



## Abstract

Present and future levels of primary production (PP) in the Arctic Ocean (AO) depend on nutrient inputs to the photic zone via vertical mixing, upwelling and external sources. In this regard, the importance of horizontal river supply relative to oceanic processes is poorly constrained at the panarctic scale. We compiled extensive historical (1954–2012) data on discharge and nutrient concentrations to estimate fluxes of nitrate, soluble reactive phosphate (SRP), silicate, DOC, DON, PON and POC from 9 large Arctic rivers and assess their potential impact on the biogeochemistry of shelf waters. Several key points can be emphasized from this analysis. The contribution of riverine nitrate to new PP (PP<sub>new</sub>) is very small at the regional scale (< 1 % to ca. 6.2 %) and negligible at the panarctic scale (ca. 0.73%), in agreement with recent studies. By consuming all this nitrate, oceanic phytoplankton would be able to use only ca. 13.5 % and 6.6–17.5 % of the river supply of silicate at the panarctic and regional scales, respectively. Corresponding figures for SRP are ca. 27.8 % and 18.4–44.4 %. On the Beaufort and Bering shelves, riverine SRP cannot fulfil phytoplankton requirements. On a seasonal basis, the removal of riverine nitrate, silicate and SRP would be the highest in spring and not in summer when AO shelf waters are nitrogen-limited. Riverine DON is potentially an important nitrogen source for the planktonic ecosystem in summer, when ammonium supplied through the photoammonification of refractory DON (ca.  $3.9 \times 10^9$  mol N) may exceed the combined riverine supply of nitrate and ammonium (ca.  $2.9 \times 10^9$  mol N). Nevertheless, overall nitrogen limitation of AO phytoplankton is expected to persist even when projected increases of riverine DON and nitrate supply are taken into account. This analysis underscores the need to better contrast oceanic nutrient supply processes with the composition and fate of changing riverine nutrient deliveries in future scenarios of plankton community structure, function and production in the coastal AO.

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## 1 Introduction

Fifty years ago, the Arctic Ocean (AO) was perceived as a small contributor to the global carbon cycle because of its extensive sea-ice cover and the relatively low light levels experienced by phytoplankton (English, 1961). The AO is now thought to contribute ca. 14 % of the global uptake of atmospheric carbon dioxide (Bates and Mathis, 2009) and, as such, is an important actor in the global carbon cycle. As a consequence of warming, the AO tends to switch towards a more subarctic state. The earlier and longer exposure of surface waters to sunlight triggers earlier vernal blooms in some parts of the Arctic Ocean (Kahru et al., 2010). Also, it has been suggested based on ocean colour remote sensing data that annual primary production (PP) is increasing (Arrigo et al., 2008). However, recent observations show that the density stratification (i.e. pycnocline) is persistent throughout the year (Tremblay et al., 2008) and strengthening as a result of increasing river discharge (Li et al., 2009). These conditions limit the vertical supply of nutrients offshore and favour small phytoplankton cells at the expense of large ones (Li et al., 2009).

Present and future trends in Arctic PP will depend on nutrient inputs into the photic zone, driven either by ocean mixing, upwelling or external sources (Tremblay and Gagnon, 2009). Mixing and upwelling replenish the photic zone with new nutrients transported upwards from below the pycnocline. These nutrients originate mostly from the local remineralization of settling organic matter and from the inflow of Atlantic and Pacific waters. Upward supply can result from tidal or wind-driven erosions of the pycnocline (Wassmann et al., 2006; Hannah et al., 2009; Le Fouest et al., 2011), upwelling when wind blows in a suitable direction along the shelf break (Tremblay et al., 2011) or the ice edge (Mundy et al., 2009) and eddy pumping in shallow anticyclonic eddies (Timmermans et al., 2008). The contribution of these oceanic processes relative to horizontal nutrient supply from rivers and adjacent seas to the Arctic PP regime is poorly constrained at the panarctic scale (Tremblay and Gagnon, 2009).

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Continental rivers surrounding the AO are a potentially significant source of nutrients for circum-arctic shelf seas. Arctic river discharge is high, representing 10 % of the global freshwater discharge pouring into only 1 % of the global ocean volume (Opshal et al., 1999). While the estimated input of allochthonous inorganic and organic compounds by rivers into the Arctic Ocean is not negligible (Holmes et al., 2000; Dittmar and Kattner, 2003), its biogeochemical significance in shelf waters remains unclear (McClelland et al., 2012). Riverine nitrate is derived from soil leaching (i.e. moved or dissolved and carried through soil by water) and terrestrial run-off (i.e. transported over land in the excess water when soil is infiltrated to full capacity). Soluble reactive phosphorus (SRP) originates from the weathering of crustal minerals (e.g. aluminium orthophosphate, apatite) and silicate from weathering of silicate and aluminosilicate minerals. Human activity may also provide nitrate and SRP in the White Sea, which has one of the most industrialized Arctic coastlines. By contrast with nitrogen-limited marine waters, phosphorus is the most limiting element in rivers mostly because its supply to the freshwater system is limited by erosion. Particulate and dissolved organic forms of nitrogen, phosphorus and carbon are also transported to the ocean by rivers. Their fate in the marine environment depends of their lability, of which little is known in Arctic settings.

Previous estimates of riverine nutrients fluxes to the coastal Arctic were either based on annual mean concentrations (Gordeev et al., 1996) or on monthly mean concentrations but derived from a single dataset and limited to a portion of the Arctic Basin (Holmes et al., 2000). Recently, an important modelling effort constrained by measurements from the PARTNERS (2003–2007) and Student Partners (2005–2008) projects during the last decade was made to assess deliveries of riverine dissolved nutrients and their seasonality (Holmes et al., 2011). In the present study, we expanded this effort by compiling extensive historical (1954–2012) data including dissolved nutrients and particulate matter for 9 large Eurasian and North-American rivers. The aim was to establish a historical baseline (or climatology) of river fluxes and assess their impact on the biogeochemistry of shelf waters. Particular attention is paid to phosphorus,

silica and particulate organic nitrogen (PON), which in recent papers received less attention than dissolved nitrogen (Tank et al., 2011) and carbon (Manizza et al., 2009). We provide the biogeochemical modelling community with time series of monthly averaged concentrations of nitrate, SRP, silicate, and dissolved organic carbon (DOC) and nitrogen (DON) to help constrain riverine boundary conditions in panarctic physical-biological models.

## 2 Material and methods

We compiled riverine nitrate ( $n = 2372$ ), SRP ( $n = 1618$ ), silicate ( $n = 1751$ ), DOC ( $n = 509$ ), DON ( $n = 383$ ), POC ( $n = 65$ ) and PON ( $n = 65$ ) data for 9 large Arctic rivers, the Yenisey (Kara Sea; at Igarka – 67.4° N, 86.5° E, and Dudinka – 69.2° N, 86.1° E), Lena (Laptev Sea; at Zhigansk – 66.8° N, 123.4° E, Kyusur – 70.7° N, 127.4° E, and Stolb – 72.37° N, 126.80° E), Ob (Kara Sea; at Salekhard – 66.6° N, 66.6° E), Mackenzie (Beaufort Sea; at Tsiigehtchic – 67.46° N, 133.7° W), Yukon (Bering Sea; at Pilot Station – 61.93° N, 162.88° W), Pechora (Barents Sea; at Oksino – 67.6° N, 52.2° E), Northern Dvina (White Sea; at Ust’Pinega – 64.1° N, 41.9° E, and Arkhanggelsk – 64.3° N, 40.3° E), Kolyma (East-Siberian Sea; at Kolymskoye – 68.7° N, 158.7° E, and Cherskii – 68.4° N, 161.2° E, and Indigirka (East-Siberian Sea; at Chokurdakh – 70.4° N, 147.6° E). Available riverine ammonium data were not used, because concentrations measured along the Eurasian side are considered dubious as a result of methodological problems (Holmes et al., 2000, 2001). Data were gathered from 8 publications (Reeder et al., 1972; Macdonald et al., 1987; Létolle et al., 1993; Lara et al., 1998; Holmes et al., 2000; Millot et al., 2003; Savenko and Shevchenko, 2005; Finlay et al., 2006) and 5 databases. The latter are from the PARTNERS project (e.g. McClelland et al., 2008) extended as the Arctic Great Rivers Observatory (Arctic-GRO) project (<http://arcticgreatrivers.org/data.html>), the United Nations GEMS/WATER Programme (<http://www.gemswater.org>), United States Geological Survey (USGS) Water-Quality Data for the Nation (<http://waterdata.usgs.gov/nwis/qw>) and the United Federal Service

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for Observation and Control of Environmental Pollution (OGSNK/GSN) (Holmes et al., 2000). Data span from 1954 to 2012 with most of the measurements starting from the mid-eighties. With respect to data quality, only a total of 2 dubious nitrate measurements (97 and 117 mmol N m<sup>-3</sup> measured in the Yenisey River at Igarka) were removed from the dataset considering maximum nitrate concentrations of ca. 37 mmol N m<sup>-3</sup> in the Yenisey watershed (e.g. Frey et al., 2007). Ammonium and DON concentrations used in this study are from the PARTNERS database. DON concentrations were obtained by subtracting nitrate, nitrite and ammonium from the total dissolved nitrogen pool. SRP is the phosphorus content measured as the orthophosphates prior to the hydrolysis of the dissolved organic phosphorus (DOP).

The source nutrient data were log-transformed to reduce skewness and approach a Gaussian frequency distribution. For nutrients, only geometric averages were used in the remaining of this study. They were obtained by back-transforming the arithmetic averages calculated on log-transformed data. The monthly averaged nutrient data were multiplied by the monthly integrated river flow rates from the R-ArcticNet database (<http://www.r-arcticnet.sr.unh.edu/v4.0/index.html>) to compute the monthly-integrated nutrient fluxes. On average, the monthly integrated flow rates lie within ca. 3–4 % (May–October, ca. 82 % of the annual flow) of the mean annual values reported in the modelling study of Holmes et al. (2011). No time interpolation or extrapolation was performed on data. Resulting fluxes are based on in-situ concentrations only hence they may represent a minima estimates. Nutrient fluxes in the polar mixed layer through Bering Strait and the Barents Sea Opening were computed using the geometric mean annual concentrations calculated between 0 and 50 m from the World Ocean Atlas 2005 (National Oceanographic Data Centre, 2006) for SRP, nitrate and silicate. Values of 0.83 Sv (1 Sv = 10<sup>6</sup> m<sup>3</sup> s<sup>-1</sup>) and of 0.2 Sv were used as the mean volume transported through Bering Strait (Roach et al., 1995) and the Barents Sea Opening (Ingvaldsen et al., 2004), respectively.

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### 3 Results and discussion

#### 3.1 Concentrations and fluxes of riverine nutrients

The different nutrients show distinct seasonal patterns in concentration, as demonstrated by the monthly data from stations located as far downriver as possible (Figs. 1 and 2). Nitrate and silicate concentrations are generally highest in winter and decrease during the freshet as a result of dilution (e.g. Finlay et al., 2006; Sferratore et al., 2008). By contrast, DOC and POC concentrations, and to a lesser extent DON and PON concentrations, peak in May–July during the freshet period and generally decrease thereafter (e.g. Finlay et al., 2006). With regards to SRP, no clear seasonal trend can be drawn from the climatology, except in some Eurasian rivers (Pechora, Ob and Dvina), where concentrations drop during the freshet along with those of nitrate and silicate.

Large differences in concentration can be found between rivers. For instance, wintertime silicate concentrations are higher in the Yukon River (ca. 200 mmol Si m<sup>-3</sup>) than in any other river, and the seasonal variations are large (130 mmol Si m<sup>-3</sup>) compared with the Mackenzie River (ca. 25 mmol Si m<sup>-3</sup>), for example. Greater silicate concentrations in the Yukon River can be explained by the higher dissolved silica yield in the Yukon catchment (Dürr et al., 2011). Regarding SRP, wintertime concentrations are generally much higher in Eurasian (Ob, Pechora and Northern Dvina) than North-American rivers. The Ob River shows the highest SRP concentrations (up to 3 mmol P m<sup>-3</sup>) prior to and after the seasonal peak discharge in July. Eurasian rivers exhibit large differences in DOC and DON concentrations throughout the year but comparable maximum values in spring (ca. 1000 mmol C m<sup>-3</sup> and ca. 20–30 mmol N m<sup>-3</sup>). In August and September, the concentrations of DOC, DON and PON in the Ob River are about twice those of its North-American and Eurasian counterparts.

The standard deviations calculated on concentrations are generally high for all variables except silicate and high values are not restricted to the period of maximum river discharge. The effect of synoptic variability in discharge (Holmes et al., 2011), which can alter concentrations, in calculating monthly averages and/or methodological

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differences amongst datasets likely contributed to the large standard deviations and impacted nutrient flux estimations.

Nutrient fluxes are highest during the freshet season (May to July) and generally peak in June (Figs. 3 and 4). They decrease in summer and, in some cases, show a second peak in September–November (Yenisey, Ob, Lena and Yukon rivers). This second peak is not linked to an intensification of freshwater discharge but to an increase in nutrient concentration in the rivers, which possibly results from changes in the watershed (e.g. enhanced permafrost melting, decomposition and/or changes in basin hydrology). The Yenisey, Lena and Ob rivers show the highest nutrient fluxes as well as the highest annual freshwater discharge and amplitude of seasonal variations, especially during the spring to summer transition.

The mean annual fluxes of riverine nutrients estimated in this study show overall agreement with previously published ones (Table 1). Note that we incorporated measurements made at stations located upstream and downstream of those used in Holmes et al. (2000, 2011). A comparison of flux estimates between stations sampled at different sites along the paths of the Yenisey, N. Dvina and Kolyma rivers showed differences for SRP and silicate, but none for nitrate. These differences possibly result from a differential temporal coverage in calculating fluxes and/or methodological differences amongst datasets but it can also be explained by discontinuities within the rivers' watersheds (Frey et al., 2009; Gustafsson et al., 2011). For instance, in the Lena River, Semiletov et al. (2011) report a ca. 20 % and 60 % variation in Si and total organic carbon concentrations, respectively, along the 1200-km stretch separating the Lena delta from Yakutsk.

Relative to the contribution of Bering Strait, the riverine flux of DIN and SRP into the Polar Mixed Layer (PML) is minor at the AO scale (Fig. 5). The combined nutrient flux from the 8 rivers (the Yukon was not accounted as it pours out in the Bering Shelf) is in fact similar to that of the Barents Sea, except for silicate. Rivers account for only ca. 2 % and 4 % of the total horizontal input of allochthonous nitrate and SRP in the surface layer, respectively, whereas their contribution for silicate reaches ca. 11 %. As such,

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rivers and Bering Strait strikingly differ in their potential relative contribution to primary production (PP).

### 3.2 Contribution of riverine nutrients to shelf water biogeochemistry

SRP, nitrate and silicate are key nutrients needed by diatoms to grow and form blooms. Diatom blooms are responsible for new (i.e. nitrate-based) PP (PP<sub>new</sub>) and for a major of this newly produced organic matter to the deep ocean. To assess the contribution of riverine nutrients to PP<sub>new</sub> in the AO, we used nutrient fluxes estimated as far as possible downstream at stations where discharge and nutrient measurements coincided (Table 1). Note, however, that these locations are hundreds of kilometres upstream from the estuaries. As such, the nutrient fluxes do not account for potential removal and enrichment processes occurring in the intervening transition zone (see Emmerton et al., 2008 and the discussion in Tanks et al., 2011). The Lena River, for which fluxes are based on measurements from the delta itself, is an exception. We converted the fluxes of phosphorus, nitrogen and silica into carbon equivalents (PP<sub>new</sub>) using a molar C : N : P : Si consumption ratio of 112 : 14 : 1 : 26 (Tremblay et al., 2008). The resulting “potential” PP<sub>new</sub> reflects how much each nutrient and each advective source, when considered separately, would contribute to AO new primary production if all was converted into organic carbon through phytoplankton growth (PP<sub>new</sub>). However, since the elemental ratios in source waters depart from the algal requirements observed during blooms, the lowest of the N, P or Si-based estimate of carbon consumption is taken as an upper bound on overall PP<sub>new</sub>. In other words, the first nutrient to be used up limits PP<sub>new</sub> in Liebig’s sense and the other nutrients remain in excess. Utilisation of these “leftovers” can occur where the source waters mix with waters in which other nutrients are in excess. We compare our river-related PP<sub>new</sub> estimates with PP<sub>new</sub> values derived from total primary production rates and f-ratios obtained from field measurements and reported in Sakshaug (2004) for the whole AO and its ancillary shelf seas.

The NO<sub>3</sub> : SRP molar flux ratio varies between seasons and rivers (Fig. 6). During the AO productive season (May to September), the NO<sub>3</sub> : SRP molar flux ratio in the

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Yenisey, Ob, Pechora and Northern Dvina rivers is always below the N : P = 14 : 1 molar consumption ratio in shelf waters (Simpson et al., 2008), but it can lie above the latter in the Lena, Kolyma, Indigirka, Yukon and Mackenzie rivers. NO<sub>3</sub> : SRP molar flux ratios below the N : P = 14 : 1 molar consumption ratio result from SRP or nitrate fluxes respectively higher and lower relative to those from their North-American counterparts (Fig. 3), where nitrate exceeds SRP. In estuaries like in the Mackenzie, SRP is removed in the river and no dissolved inorganic phosphate is supplied to marine waters (Macdonald and Yu, 2006). Hence, other sources of phosphorus are needed for phytoplankton to consume the riverine nitrate such as dissolved organic phosphorus and the admixture of Pacific-derived waters enriched in SRP and silicate relative to nitrate (Yamamoto-Kawai et al., 2006). In late winter prior to the bloom period, SRP is present in excess relative to nitrate in the High AO (N : P : Si = 4.2 : 1 : 13; from Canadian Arctic Shelf Exchange Study and Circumpolar Flaw Lead data) and in the Pacific waters flowing in through Bering Strait (N : P : Si = 5.5 : 1 : 16; from the World Ocean Atlas 2005, National Oceanographic Data Centre, 2006). Integrated over January to March, the molar fluxes of nitrate and SRP entering the AO are respectively  $81 \times 10^9$  mol N and  $15 \times 10^9$  mol P through Bering Strait and  $5.9 \times 10^9$  mol N and  $1.7 \times 10^9$  mol P from rivers. If all nitrate supplied by Bering Strait was taken up by phytoplankton according to a molar consumption ratio of 14 : 1,  $9.2 \times 10^9$  mol P would remain in Pacific-derived waters. This residual stock would increase to  $10.5 \times 10^9$  mol P after taking into account river deliveries of SRP and the complete use of riverine nitrate. The inorganic phosphorus present in Arctic shelf waters is thus sufficient to support the total consumption of inorganic nitrogen brought by rivers as well as Bering Strait.

On an annual basis, the riverine nitrate contribution (< 0.73 %, Table 2) to AO PPnew is small relative to that of the Bering Strait inflow (< 41.2 %), in accord with previous studies (Gordeev et al., 1996; Tank et al., 2011). However, large differences are found across shelf seas (Fig. 7). Rivers contribute the least to PPnew in the Barents Sea (ca. 0.04 %), the Bering Shelf (< 0.12 %) and the East-Siberian Sea (ca. 0.4 %) and the most in the White Sea (ca. 6.2 %). The Kara and the Beaufort seas show

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intermediate values (ca. 2.7–3.3%). Riverine contributions to PPnew are likely to be less than estimated here as potential biological uptake in the estuarine transition zone (e.g. Emmerton et al., 2008) is not included in the calculation.

The  $\text{SiO}_4:\text{NO}_3$  molar flux ratio departs by one to two orders of magnitude from the molar Si:N ratio (1.8) of phytoplankton consumption estimated for the Mackenzie Shelf (Tremblay et al., 2008) and Franklin Bay (Simpson et al., 2008) (Fig. 6). Using a Si:N ratio of 1.8, we assessed how much riverine silicate would be removed by phytoplankton if the entire riverine nitrate pool was used for PPnew (Fig. 8). For the whole AO, ca. 13.5% of the riverine silicate would be removed. This percentage is lower in the East-Siberian Sea, the Beaufort Sea, Bering Shelf and Kara Sea (ca. 6.6%, 8.7%, 9.6% and 13%, respectively) and higher in the Laptev and White seas (ca. 18.1 and 17.5%, respectively). This explains why silicate behaves quasi conservatively when riverine and oceanic waters mix in the coastal zone (Simpson et al., 2008, for the Beaufort Sea; Létolle et al., 1993, for the Laptev Sea). With respect to riverine SRP and using a molar N:P consumption ratio of 14:1, ca. 27.8% of riverine SRP would be removed by phytoplankton across the whole AO if riverine nitrate was fully consumed. The fraction of riverine SRP used by phytoplankton generally increases from the western Eurasian Basin (ca. 18.5%, 21.3% and 21.8% in the Barents, White and Kara seas, respectively) towards its eastern counterpart (ca. 44.4% and 38.4% in the Laptev and Eastern-Siberian seas, respectively) (Fig. 8). By contrast, on the North-American side, riverine SRP does not fulfil phytoplankton requirements and 1.8-fold and 1.2-fold more SRP, likely of oceanic origin, is required to allow riverine nitrate to be fully consumed in the Bering Shelf and Beaufort Sea, respectively. Note that these estimates ignore other processes (e.g. biological uptake, transfer of SRP to the sediment via chemical reactions with iron), which may influence concentrations along the river-coastal ocean transition zone (Macdonald and Yu, 2006). Nevertheless, our result is consistent with the high SRP removal reported in the estuarine transition zone (Emmerton et al., 2008) of the Mackenzie River in the Beaufort Sea.

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So far our analysis ignored the seasonality of riverine fluxes with respect to primary production. The general picture in our data is that the riverine inorganic flux peaks during the phytoplankton bloom period occurring in May–June in Arctic shelf waters. The bloom accounts for ca. 55 % of annual PP (Pabi et al., 1998) and is mostly sustained by nitrate (f-ratio ca. 0.7; e.g. Le Fouest et al., 2011). In summer when phytoplankton face nitrogen or silica limitation (Walsh and McRoy, 1986; Reigstad et al., 2002; Simpson et al., 2008), PP represents ca. 45 % of annual PP (Pabi et al., 1998) and it is mostly regenerated (f-ratio ca. 0.2; e.g. Le Fouest et al., 2012). Here we assessed the effect of seasonality for the Mackenzie shelf, where the inflowing Mackenzie River shows one of the highest annual discharge and riverine nitrate contribution to PP-new (Tables 1 and 2). In this analysis, the contribution of riverine nitrate to PPnew is only 0.92 % (0.028 Tg C) during the bloom (total of ca. 3.1 Tg C) but rises to ca. 4.2 % (0.03 Tg C) in July–October (total of 0.72 Tg C). The corresponding proportions of riverine silicate needed to fully consume riverine nitrate would be ca. 14.3 % (ca.  $0.623 \times 10^9$  mol Si) during the bloom, decreasing to ca. 8.6 % (ca.  $0.702 \times 10^9$  mol Si) afterwards. SRP inputs from the Mackenzie River are not sufficient for phytoplankton to fully take up riverine nitrate. More SRP, likely of oceanic origin, would be required in a larger quantity in May–June (ca. 48 %, ca.  $0.008 \times 10^9$  mol P) than in July–October (ca. 19 %,  $0.004 \times 10^9$  mol P). While riverine nitrate potentially contributes more to summer PPnew, the effect must be confined to surface waters due to the strong seasonal stratification (e.g. Li et al., 2009) and isolated from the productive deep-chlorophyll maximum responsible for most of summer PP. In this respect, riverine nutrient contributions would be limited to the spring bloom period. A possible mismatch between river floods and shelf blooms (e.g. Kahru et al., 2010) might not affect shelf blooms' intensity owing to the small contribution of terrigenous nutrients.

The summer season is characterized by the highest riverine inputs of dissolved and particulate organic matter (Figs. 3 and 4). When averaged for the Ob, Yenisey, Lena, Kolyma and Mackenzie rivers, the mean DOC : POC mass flux ratio lies in the range 3.3–12.5 between July and October indicating the predominant contribution of DOC

versus POC to the organic carbon flux. Conversely, the lower DON : PON mass flux ratio (0.9–1.7) suggests a higher contribution of PON than DON to the organic nitrogen flux. The potential contribution of riverine PON as a significant source of inorganic nitrogen available for phytoplankton growth is, however, limited. The POC : PON molar ratio averaged for July–August for the Ob, Yenisey, Lena, Kolyma and Mackenzie rivers is ca. 11.2 that is twice the bacterial C : N molar ratio (ca. 6–7; Fukuda et al., 1998). High POC : PON molar ratios would promote nitrogen limitation of bacteria attached on riverine particles with, as a consequence, the consumption by bacteria and not oceanic phytoplankton of nitrogen resulting from PON degradation. Measurements made during the Malina project in summer 2009 in the Beaufort Sea showed that PON could also be photo-degraded into ammonium under the action of the ultraviolet radiation (photoammonification process). Nevertheless, the ammonium hereby photo-produced (ca.  $0.002 \text{ mmol N m}^{-2} \text{ d}^{-1}$  in August; Xie et al., 2012) in the upper 10 m is negligible with respect to phytoplankton nitrogen demand for PP ( $> 0.1 \text{ mmol N m}^{-2} \text{ d}^{-1}$  from data of the summer 2009 Malina cruise).

Riverine DON is another substantial source of nitrogen for AO shelf waters (Table 1; see also Holmes et al., 2011). When summing the total riverine fluxes for the Yenisey, Lena, Ob, Mackenzie and Kolyma rivers the input of DON (ca.  $30.3 \times 10^9 \text{ mol N yr}^{-1}$ ) is ca. 6-fold higher than the corresponding input of riverine nitrate (ca.  $4.9 \times 10^3 \text{ mol N yr}^{-1}$ ). But the relative contribution of DON strongly varies amongst rivers. For instance, the DON flux is ca. 12-fold higher than the flux of nitrate in the Laptev Sea but only ca. 6-fold higher in the Kara Sea. The labile fraction of DON is reported to vary from 30 to 40 % in river water (Dittmar et al., 2001; Stepanauskas et al., 2002) to less than 10 % in marine water (Jørgensen et al., 1999; Dittmar et al., 2001). Labile terrigenous DON is actively degraded by marine bacteria (Jørgensen et al., 1999), whereas the refractory pool is either exported to the deep ocean (Dittmar, 2004) or photoammonified and subsequently used by bacteria and phytoplankton (Vähätalo et al., 2011; Le Fouest et al., 2012). Xie et al. (2012) estimated that ca. 16 % of the total refractory DON in surface waters of the Beaufort Sea was

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potentially photoammonified between June and August. From the climatology, ca. 80 % of the combined supply of DON (i.e.  $24.3 \times 10^9$  molN) from the Ob, Yenisey, Lena, Kolyma and Mackenzie rivers takes place between June and August. Applying this rate to this flux, rivers could indirectly supply  $3.9 \times 10^9$  molN in the form of ammonium. This ammonium exceeds the riverine nitrate flux in summer for the same 5 rivers (ca.  $2.3 \times 10^9$  gN for the June–August period from the climatology). For comparison, the June–August riverine ammonium flux summed up for the same 5 rivers is ca.  $0.6 \times 10^9$  molN, hence 6-fold to 11-fold lower. Photoammonification of refractory riverine DON is potentially a greater source of nitrogen for phytoplankton production than the direct combined supply of nitrate and ammonium.

If all the ammonium photo-produced in summer (ca.  $3.9 \times 10^9$  molN) was to be consumed by phytoplankton in shelf waters, the stock of inorganic phosphorus would be ca.  $10.2 \times 10^9$  molP. Even with a projected 50 % increase of riverine DON and nitrate in response to global warming (Frey et al., 2007; McClelland et al., 2007) there would still be sufficiently SRP (ca.  $9.1 \times 10^9$  molP) in shelf waters to sustain the consumption of nitrogen derived from this pool. The sum of the ammonium photo-produced in summer (ca.  $3.9 \times 10^9$  molN) and the total riverine influx of ammonium (ca.  $1.6 \times 10^9$  molN) and nitrate (ca.  $5.9 \times 10^9$  molN) gives an estimated DIN input ranging from ca.  $11.4 \times 10^9$  molN in coastal waters. Assuming no change in the input of SRP and nitrate from Bering Strait or SRP from rivers, an 11-fold increase of riverine DIN supply would be necessary to enable phytoplankton to consume all the SRP present in shelf waters and induce a shift from a nitrogen-limited PP regime to a phosphorus-limited PP regime. These results support the hypothesis of Tremblay and Gagnon (2009) that primary production is nitrogen-limited in the AO and is likely to remain that way in the face of rapid physical changes in the environment.

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## 4 Concluding remarks

In this study we compiled historical measurements of dissolved inorganic nutrients (nitrate, SRP and silicate) and dissolved and particulate organic (carbon and nitrogen) matter from the 9 most important rivers in terms of annual discharge. We used these data to compute time series of monthly averaged concentrations (given in the appendix) and annual fluxes.

From these data, several key points can be emphasized:

1. On an annual basis, riverine nitrate contribution to AO PPnew is negligible (<0.73%) and to <1% to ca. 6.2% regionally. This result is in line with previous studies (Gordeev et al., 1996; Tank et al., 2011);
2. Only ca. 13.5% of the riverine silicate would be removed by phytoplankton at the Arctic scale (ca. 6.6–17.5% regionally) if all riverine nitrate was consumed;
3. Excluding estuarine removal processes from the calculations, ca. 27.8% of the riverine SRP would be removed by phytoplankton at the Arctic scale (ca. 18.5–44.4% regionally) assuming all riverine nitrate was consumed. 1.8-fold and 1.2-fold more SRP from sources other than riverine are required in the Bering Shelf and Beaufort Sea, respectively;
4. On a seasonal basis, the removal of riverine nitrate, silicate and SRP would be the highest in spring and not in summer when AO shelf waters are nitrogen-limited;
5. The AO will likely remain nitrogen-limited even when considering projected increases in the supply of riverine dissolved inorganic and organic nitrogen. An 11-fold increase of riverine DIN supply would be necessary to induce a shift from a nitrogen-limited PP regime to a phosphorus-limited PP regime.

Setting biogeochemical conditions at river points in panarctic physical-biological models is relevant in a context of increasing river discharge (Shiklomanov and Lambers, 2011) and permafrost melt (Frey and Smith, 2005) resulting from the Arctic

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warming. River discharge accounts for ca. 38 % of the Arctic freshwater budget (Serreze et al., 2006) and is equivalent to a 0.5 m layer made of riverine freshwater in the PML (ca. 50 m in average). This freshwater spreads onto the continental plateau, which makes 53 % of the total surface area of the AO and ensures ca. 80 % of total AO PP (Sakshaug, 2004). In addition, there is some evidence of an increase in riverine nitrate concentration per unit of discharge in the western Arctic (McClelland et al., 2007) and future projections suggest that riverine nutrient inputs will increase substantially by the end of this century. In West Siberia, predicted warming has been linked to a probable increase of riverine total dissolved nitrogen and DON by 30–50 % and 32–53 %, respectively (Frey and al., 2007). Nevertheless, more data relative to Arctic rivers DON and DOC lability and trophic pathways (e.g. balance between autotrophic and heterotrophic processes) are needed to accurately assess their effect on shelf biogeochemistry (e.g. McClelland et al., 2012). Dissolved silica mobilization into the North-American Arctic river system is also projected to increase between 35 % and 70 % (Moosdorf et al., 2010) but it might impact new primary production in North Atlantic waters rather than the Arctic waters. This analysis underscores the need to better contrast oceanic nutrient supply processes (i.e. mixing, upwellings and mesoscale activity) with the composition and fate of changing riverine nutrient deliveries in future scenarios of plankton community structure, function and production in the coastal AO.

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**Table 1.** Annual discharge of freshwater, dissolved inorganic nutrients (nitrate, silicate and soluble reactive phosphate) and dissolved organic carbon (DOC) and nitrogen (DON) for 9 rivers entering the Arctic Ocean. Estimates calculated from the discharge and nutrients measured at the same station are in bold. Between brackets is the number of months accounted in calculations.

		Discharge km <sup>3</sup> yr <sup>-1</sup>	NO <sub>3</sub> 10 <sup>9</sup> gN	SiO <sub>2</sub> 10 <sup>9</sup> gSi	SRP 10 <sup>9</sup> gP	DOC 10 <sup>9</sup> gC	DON 10 <sup>9</sup> gN	POC 10 <sup>9</sup> gC	PON 10 <sup>9</sup> gN
Yenisey	<b>Climatology</b> <sup>1a</sup>	<b>580</b>	<b>19.7</b> <sup>(9.91%)</sup>	<b>699</b> <sup>(9.91%)</sup>	<b>13.3</b> <sup>(9.91%)</sup>	<b>n.d.</b>	<b>n.d.</b>	<b>n.d.</b>	<b>n.d.</b>
	Climatology <sup>1b</sup>	580	21.1 <sup>(9.91%)</sup>	1123 <sup>(7.77%)</sup>	5 <sup>(8.89%)</sup>	3616 <sup>(7.77%)</sup>	110 <sup>(7.77%)</sup>	190 <sup>(7.77%)</sup>	27 <sup>(8.79%)</sup>
	Gordeev et al. (1996), Gordeev and Kravchishina (2009)	620	8.7	1857	5.8	4860	n.d.	170	n.d.
	Holmes et al. (2000)	577	18.4	n.d.	6.2	n.d.	n.d.	n.d.	n.d.
	Dittmar and Kattner (2003) Holmes et al. (2011)	562–577 636	n.d. 49	200–1223 1740	n.d. n.d.	4100–4900 4645	82 111	170 n.d.	17 n.d.
Lena	Climatology <sup>2a</sup>	529	9.7 <sup>(7.64%)</sup>	701 <sup>(7.64%)</sup>	4.3 <sup>(4.55%)</sup>	4000 <sup>(7.64%)</sup>	111 <sup>(7.64%)</sup>	727 <sup>(8.76%)</sup>	72 <sup>(8.76%)</sup>
	<b>Climatology</b> <sup>2b</sup>	<b>529</b>	<b>15.4</b> <sup>(6.93%)</sup>	<b>306</b> <sup>(6.93%)</sup>	<b>4.5</b> <sup>(6.93%)</sup>	<b>n.d.</b>	<b>n.d.</b>	<b>n.d.</b>	<b>n.d.</b>
	<b>Climatology</b> <sup>2c</sup>	<b>486</b>	<b>9.2</b> <sup>(6.59%)</sup>	<b>197</b> <sup>(6.59%)</sup>	<b>5.5</b> <sup>(6.59%)</sup>	<b>n.d.</b>	<b>n.d.</b>	<b>n.d.</b>	<b>n.d.</b>
	Gordeev et al. (1996), Gordeev and Kravchishina (2009)	525	22	1029	4.9	3600	243	1200	n.d.
	Holmes et al. (2000) Dittmar and Kattner (2003) Holmes et al. (2011)	532 524–533 581	19.5 n.d. 24	n.d. 890–1640 1347	3.5 n.d. n.d.	n.d. 3400–4700 5681	n.d. 80–245 135	n.d. 470 n.d.	n.d. 54 n.d.
Ob	<b>Climatology</b> <sup>3</sup>	<b>596</b>	<b>22</b> <sup>(12.100%)</sup>	<b>494</b> <sup>(12.100%)</sup>	<b>18</b> <sup>(9.90%)</sup>	<b>3471</b> <sup>(10.94%)</sup>	<b>108</b> <sup>(9.92%)</sup>	<b>650</b> <sup>(9.90%)</sup>	<b>82</b> <sup>(9.90%)</sup>
	Gordeev et al. (1996), Gordeev and Kravchishina (2009)	429	9.4	1929	18.2	3680	n.d.	360	n.d.
	Holmes et al. (2000)	404	34.8	n.d.	23.5	n.d.	n.d.	n.d.	n.d.
	Dittmar and Kattner (2003)	404–419	n.d.	311	n.d.	3100–3200	66	310–600	28–54
	Holmes et al. (2011)	427	57	1453	n.d.	4119	110	n.d.	n.d.
Mackenzie	<b>Climatology</b> <sup>4</sup>	<b>285</b>	<b>11.2</b> <sup>(5.74%)</sup>	<b>464</b> <sup>(12.100%)</sup>	<b>1.5</b> <sup>(12.100%)</sup>	<b>1234</b> <sup>(6.74%)</sup>	<b>41.3</b> <sup>(6.61%)</sup>	<b>447</b> <sup>(5.61%)</sup>	<b>29</b> <sup>(5.61%)</sup>
	Gordeev et al. (1996)	249	12.5	467	1.5	n.d.	n.d.	n.d.	n.d.
	Dittmar and Kattner (2003)	249–333	n.d.	470	n.d.	1300	27	1800–2100	160–190
	Holmes et al. (2011)	298	24	554	n.d.	1377	31	n.d.	n.d.

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Table 1. Continued.

		Discharge km <sup>3</sup> yr <sup>-1</sup>	NO <sub>3</sub> 10 <sup>9</sup> gN	SiO <sub>2</sub> 10 <sup>9</sup> gSi	SRP 10 <sup>9</sup> gP	DOC 10 <sup>9</sup> gC	DON 10 <sup>9</sup> gN	POC 10 <sup>9</sup> gC	PON 10 <sup>9</sup> gN
Yukon	<b>Climatology</b> <sup>5</sup>	<b>204</b>	<b>16</b> <sup>(9.91%)</sup>	<b>601</b> <sup>(11.95%)</sup>	<b>1.4</b> <sup>(9.84%)</sup>	<b>1279</b> <sup>(10.92%)</sup>	<b>31</b> <sup>(8.81%)</sup>	<b>406</b> <sup>(8.81%)</sup>	<b>44</b> <sup>(8.81%)</sup>
	Holmes et al. (2011)	208	24	694	n.d.	1472	47	n.d.	n.d.
Pechora	<b>Climatology</b> <sup>6</sup>	<b>137</b>	<b>4.7</b> <sup>(12.100%)</sup>	<b>n.d.</b>	<b>4</b> <sup>(12.100%)</sup>	<b>n.d.</b>	<b>n.d.</b>	<b>n.d.</b>	<b>n.d.</b>
	Gordeev et al. (1996), Gordeev and Kravchishina (2009)	131	9.1	400	1.62	1666	n.d.	40	n.d.
	Dittmar and Kattner (2003)	135	n.d	n.d	n.d	2100	44	n.d.	n.d.
	Holmes et al. (2000)	135	7.1	n.d.	4.2	n.d.	n.d.	n.d.	n.d.
Northern Dvina	<b>Climatology</b> <sup>7a</sup>	<b>105</b>	<b>5.1</b> <sup>(12.100%)</sup>	<b>105</b> <sup>(12.100%)</sup>	<b>3.8</b> <sup>(12.100%)</sup>	<b>n.d.</b>	<b>n.d.</b>	<b>n.d.</b>	<b>n.d.</b>
	<b>Climatology</b> <sup>7b</sup>	105	5.1 <sup>(12.100%)</sup>	n.d.	1.8 <sup>(12.100%)</sup>	n.d.	n.d.	n.d.	n.d.
	Gordeev et al. (1996), Gordeev and Kravchishina (2009)	110	9.2	388	2	1280	n.d.	28	n.d.
	Dittmar and Kattner (2003)	106	n.d.	n.d.	n.d.	1700	35	n.d.	n.d.
	Holmes et al. (2000)	105	6.7	n.d.	2	n.d.	n.d.	n.d.	n.d.
Kolyma	<b>Climatology</b> <sup>8a</sup>	<b>103</b>	<b>3.4</b> <sup>(8.97%)</sup>	<b>n.d.</b>	<b>1.9</b> <sup>(7.96%)</sup>	<b>n.d.</b>	<b>n.d.</b>	<b>n.d.</b>	<b>n.d.</b>
	<b>Climatology</b> <sup>8b</sup>	103	3.7 <sup>(7.93%)</sup>	188 <sup>(7.93%)</sup>	0.58 <sup>(8.97%)</sup>	633 <sup>(10.95%)</sup>	16.4 <sup>(7.93%)</sup>	90 <sup>(7.93%)</sup>	12 <sup>(6.88%)</sup>
	Gordeev et al. (1996), Gordeev and Kravchishina (2009)	132	3.7	248	1.22	740	52.8	380	n.d.
	Holmes et al. (2000)	70	2.5	n.d.	0.76	n.d.	n.d.	n.d.	n.d.
	Dittmar and Kattner (2003)	71–98	n.d.	n.d.	n.d.	460–700	16	310	34
	Holmes et al. (2011)	111	5	276	n.d.	818	17	n.d.	n.d.
Indigirka	<b>Climatology</b> <sup>9</sup>	<b>50</b>	<b>2</b> <sup>(7.99%)</sup>	<b>n.d.</b>	<b>0.34</b> <sup>(6.98%)</sup>	<b>n.d.</b>	<b>n.d.</b>	<b>n.d.</b>	<b>n.d.</b>
	Dittmar and Kattner (2003)	50	n.d.	0.7	n.d.	240–400	8.4	170	24
	Holmes et al. (2000)	50	2.3	n.d.	0.35	n.d.	n.d.	n.d.	n.d.
	Gordeev et al. (1996)	61	1.7	80	0.4	n.d.	24.4	n.d.	n.d.

<sup>1a</sup> discharge at Igarka, DIN/DOC/DON at Igarka  
<sup>1b</sup> discharge at Igarka, DIN/DOC/DON at Dudinka (ca. 250 km downstream Igarka)  
<sup>2a</sup> discharge at Kyusur, DIN/DOC/DON at Zhigansk  
<sup>2b</sup> discharge at Kyusur, DIN/DOC/DON at Kyusur (ca. 400 km downstream Zhigansk)  
<sup>2c</sup> discharge at Stolb, DIN/DOC/DON near Stolb (delta ca. 520 km downstream Zhigansk)  
<sup>3</sup> discharge at Salekhard, DIN/DOC/DON at Salekhard  
<sup>4</sup> discharge at Red Arctic, DIN/DOC/DON at Tsiighehtchic  
<sup>5</sup> discharge at Pilot Station, DIN/DOC/DON at Pilot Station  
<sup>6</sup> discharge at Oksino, DIN/DOC/DON at Oksino  
<sup>7a</sup> discharge at Ust'Pinega, DIN/DOC/DON at Ust'Pinega  
<sup>7b</sup> discharge at Ust'Pinega, DIN/DOC/DON at Arkhangelsk (ca. 60 km downstream Ust'Pinega)  
<sup>8a</sup> discharge at Kolymskoye, DIN/DOC/DON at Kolymskoye  
<sup>8b</sup> discharge at Kolymskoye, DIN/DOC/DON at Cherskii (ca. 120 km downstream Kolymskoye)  
<sup>9</sup> discharge at Vorontsovo, DIN/DOC/DON at Chokurdakh (ca. 100 km downstream Vorontsovo)



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**Table 2.** Annual primary production (total and new), riverine nitrate flux and contribution of riverine nitrate to new primary production for the High Arctic Ocean and its river-influenced shelf seas.

	PP (TgC) <sup>1</sup>	f-ratio <sup>1</sup>	PPnew (TgC) <sup>1</sup>	Riverine nitrate flux (10 <sup>9</sup> gN)	Riverine nitrate flux in carbon equivalent (TgC)	Riverine nitrate contribution to PPnew (%)
High Arctic Ocean	> 329	0.2	> 65.8	84.9	0.48	< 0.73
Barents Sea	136	0.5	68	4.7	0.03	0.04
White Sea	2	0.24	0.48	5.1	0.03	6.2
Kara Sea	37	0.24	8.9	43.1	0.24	2.7
Laptev Sea	16	0.25	4	15.4	0.09	2.2
East-Siberian Sea	30	0.25	7.5	5.4	0.03	0.4
Bering Shelf	> 300	0.25–0.4	75–120	16	0.09	0.07–0.12
Beaufort Sea	8	0.24	1.9	11.2	0.06	3.3

<sup>1</sup>From Sakshaug (2004)

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**Table A1.** Monthly climatology of nitrate ( $\text{mmol N m}^{-3}$ ).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Northern Dvina <sup>a</sup>	7.8	17.1	16.4	21.5	1.6	1.2	1.0	0.9	1.0	1.0	2.2	4.7
Northern Dvina <sup>b</sup>	7.4	14.1	14.6	16.6	2.0	0.8	1.3	1.6	1.3	1.7	3.6	8.8
Pechora	8.0	14.8	12.3	12.8	2.9	1.6	0.7	1.1	1.0	1.7	2.9	3.0
Yenisey <sup>c</sup>		0.7	18.2	12.1	6.5	1.1	1.0	1.0	1.1	1.1		
Yenisey <sup>d</sup>			15.9	5.6	4.2	2.0	1.4	1.0	1.2	1.8	8.3	
Ob	7.8	9.4	10.7	7.9	10.7	3.8	1.0	1.1	1.3	3.6	3.5	7.4
Lena <sup>e</sup>			15.1	16.0	4.3	1.4		1.0		2.4	4.5	
Lena <sup>f</sup>					8.0	3.1	1.1	1.7	1.2	1.3		
Lena <sup>g</sup>				5.3	9.5		1.3	1.6	2.9	1.8		
Indigirka				9.3	4.8	4.5	1.4	2.7	2.7	1.9		
Kolyma <sup>h</sup>			10.7	6.5	4.7	2.8	1.5	2.1	2.0	2.4		
Kolyma <sup>i</sup>				6.0	5.0	2.4	4.1	1.7	2.2		2.6	
Yukon	13.4		16.1	13.7	7.7	5.0	5.3	4.4	8.3	5.0		
Mackenzie			7.3		4.1	3.7	3.4	3.3	3.9			

<sup>a</sup>Ust'Pinega<sup>b</sup>Arkhangelsk<sup>c</sup>Igarka<sup>d</sup>Dudinka<sup>e</sup>Zhigansk<sup>f</sup>Kyusur<sup>g</sup>Stolb<sup>h</sup>Kolymskoye<sup>i</sup>Cherskii

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**Table A2.** Monthly climatology of SRP ( $\text{mmol P m}^{-3}$ ).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Northern Dvina <sup>a</sup>	1.21	1.24	1.52	1.36	1.36	1.01	0.90	0.89	0.98	0.84	0.92	1.33
Northern Dvina <sup>b</sup>	0.58	0.74	0.90	0.86	0.44	0.42	0.42	0.65	0.53	0.50	0.89	0.70
Pechora	1.54	1.19	1.29	0.98	1.20	0.69	0.88	0.95	0.91	1.12	1.02	1.09
Yenisey <sup>c</sup>		0.58	1.10	1.69	0.88	0.86	0.60	0.80	0.62	0.67		
Yenisey <sup>d</sup>				0.23	0.38	0.33	0.28	0.26	0.30	0.33	0.17	
Ob			2.49	2.83	1.09	0.78	1.92	1.98	2.77	1.77		0.60
Lena <sup>e</sup>					0.23	0.25		0.27			0.25	
Lena <sup>f</sup>					0.24	0.43	0.21	0.18	0.25	0.23		
Lena <sup>g</sup>				0.38	0.39		0.37	0.56	1.30	0.49		
Indigirka					0.26	0.20	0.14	0.24	0.37	0.37		
Kolyma <sup>h</sup>				0.14	0.35	0.95	0.33	0.58	0.49	0.27		
Kolyma <sup>i</sup>				0.06	0.24	0.18	0.17	0.23	0.22	0.10	0.07	
Yukon	0.17		0.46	0.22	0.18	0.30	0.20	0.14	0.29			0.97
Mackenzie	0.11	0.11	0.11	0.14	0.37	0.27	0.25	0.18	0.14	0.14	0.13	0.12

<sup>a</sup>Ust' Pinega

<sup>b</sup>Arkhangelsk

<sup>c</sup>Igarka

<sup>d</sup>Dudinka

<sup>e</sup>Zhigansk

<sup>f</sup>Kyusur

<sup>g</sup>Stolb

<sup>h</sup>Kolymskoye

<sup>i</sup>Cherskii





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**Table A5.** Monthly climatology of DOC ( $\text{mmol C m}^{-3}$ ).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Yenisey <sup>a</sup>			265			827	753	465	441	583	334	
Ob			616	458	589	696	942	857	849	708	889	605
Lena <sup>b</sup>			700	558	946	1252		577		589	684	
Kolyma <sup>c</sup>	212		223	311	456	797	463	316	312		307	196
Yukon	245	241	234	219	842	759	464	382	459	710		
Mackenzie			379		740	559	403	381	345			

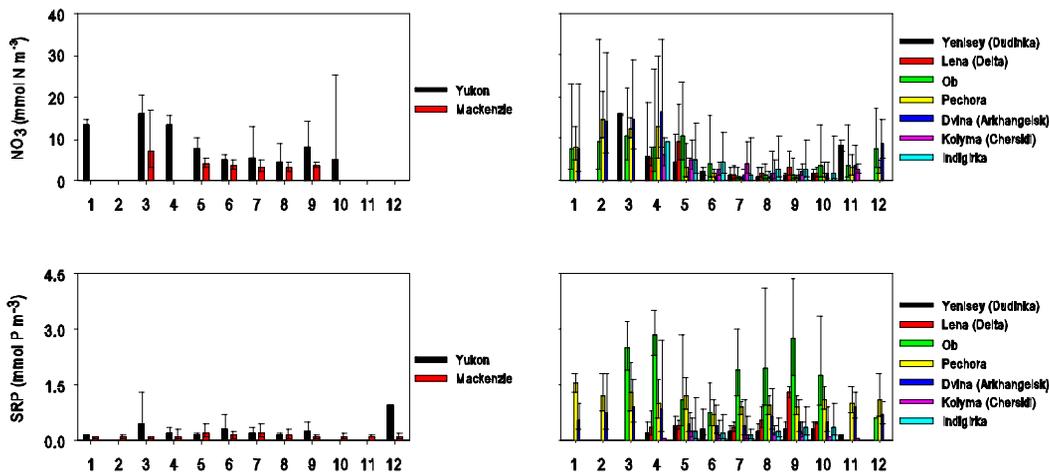
<sup>a</sup>Dudinka

<sup>b</sup>Zhigansk

<sup>c</sup>Cherskii

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**Fig. 1.** Monthly climatologies of nitrate, SRP, silicate, DOC and DON for 2 North-American and 7 Eurasian rivers.

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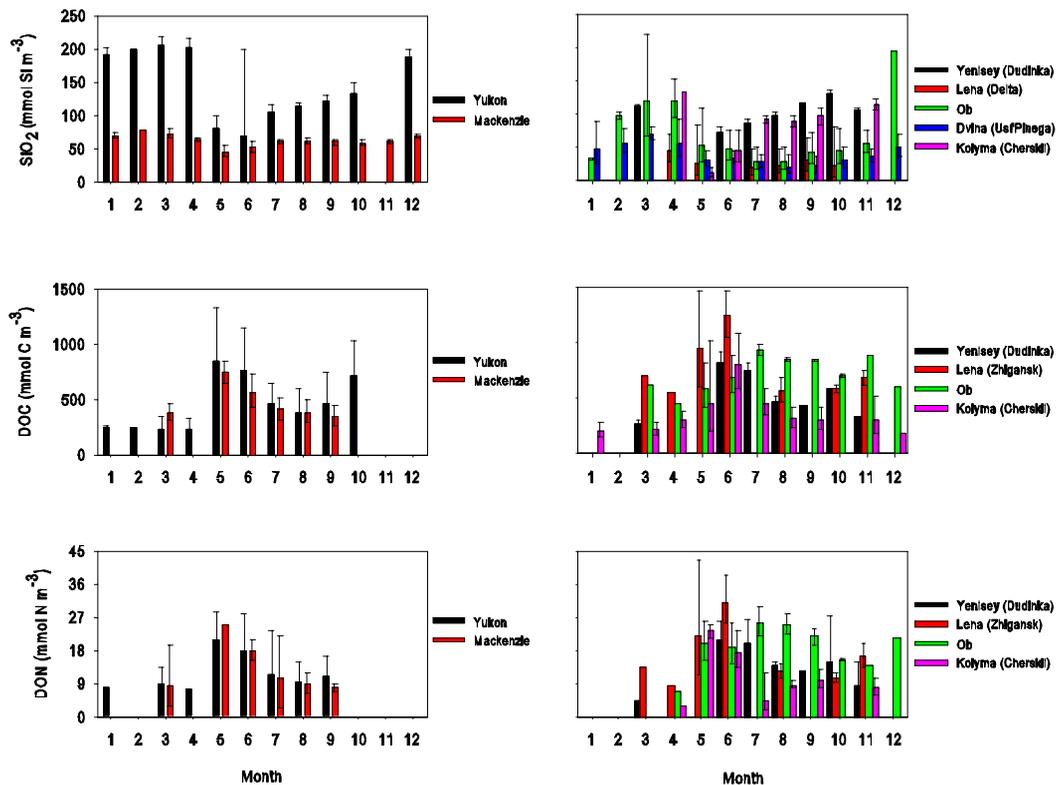


Fig. 1. Continued.

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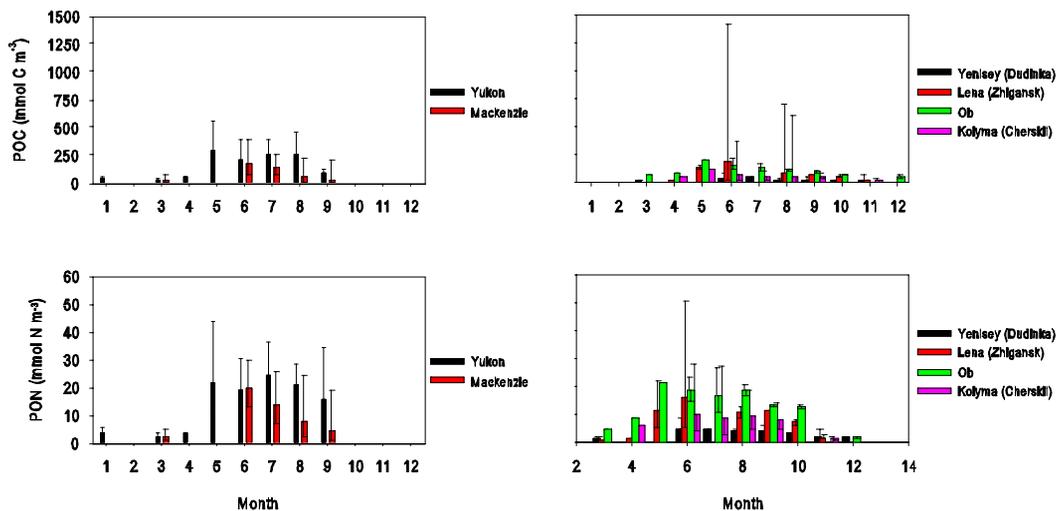
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**Fig. 2.** Monthly climatology of POC and PON for 2 North-American and 7 Eurasian rivers.

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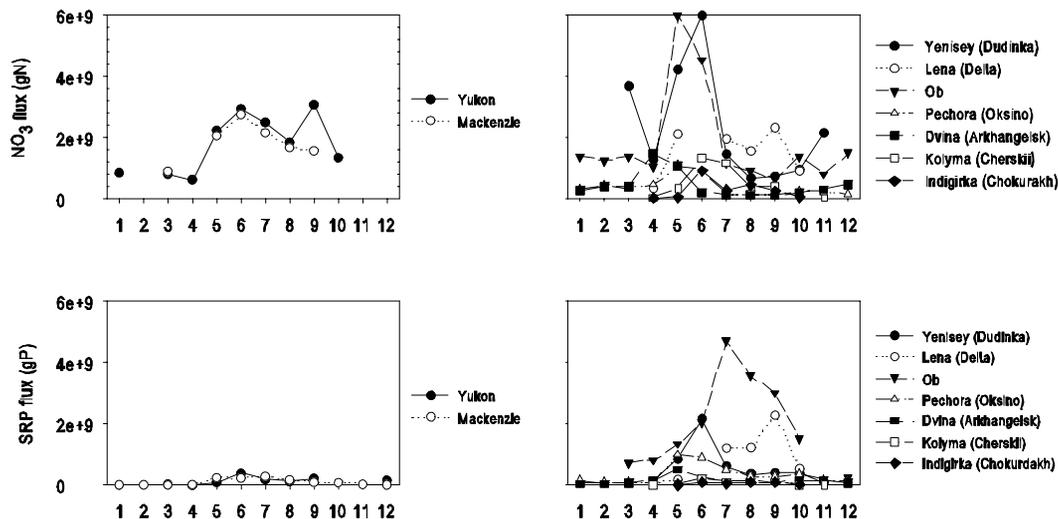


Fig. 3. Time course of the nitrate, SRP, silicate, DOC and DON flux for 2 North-American and 7 Eurasian rivers.

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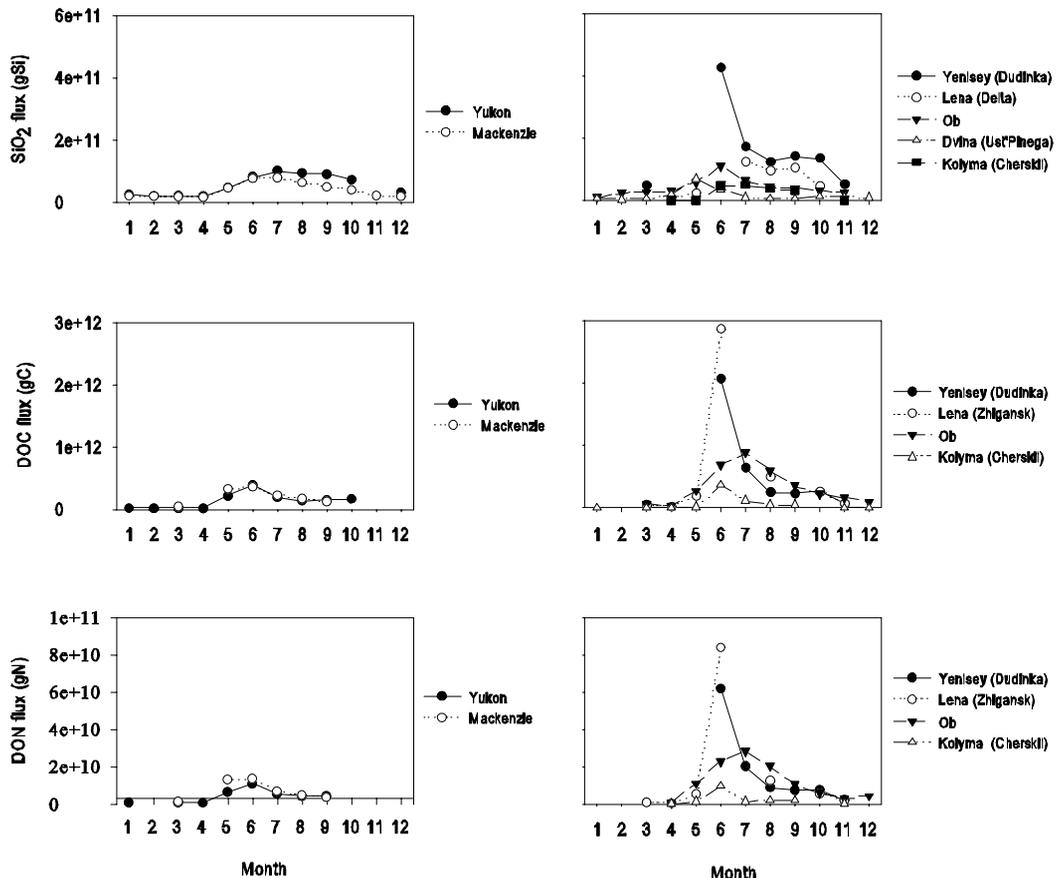


Fig. 3. Continued.

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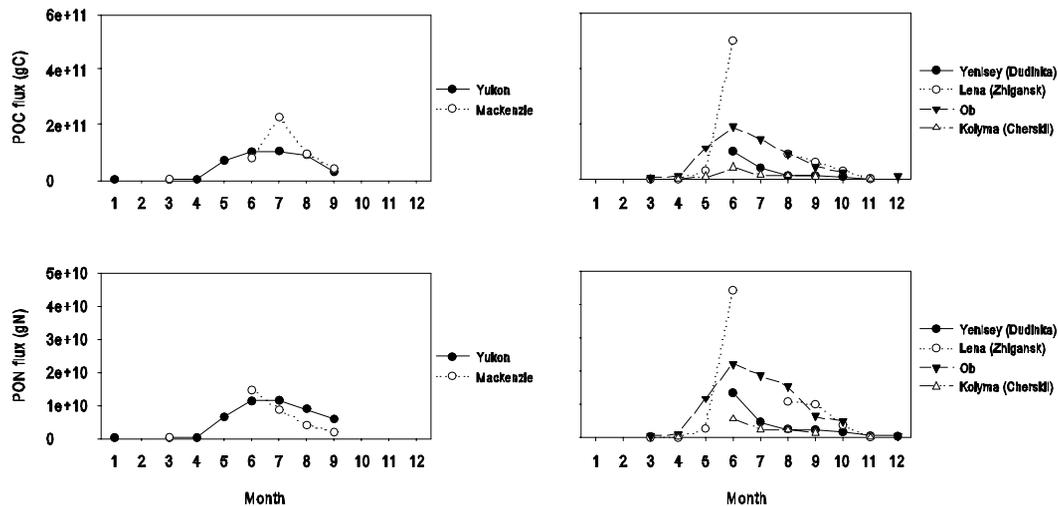


Fig. 4. Time course of the POC and DON flux for 2 North-American and 7 Eurasian rivers.

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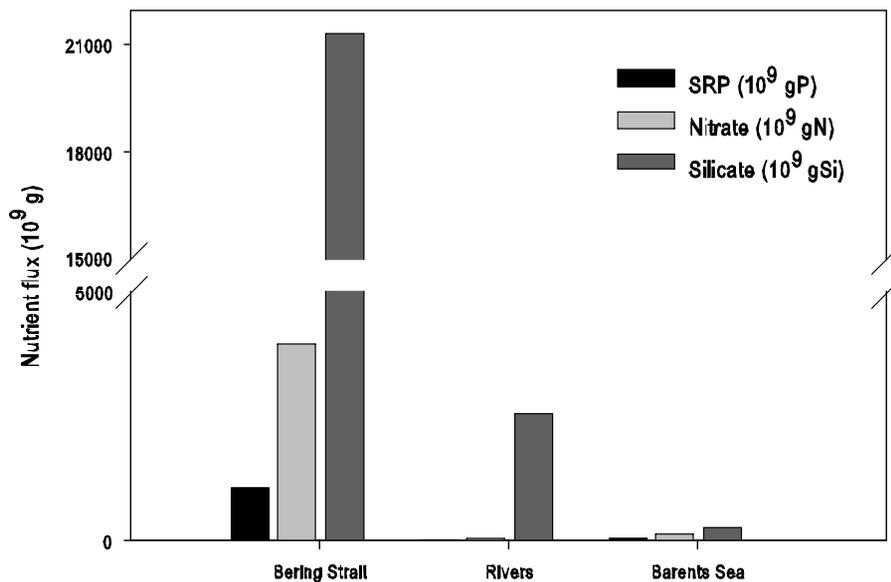
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**Fig. 5.** Annual lateral influx of SRP ( $10^9$  gP), nitrate ( $10^9$  gN) and silicate ( $10^9$  gSi) from Bering Strait, 8 panarctic rivers (see text for details) and the Barents Sea.

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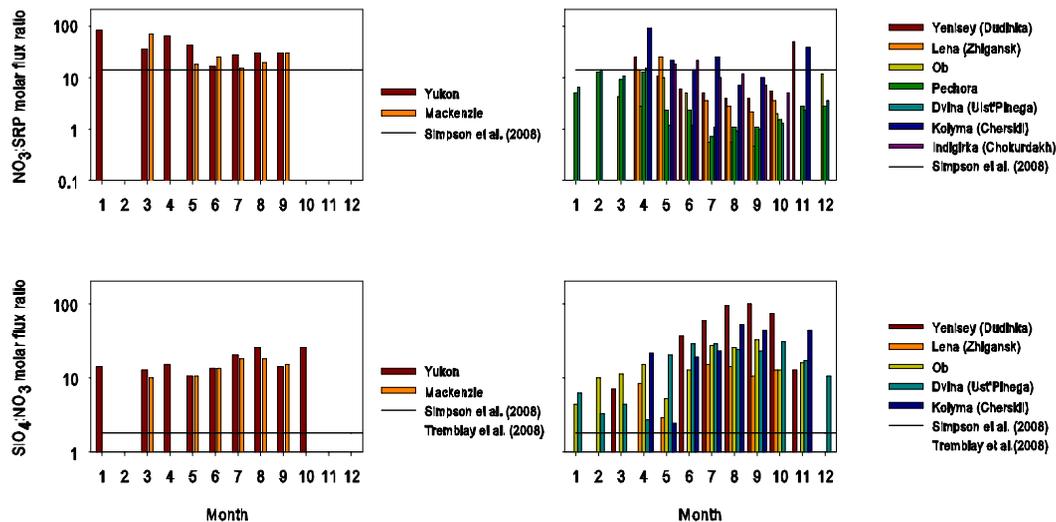
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**Fig. 6.** Time course of  $\text{NO}_3:\text{SRP}$  and  $\text{SiO}_4:\text{NO}_3$  molar fluxes for 2 North-American and 7 Eurasian rivers.

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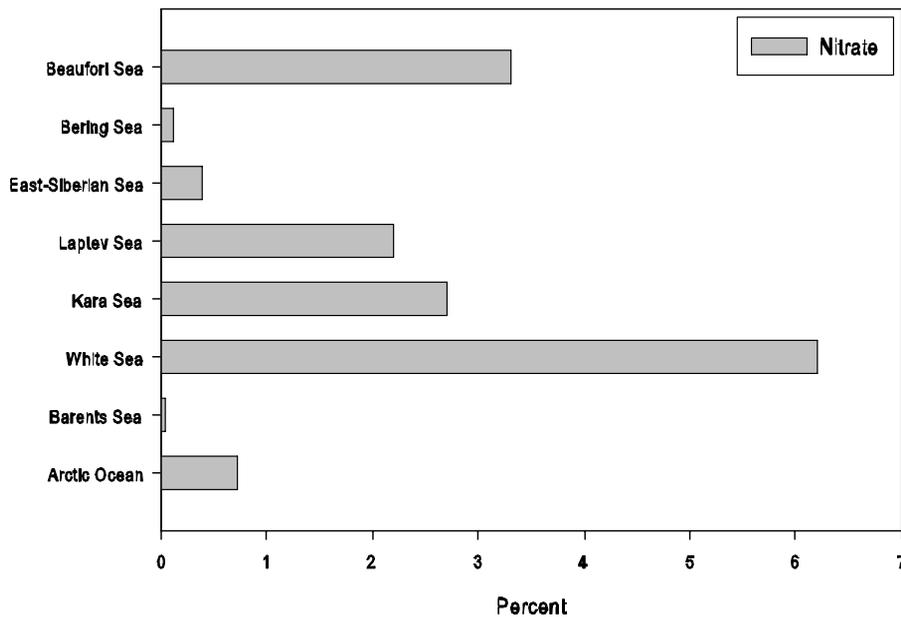
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**Fig. 7.** Contribution of riverine nitrate to new primary production.

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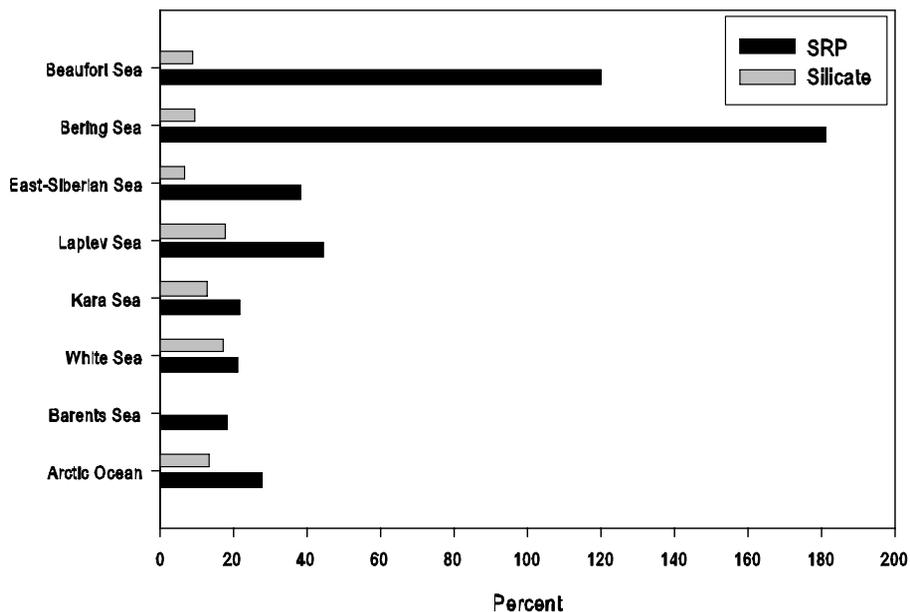
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## The fate of riverine nutrients

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**Fig. 8.** Fraction of riverine SRP and silicate consumed by phytoplankton in case all riverine nitrate is taken up. Note there were no silicate data for the East-Siberian Sea and Barents Sea rivers.

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