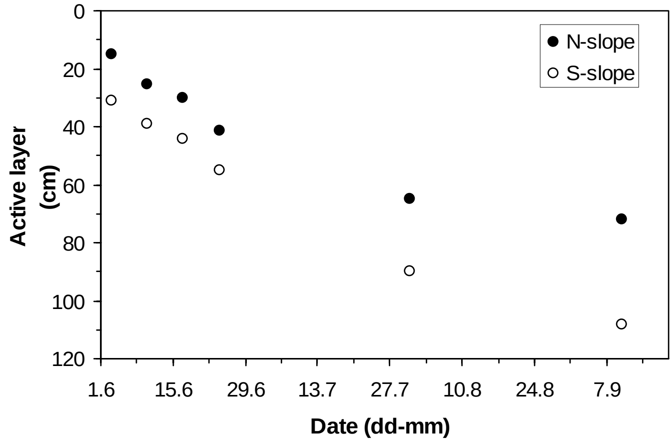


Fig. 2. Dynamics of soil active layer on contrasting north- and south-facing slopes in 2005. Zero value is moss surface.

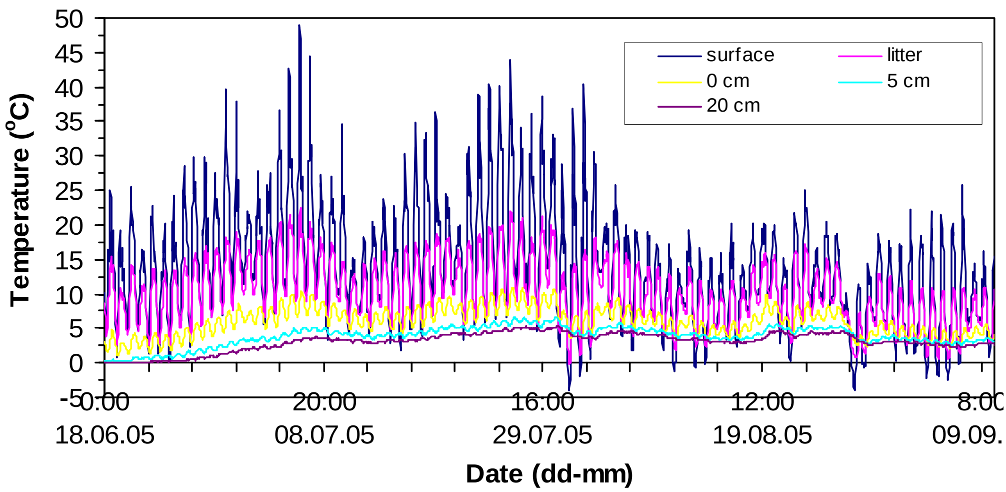


Fig. 3. Dynamics of soil temperature on north-facing slope in 2005.

Table 1. Average monthly soil temperatures on the south- and north-facing slopes in 2005.

	Soil temperature									
	moss surface		Oe		0 cm		5 cm		20 cm	
	Nfs	Sfs	Nfs	Sfs	Nfs	Sfs	Nfs	Sfs	Nfs	Sfs
June	14.5	15.4	10.1	11.0	3.9	8.3	0.6	4.7	0.3	1.8
July	17.8	18.7	12.9	14.4	7.5	12.1	4.7	10.6	3.7	6.9
August	11.2	12.7	9.1	11.2	5.9	10.4	4.4	8.6	3.8	7.1
September*	8.4	10.2	6.3	8.9	4.0	8.4	3.2	7.3	2.7	6.2

Nfs and Sfs are north- and south-facing slopes correspondingly.
* averaged till September, 18.

Summer precipitation differs sufficiently between years (Fig. 4), and summer of 2005 is considered as a deficient in precipitation. Total amount of summer precipitation in 2004 and 2005 was 150 mm and 112 mm according to local meteorological station, correspondingly. Meanwhile, in 2005 the canopy interception in the forests of both slopes accounted about 15%. Even greater interception was found for forest floor. Our data demonstrated that only 35% of rain water could achieve the surface of mineral soil in the S-slope and 20% on the N-slope. In 2004 these values were as much as 57% and 54%, correspondingly. For comparison, in exceptionally wet year of 2001 it was 88% and 76%, respectively. Main reason of lower penetration of rain waters to mineral soil is prevailing of low intensity rainfalls (up to 4 mm, Fig. 5) absorbed by porous organic matter and finally evaporated and/or transpired.

Precipitation is shown to be important factor driving DOC mobilization in the forest floor layer and the only DOC to be measured in this layer appears after rainfall. Concentrations of DOC in forest floor seepage water were highly variable for both slopes and in some extent were controlled by amount of percolated water (Fig. 6). In 2005 it ranged in an individual

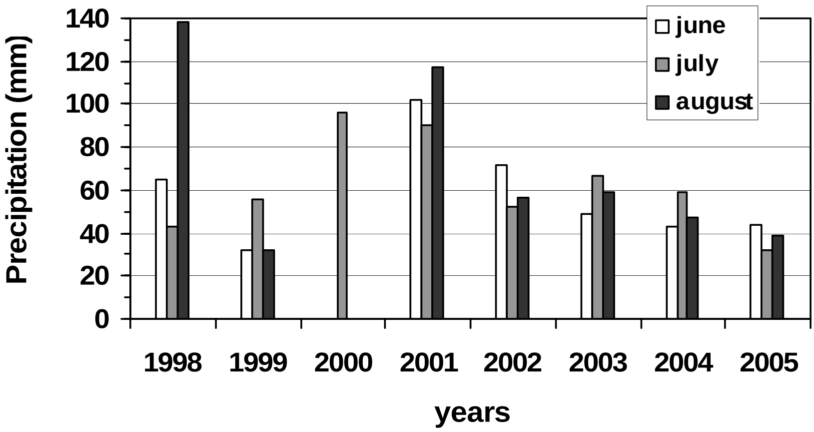


Fig. 4. Monthly precipitation on the open location (data of the State Meteorological Station in Tura, Evenkian Autonomous District).

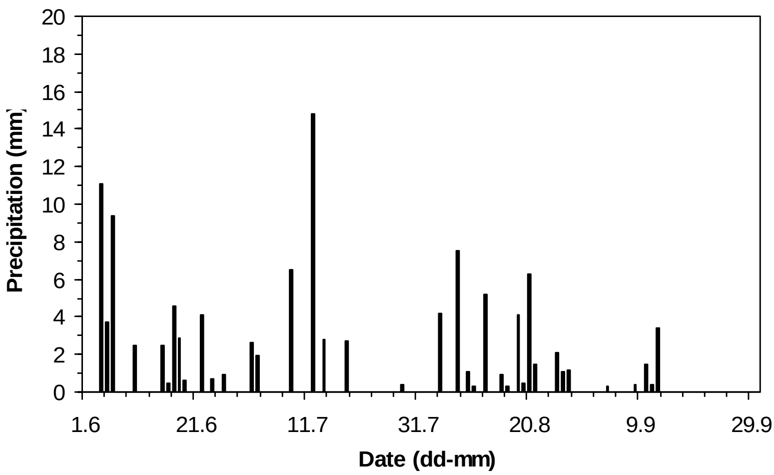


Fig. 5. Summer and early autumn precipitation pattern of year 2005 (clear cut area on experimental watershed).

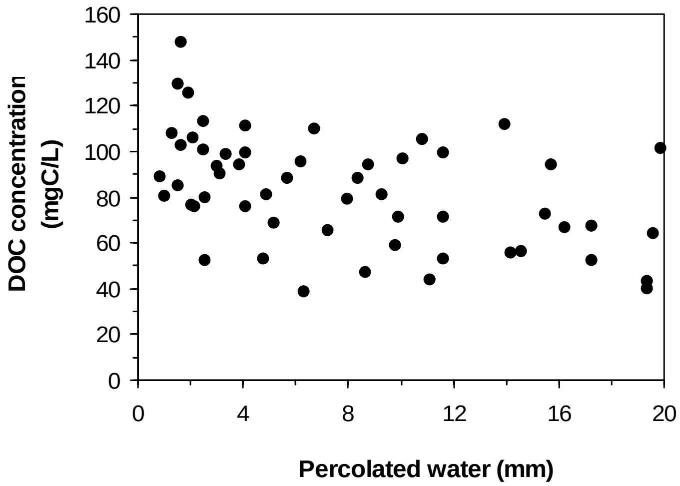
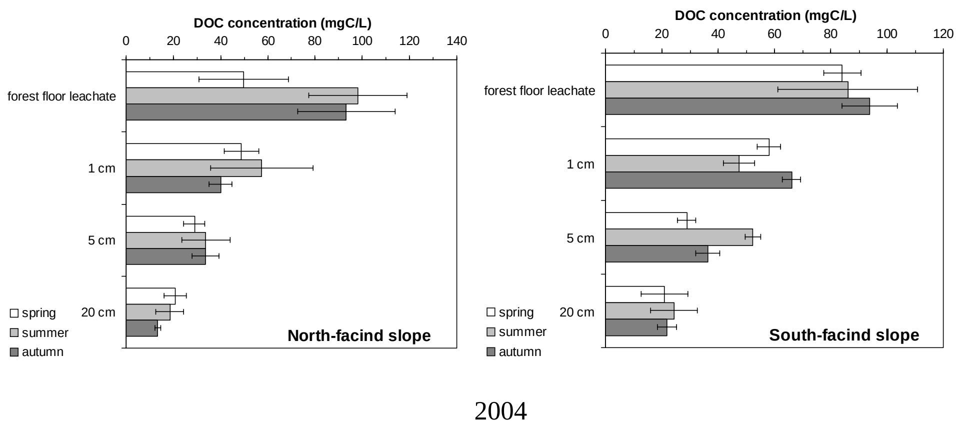


Fig. 6. DOC concentrations in forest floor seepage water of the north-facing slope in dependence from amount of water percolated through forest floor.



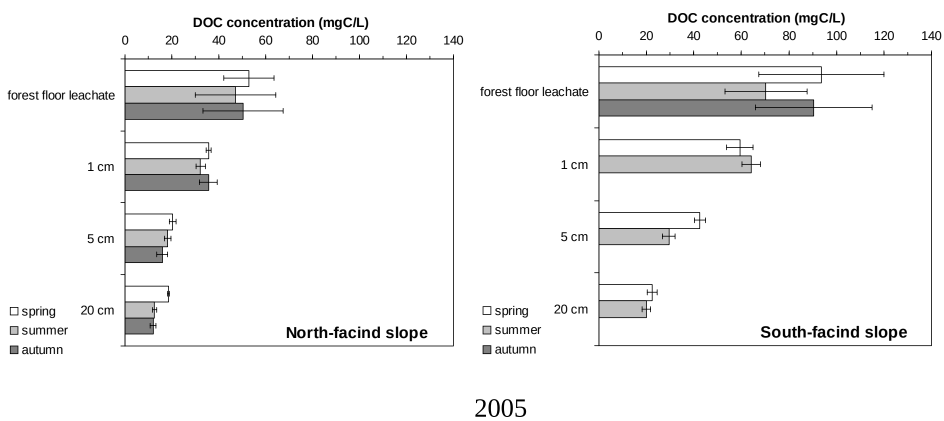


Fig. 7. Seasonal trends in DOC concentrations in forest floor seepage water and soil solution in 2004 and 2005.

lysimeter during frost-free period from 43 to 215 mgC/L on the S-slope and from 25 to 72 mgC/L on the N-slope. In general, average DOC concentrations for whole period of measurements in seepage water on the S-slope were in 2005 almost two-fold higher than on the N-slope (91 and 50 mgC/L, correspondingly). Surprisingly similar values of DOC concentrations were found in 2004 (90 and 86 mgC/L, correspondingly). Seasonal changes of DOC concentrations are mainly attributed to the some increase from spring to summer, which is more pronounced in heat deficient north-facing slope (Fig. 7). However, moisture regime of year is believed to control this trend and under drought (i.e. July 2005) there is the decrease of mobilized DOC. Therefore, autumnal higher DOC values in forest floor leachates entering mineral soil might be explained by most favourable combination of moisture and temperature driving decomposition process. At the same time, it might be site specific and not be obvious in the N-slopes where soil temperatures are decreased significantly in September.

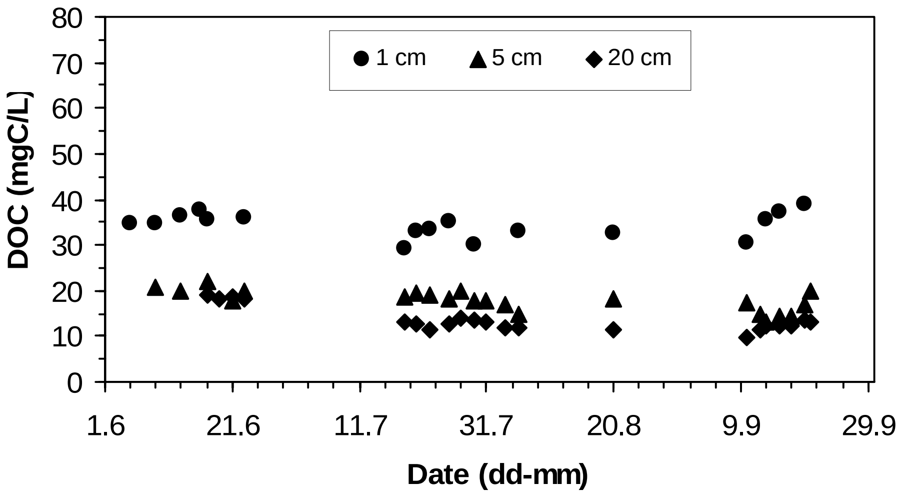


Fig. 8. Dynamics of DOC concentrations in soil solution of different depths on the north-facing slope in 2005

In opposite to findings concerning some negative dependency between forest floor DOC concentrations and water input found in 2005 shown on figure 6, there was no any response of DOC concentrations in soil solution to water input (Fig. 8). It is shown that DOC concentrations at three soil depths remained almost constant (1 cm depth) or demonstrated certain decrease from June to September (5 and 20 cm depths). Moreover, in the weather conditions of 2005 there was no available water in all studied soil layers on the S-facing slope starting from July 22 (Fig. 7). In contrary, in 2004 there was the increase of DOC concentrations in soil solution during July at 5 and 20 cm depths. Therefore, moisture rather than temperature may drive production and mobilization of DOC in high latitude soils with deficient precipitation input during frost-free period (Prokushkin et al. 2005).

In general, soil solutions demonstrated considerably lower concentrations of DOC comparatively to forest floor seepage water. It suggests removal of DOC by microbial decomposition and/or sorption (Kaiser and Guggenberger 1996, Guggenberger and Kaiser 2003) on both slopes. However, the decrease of DOC concentrations with soil depth was more apparent in warmer south-facing slope.

Similar to soil solution descending trend of DOC concentrations was found in the stream. Highest concentrations are measured in spring time when organic-rich layer of soil is almost ultimate source of stream water (Fig. 9). Later season precipitation is believed to be major

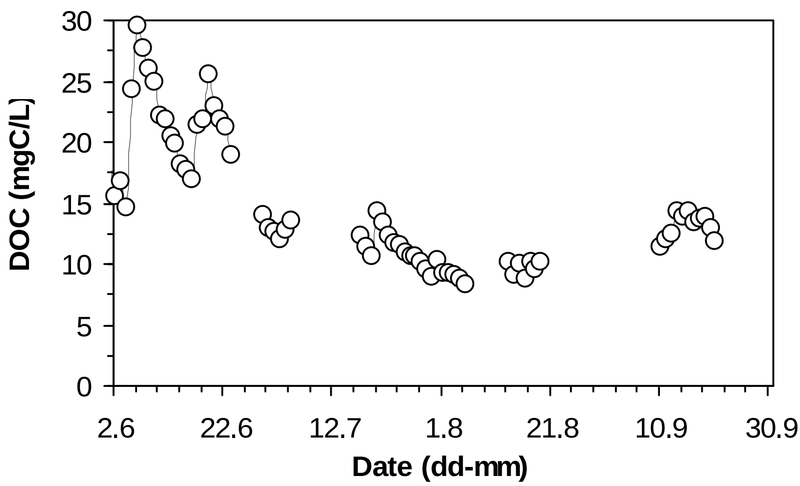


Fig. 9. Dynamics of DOC concentrations in Kulingdakan stream in 2005.

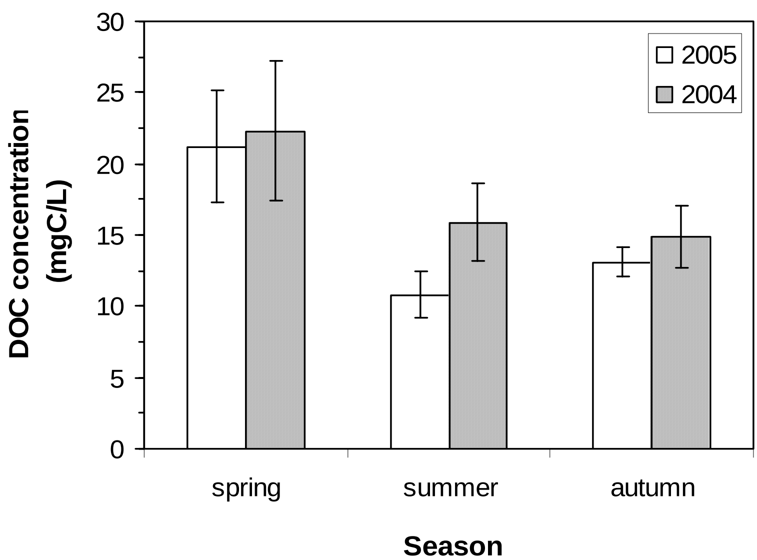


Fig. 10. Seasonal dynamics of DOC concentrations in Kulingdakan stream in 2004 and 2005.

factor for the export of terrestrial DOC to stream. At droughts like in 2005 concentrations of DOC in stream drop in July to 7-10 mgC/L that is originated primarily from the melting deeper mineral soil layers poor in organic matter (McLean et al. 1999). In comparison, in wetter year of 2004 the summer average value of DOC concentrations in stream was 1.5 times higher than in 2005 (Fig. 10). Even higher values were monitored in 2000 and 2001 (23 and 20 mgC/L, correspondingly) when monthly precipitation in July was higher 90 mm. In general, progressively increasing active soil layer is thought to control DOC export from terrestrial ecosystems through the increased sorption capability (McLean et al. 1999). Meanwhile, intense precipitation occurred throughout frost-free period may significantly alter DOC input to streams. DOC appeared under stormflow conditions is originated from both organic rich top soil layers escaped mineral soil and melted deeper mineral layer. While, baseflow conditions suggest DOC export to stream ultimately from deep soil layers. Therefore, terrestrial flux of

DOC to stream is contributed from different sources of different qualities and quantities differing at different hydrological phases and seasons. To trace the share of every one of these fluxes is still required for further understanding of DOC production and mobilization in the permafrost affected ecosystems.

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