Carbon and nutrients in the Yenisei River tributaries draining the Western Siberia Peatlands

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Abstract. The study is focused on carbon and nutrient behaviour in tributaries of the Yenisei River draining the Western Siberian Plain. The previous studies showed that dissolved organic carbon (DOC) concentrations in riverine systems are influenced by wetland cover within a watershed and modulating effect of permafrost. Our data point out more complex interactions within the south-north transect of the Yenisei River basin including a partitioning of sources at different seasons and in-river metabolic processing of DOC involving utilization of nutrients and production of DIC. On the other hand, DOC concentration in rivers is driven by available stock of labile carbon and, thus, is a function of total organic matter stored in soils. Terrigenic C and nutrient fluxes to rivers are enhanced in colder environments of northern Western Siberia, contradicting the earlier observations and respective future projections of permafrost degradation effects on riverine C release.

1. Introduction
The Western Siberian Plain (WSP) hosts likely the largest pool of organic carbon in boreal biome. The C-rich peat deposits cover the area up to 592 million km², and C stocks account from 40 to 70 PgC [1, 2]. A fate of this ancient carbon (ages up to 15,000 years [3]) under a warming climate remains among major unanswered questions of carbon budget of the boreal biome. Moreover, a considerable portion of this carbon is entrapped in permafrost (northwards of 60°N) [4], whose degradation might accelerate mineralization of peat C resulting to the increase of emissions of CO₂ and CH₄ to the atmosphere [5]. Recently, the release of terrestrial C to the WSP rivers has emerged as another critical negative term in the carbon balance of peatlands [6].

The riverine C and nutrient fluxes within the Ob’ River basin has received recently the large attention aimed to explore mechanisms of spatial patterns and estimate the response of C and nutrient concentrations and fluxes to warming air temperatures [6, 7, 8]. The much less is known about the Western tributaries of the Yenisei River. In this study, we examined the seasonal variations in
concentrations of C species and nutrients in tributaries of the Yenisei River draining the Western Siberian Plain. Our objective was to understand how climatic and hydrological processes interact to control C and nutrients fluxes. Specifically, we addressed the following questions: (1) what are the differences in concentrations of C and nutrients among rivers draining peatland areas under a different climatic context? (2) how do seasonal changes in flow paths (sources) control river dissolved C species and nutrients?

2. Data and Methods

2.1. Spatial data

The Yenisei River basin has the large asymmetry (figure 1): its major western tributaries (above 58°N) covers only 5.6% of entire basin area and release annually only about 40 km$^3$ of freshwater or 6.5% of total annual discharge of the Yenisei River to the AO. Basin characteristics shown in table 1 were obtained to create the regional GIS “Lower Yenisei”: watershed areas were delineated with ESRI ArcGIS v. 10; permafrost types extent was established as mapped by [9], the percentage of vegetation cover contained within each watershed was computed using the comprehensive TerraNorte Russian Land Cover map (250 m) [10]; the mean annual air temperatures (MAAT) were obtained for the grid 0.5° x 0.5° [11]. The length of rivers and their discharges were received from Roshydromet (Sredensibisrkoe UGMS).

![Figure 1. Location of main western tributaries of the Yenisei River within its watershed boundaries. Numbers of rivers are given below in Table 1. The red line is the track during sampling campaigns](image)

2.2. Sampling and Analyses

Sampling campaigns were undertaken in spring flood periods of 2012, 2015 and 2016; late summer of 2015 and 2016 and winter lowflow periods of 2015 and 2016. Seasonal samples (biweekly interval) were collected during 2010-2016 in two rivers near ZOTTO (www.zottoproject.org), representing the areas of largest extent of peatlands (26-82%) among the rivers draining the WSP.

Water samples were collected from just beneath the water surface at the mid-point of rivers. Samples were immediately filtered (pre-rinsed 0.22 μm nitrocellulose filters, Millipore) and stored
frozen prior to analyses. DOC concentrations (as non-purgeable organic carbon (NPOC)) and DIC concentrations were measured via high temperature combustion (TOC minicube analyzer, Elementar). Specific ultraviolet absorbance (SUVA) was measured at 254 nm by Varian 100 UV-Vis spectrophotometer and further normalized to DOC concentration (m/l/mg C). Concentrations of nutrients (DIN = N-NO\textsubscript{3} + N-NO\textsubscript{2} + N-NH\textsubscript{4} and TDP = P-PO\textsubscript{4}) were obtained by colorimetric methods using Flow injection analyzer (Lachat Quikchem 8500). Total dissolved nitrogen (TDN) has been measured by AnalytikJena Multi C/N Analyzer.

River suspended matter collected by sedimentation was subjected to the analysis of total C and N content (particulate organic carbon (POC) and nitrogen (PON)) together with their isotopic composition by Vario Isotope Cube (Elementar) connected to IsoPrime100 (IRMS).

Table 1. Characteristics of main tributaries of the Yenisei River, draining Western Siberian Plain

| River name | Outlet latitude°N | Basin area km\textsuperscript{2} | Length km | Annual discharge km\textsuperscript{3} | MAAT °C | Wetlands % | Tundra/ Palsa |
|------------|-------------------|--------------------------------|-----------|--------------------------------------|--------|------------|-------------|
| 1. Kem'    | 58.52             | 9014                           | 356       | 1.28                                 | 0.0    | 0          | 0           |
| 2. Kas     | 59.99             | 11775                          | 464       | 2.60                                 | -0.9   | 12         | 0           |
| 3. Sym     | 60.25             | 31849                          | 694       | 8.34                                 | -1.7   | 22         | 0           |
| 4. Tugulan | 60.79             | 1195                           | 92        | 0.31                                 | -2.0   | 34         | 0           |
| 5. Dubches | 60.99             | 15376                          | 433       | 5.22                                 | -2.7   | 5          | 0           |
| 6. Yeloguy | 63.19             | 27143                          | 464       | 8.73                                 | -3.1   | 11         | 1           |
| 7. Pakulikha| 64.38             | 4740                           | 208       | 1.52                                 | -4.1   | 18         | 10          |
| 8. Turukhan| 65.90             | 35726                          | 639       | 12.02                                | -5.7   | 19         | 32          |
| 9. Bolshaya Igarka | 67.41 | 1720                           | 156       | 0.58                                 | -6.7   | 13         | 54          |
| 10. Malaya Kheta\textsuperscript{a} | 69.33 | 5942                           | 298       | 1.90                                 | -7.9   | 0          | 100         |
| 11. Bolshaya Kheta\textsuperscript{a} | 69.31 | 20800                          | 646       | 6.65                                 | -7.1   | 0          | 92          |

| Total WPL: | 138538 | 40.60   |

Note: Malaya and Bolshaya Kheta mouths are located downstream of the terminal gauging station on the Yenisei River at Igarka (excluded from a sum of basin area and discharge).

According to [5].

3. Results and Discussion

3.1. Spatial and temporal variation of dissolved C and nutrients in major rivers of the Yenisei basin

Measured DOC and DIC concentrations in West Siberian rivers entering Yenisei main channel reveal a remarkable differences between seasons and locations within south-north transect with mean annual air temperature range from ca. 0 to -7.9 °C (figure 2). Only a spring freshet season showed the clear spatial pattern with decreasing DOC (Figure 2a) and dissolved nutrients (TDP and DIN, figure 3a and b) concentrations northward along with decreasing MAAT. In opposite, an aromaticity of DOC was tended to increase northward with the highest effect appeared under winter low-flow regimes (figure 2c). Under the lowflow regimes (summer and winter) lower concentrations of DOC, DIC, TDP and DIN were attributed to the middle section of studied south-north transect, namely between 60.5 to 65.0 °N (-1 – -4°C MAAT), surprisingly corresponding to the largest extent of peatlands. Seasonal amplitude of DOC concentrations has the tendency to decline with the latitude, but opposite appeared for DIC concentrations, which likely is driven by
partitioning of hydrocarbonate-C and pCO$_2$. Dissolved CO$_2$ contributed to DIC additionally up to 9 mgC/l, e.g. in Kas and Sym, which have demonstrated lowest DIC values.

![Graph](https://example.com/graph.png)

**Figure 2.** Dependence of DOC (a) and DIC (b) concentrations and aromaticity (SUVA) of DOC (c) on mean annual temperatures (MAAT) of watershed at different seasons: winter lowflow, spring freshet and summer lowflow.

Total dissolved nitrogen (TDN) concentrations in rivers of Western Siberia are descending with northward decrease of MAAT (figure 3c), but this 2-fold drop is pronounced much less in comparison to inorganic species of N and P (4-5-fold differences among south and north). This dependence is driven by difference in DOC concentrations, as dissolved organic nitrogen (DON = TDN – DIN) constitutes 75-98% of TDN.

Concentrations of river suspended matter at freshet period were decreasing exponentially with averaged MAAT of a watershed ($RSM = 7.98 e^{0.33 \times MAAT}$, $R^2 = 0.72$, $p<0.05$, $n = 14$) and similar pattern we have obtained for particulate forms of OC and ON. Those ranged from 0.3 to 3.3 mgC/l (1.5-20% of total riverine C) and from 50 to 280 μgN/l (6-40% of total riverine N).
Interestingly that both OC and ON content of RSM, nevertheless, showed an opposed tendency and increased with mean MAAT of a watershed. POC isotopic composition demonstrated depletion in $^{13}$C southward, suggesting an increased autochtonous POC production that is further supported by similarly low $\delta^{13}$C-POC in summer period ($-31.7\pm1.7$‰).

These results show (i) concentrations of DOC and dissolved nutrients in freshet period have a strong correlation with MAAT, regardless of peatland cover and/or tundra palsa vegetation; (ii) decreased concentrations of dissolved C species and nutrients at lowflow regimes appear in the middle section of studied south-north transect, corresponding to the largest extent of peatlands within the middle taiga subzone; and (iii) a decline in DOC aromaticity occurs in southernmost rivers. These findings are particularly interesting while previous studies have reported that DOC concentrations in riverine systems are influenced (i) by the percent cover of wetlands within a watershed and (ii) permafrost can exert a threshold level to DOC release from terrestrial environments [6, 8], our data point out more complex interactions within the south-north transect of the Yenisei River basin including a partitioning of sources at different seasons (e.g. different DOC quality shown as SUVA) and in-river metabolic processing of DOC involving utilization of nutrients and production of DIC. On the other hand, DOC concentration in rivers is driven by available stock of labile carbon and, thus, is a function of total organic matter stored in soils [12]. The analysis of the latitudinal pattern of C accumulation in peatlands of Western Siberia provided by [2, 3] showed that SOC decreases from 42-88 kgC/m$^2$ at south of 60°N to 7-35 kgC/m$^2$ in northernmost locations with palsa mire domination. At
the freshet, period when river solutes originates primarily in organic-rich horizons of soils, DOC concentrations in rivers show strong correlation with mean SOC stocks [4, 13] within their watersheds. Nevertheless, the coldest northernmost rivers (>67°N) with intermediate amounts of SOC lay apart of the dependence (figure 4) that suggests a lower mobilization of DOC due to either retardation of temperature-dependent DOC production or lower lability of already produced DOC or its utilization in soil profiles.

Figure 4. Dependence of DOC concentrations at freshet on mean stock of soil organic carbon (SOC) in upper 1 m of soil on watershed. Blue circle highlights the northernmost rivers Bolshaya Igarka, Bolshaya Kherta and Malaya Kheta with continuous permafrost distribution 50, 100 and 72%, correspondingly.

3.2. Seasonal variation of dissolved C species concentrations and C flux estimates for peatland basins

Hydrology of peatland-rich watersheds differs significantly from forested and mountainous basins of boreal biome [14]. Particularly DOC concentrations in stream is apparently diluted at spring flood periods and increased in summer-fall season due to carbon flushing when moist conditions return to previously aerated peat soils (figure 5). Correspondingly, high fluxes of dissolved C, which amount to a half of spring flood season, usually occur in fall period (September-October). For the middle taiga subzone estimated annual dissolved C fluxes in the 2nd order Razvilki stream (60.48°N, 89.23°E, near ZOTTO observatory, S = 17 km²), based on monthly mean estimates of concentrations and discharges in 2010-2016, were highly variable averaging 2.87±0.98 gC/m²/year as DOC and 0.58±0.74 gC/m²/year as DIC. Within this subzone an increase of the basin size led to the growth of DIC riverine fluxes at all seasons, though DOC showed only little changes with the watershed area. Meanwhile, lower aromaticity and lighter isotopic composition of C-DOC in larger basins suggest changes in DOC origin: i.e. shift from allochtonous to more autochthonous production.

In latitudinal context we have observed a strong negative relationship between the annual DOC flux in rivers draining Western Siberia and respective basin MAAT: $f_{DOC} = -0.45 \times MAAT + 2.5, R^2 = 0.97, p < 0.01$. Similar, but much less significant dependence ($R^2 = 0.22, p > 0.2$) has been found between MAAT and DIC fluxes.

Our findings evidenced that (i) intraseasonal and interannual variations in river discharges significantly control the annual estimates of C fluxes, (ii) in-river processes as a function of basin size are responsible for changes in partitioning of dissolved riverine C species and an origin of riverine organic matter and (iii) terrigenic C and nutrient fluxes to rivers are enhanced in colder environments of northern Western Siberia, contradicting the earlier observations and respective future projections of permafrost degradation effects on riverine C release [6].
Figure 5. Seasonal dynamics of water level and DOC concentrations in 1st order stream draining peatland basin (82% coverage) within the middle taiga subzone (ca. 61 °N)

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