**Biogeosciences
Discussions**

Interactive comment on "The fate of riverine nutrients on Arctic shelves" *by* V. Le Fouest et al.

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We gratefully thank referee #1 for her/his constructive comments with respect to our manuscript results, discussion and conclusion. In order to improve the manuscript with respect to these comments, we amended the manuscript as suggested by the referee wherever it was possible. Note that, when needed, comments were merged together to bring more clarity in the answer:

1) "Calculating annual inputs without interpolating values for missing months results in under-estimation."

In order to overcome this issue, nutrients concentrations were linearly interpolated for missing months. Tables 1 and A1-A5 were corrected accordingly. Note that we also added two more tables in the appendix to include POC and PON data. The 8 new tables are given in the file providing supplementary material.

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Page 13402 (lines 19-21): the sentences "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" were hence removed.

As a result of the interpolation procedure, several sections of the text have been modified accordingly (mostly values calculated without any data interpolation). These modifications, however, did not affect the main results and conclusions:

Page 13406 (line 15): annual fluxes, instead of January to March integrated fluxes as mentioned in the text, were given by mistake for nitrate and SRP. The erroneous values were replaced by the appropriate ones: "Integrated over January to March, the molar fluxes of nitrate and SRP entering the AO are respectively 81x109 mol N and 15x109 mol P through Bering Strait and 1.4x109 mol N and 0.1x109 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, 9.2x109 mol P would remain in Pacific-derived waters." The following sentence "This residual stock would increase to 10.5x109 mol P after taking into account river deliveries of SRP and the complete use of riverine nitrate" was removed as it did not apply anymore with the corrected values.

Page 13407 (line 15): "For the whole AO, 14.3% of the riverine silicate would be removed. This percentage is lower in the East-Siberian Sea, the Beaufort Sea, Bering Shelf and Kara Sea (9.7%, 8.7%, 9.6% and 11.4%, respectively) and higher in the Laptev and White seas (24.5% 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, 28.9% 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 (18.6%, 21.2% and 19.8% in the Barents, White and Kara seas, respectively) towards its eastern counterpart (46% 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 1.6-fold and 1.8-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."

Page 13408 (line 11): "In this analysis, the contribution of riverine nitrate to PPnew is only 0.92% (0.028 Tg C) during the bloom (total of 3.1 Tg C) but rises to 5.5% (0.04 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 14.5% (0.634×10^9 mol Si) during the bloom, decreasing to 9.6% (0.905×10^9 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 July-October (56%, 0.013×10^9 mol P) than in May-June (48%, 0.008×10^9 mol P)."

Page 13408 (line 27): "In the Ob, Yenisey, Lena, Kolyma and Mackenzie rivers, the mean DOC:POC mass flux ratio lies in the range 2.8-24.2 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 (0.5-4.3) 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. 9.1 that is higher than the bacterial C:N molar ratio (5-7; Anderson and Williams 1998; Fukuda et al., 1998). Higher 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 riverine PON degradation."

Page 13409 (line 16): "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 (33.7×10^9 mol N yr^{-1}) is ca. 5-fold higher than the corresponding input of riverine nitrate (6.8×10^9 mol N yr^{-1}). But the relative contribution of DON varies amongst rivers.

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For instance, the DON flux is 7-fold higher than the flux of nitrate in the Laptev Sea but only 3-fold higher in the Beaufort Sea."

Page 13410 (line 1): "From the data, ca. 70% of the combined supply of DON (i.e. 23.4×10^9 mol N) 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 3.9×10^9 mol N in the form of ammonium. This ammonium exceeds the riverine nitrate flux in summer for the same 5 rivers (ca. 2.8×10^9 g N for the June-August period from the data). For comparison, the June-August riverine ammonium flux summed up for the same 5 rivers is only ca. 0.6×10^9 mol N."

Page 13410 (line 11): "If all the ammonium photo-produced in summer (3.9×10^9 mol N) was to be consumed by phytoplankton in shelf waters, the stock of inorganic phosphorus would be 8.92×10^9 mol P. 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 (8.05×10^9 mol P) in shelf waters to sustain the consumption of nitrogen derived from this pool. The sum of the ammonium photo-produced in summer (3.9×10^9 mol N) and the annual riverine influx of ammonium (3.5×10^9 mol N) and nitrate (6.8×10^9 mol N) gives an estimated DIN input ranging from 14.2×10^9 mol N in coastal waters. Assuming no change in the input of SRP and nitrate from Bering Strait or SRP from rivers, a 9-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."

Page 13411 (line 8): "1. On an annual basis, riverine nitrate contribution to AO PPnew is negligible (<0.83%) and to <1% to 6.7% regionally. This result is in line with previous studies (Gordeev et al., 1996; Tank et al., 2011); 2. Only 14.3% of the riverine silicate would be removed by phytoplankton at the Arctic scale (8.7-24.5% regionally) if all riverine nitrate was consumed; 3. Excluding estuarine removal processes from the calculations, 28.9% of the riverine SRP would be removed by phytoplankton at the Arctic scale (18.6-46% regionally) assuming all riverine nitrate was consumed. 1.6-

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fold and 1.8-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. A 9-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."

2) "One drawback is that different methods, sampling locations, timeframes, and errors associated with various data sources make it difficult to assess overall uncertainty with respect to the input estimates that the authors ultimately use for calculating how much primary production is supported."

"On the primary production side, it would be helpful to consider not only riverine influence at the large scale (shelf areas and entire Arctic Ocean basin) but also effects more closely associated with the river input locations."

"Results and discussion, section 3.2. Consider using a range of input values rather than a single estimate for each river to calculate potential effects on primary production. Using a range of input values would convey some sense of the uncertainty associated with the calculations and help show that your general conclusions are robust despite that uncertainty. Also, given that the rivers used in the study only represent a proportion of the total inputs from rivers to the various shelf regions, the authors need to make it clear that their estimates of how much primary production is supported by river inputs represents a lower bound (and provide at least a semi-quantitative estimate of how much primary production might be supported if all river inputs were accounted for)."

In order to account for the overall uncertainty on interpolated riverine nitrate concentrations, we computed monthly averages of nitrate $\pm$ standard deviation for each river sampling location. We thereafter introduced a range of contribution of riverine nitrate to marine primary production in Table 2. The new Table 2 is given in the file providing

supplementary material.

The text was hence adapted accordingly:

Page 13406 (line 24): "On an annual basis, the mean riverine nitrate contribution to AO PPnew (<0.83%, Table2) 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 (0.04%), the Bering Shelf (0.11%) and the East-Siberian Sea (0.4%), and the most in the White Sea (6.7%). The Kara and the Beaufort seas show intermediate values (2.7-4.7%). Accounting for the higher range of uncertainty relative to nitrate concentrations makes this contribution to PPnew rise to 6.7-8.3% in the White, Kara, Laptev and Beaufort seas. However, the 9 most important rivers taken into account in this study only represent a fraction of the total continental freshwater flow into shelf seas. Using total (i.e. river and groundwater) freswater discharge esti-mates from literature, and assuming a proportional relationships with the mean nitrate flux given in Table 1, we can provide a coarse estimate of how much PPnew might be supported in shelf seas if all continental inputs of freshwater were accounted for. The total discharge (river + groundwater) is estimated to 1630 Km3 yr-1, 802 Km3 yr-1, and 267 Km3 yr-1 in the Kara, Laptev and East-Siberian seas, respectively (Gordeev et al., 1999). This is respectively 38%, 60% and 57% more than the freshwater discharge by the Ob and Yenisey rivers, the Lena River, and the Kolyma and Indigarka rivers. In the Beaufort Sea, the Colville River, second most important river after the Mackenzie River (285 Km3 yr-1), has a discharge of ca. 15 Km3 yr-1 (source: USGS). Accounting for the total freshwater discharge in shelf seas, the mean riverine nitrate contribution to PPnew would rise to 3.8% (Kara Sea), 5.4% (Laptev Sea), 0.8% (East-Siberian Sea) and 5.3% (Beaufort Sea) but would still remain relatively low. Nevertheless, it could be much larger at local scale. Based on ocean color data, PPnew close to the mouth of Mackenzie River would reach up to 0.24 Tg C yr-1 (S. Bélanger, pers. comm.). Here, riverine nitrate would meet, in average, 37% of phytoplankton nitrogen requirements.

Note, however, that this contribution to PPnew is probably 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."

3) "The method used by the authors to estimate annual river inputs also introduces bias in two distinct ways. First, monthly binning does not allow for coupled variations in concentration and water discharge within months. For constituents that are positively correlated with discharge this leads to under-estimation. For constituents that are negatively correlated with discharge this leads to over-estimation."

"Uncertainty associated with different data sets and underestimation of fluxes associated with calculation methods are mentioned briefly in the manuscript, but more thorough treatment of these issues is needed."

We agree on the need to develop this issue. We hence modified the text as follows: Page 13403 (line 25): "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 and interannual variability in discharge (Holmes et al., 2011), which can alter concentrations, in calculating monthly averages likely contributed to the large standard deviations and impacted nutrient flux estimations. Furthermore, the monthly binning procedure in calculating nutrients fluxes prevented any coupled variations in nutrients concentrations and water discharge within month. For constituents that are positively (negatively) correlated with discharge this leads to under-estimation (over-estimation). Nevertheless, 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, Lena, Northern Dvina and Kolyma rivers showed differences for SRP, silicate and, but to a lesser extent, for nitrate. These differences may result, as mentioned above, from uncoupled variations between nutrients concentrations and wa-

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ter discharge in the flux calculation, and/or from differences in data "quality" amongst datasets (e.g. Holmes et al., 2001). Note that using older datasets did not necessarily translate into higher uncertainty in fluxes. For instance, in the Lena River, the mean annual fluxes of SRP at Zhigansk and Kyusur are similar using either recent (A-GRO [2009-2010]) or older datasets (GEMS/WATER [1984-1992] and OGSNK/GSN [1984-1995]) (Table 1). This is, however, not the case for silicate (Table 1). Differences can also be partly explained by discontinuities within the rivers' watersheds (Frey et al., 2009; Gustafsson et al., 2011). In the Lena River, Semiletov et al. (2011) report a substantial variation in Si and total organic carbon concentrations (20% and 60%, respectively) along the 1200-Km stretch separating the Lena delta from Yakutsk. The difficulty to quantitatively distinguish between these possible factors is a limitation in our attempt to quantify precisely the riverine nutrients fluxes. At the seasonal scale, 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."

4) Introduction, third paragraph, third sentence: Insert "surface" between "terrestrial" and "run-off".

The sentence has been modified accordingly:

Page 13400 (line 7): "Riverine nitrate is derived from soil leaching (i.e. moved or dissolved and carried through soil by water) and terrestrial surface run-off (i.e. transported over land in the excess water when soil is infiltrated to full capacity)."

5) "Materials and methods, first paragraph. Clarify whether or not ammonium data were used. In one place it seems to say that ammonium data were not used then later in the paragraph an ammonium dataset is identified."

On page 13401 (line 18), the sentence "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)" was removed. Sentence on page 13402 (line 6) was modified as follows: "Ammonium concentrations used in this study are restricted to those of the PARTNERS database, because concentrations measured along the Eurasian side are considered dubious as a result of methodological problems (Holmes et al., 2000; 2001). DON concentrations are also derived from the PARTNERS database."

6) "Results and discussion, section 3.1, first paragraph, second sentence. The Finlay et al. (2006) reference seems out of place here. This paper is about DOC, not nitrate and silicate."

We corrected the mistake. Page 13403 (line 6), the reference to Finlay et al. (2006) was removed.

7) "Concluding remarks, second sentence. Time series were not computed. Please clarify."

We removed the inappropriate term "time series" from the sentence (page 13411, line 5).

8) "Table 1. In the footnotes, or in the main body of the text, more information is needed about where the data for the "climatology" values came from. Although a general description of the various data sets that were used is provided in the materials and methods section, readers need to know specifically what data sets contributed to the calculations for each constituent at each river. Same goes for the auxiliary tables."

A new table providing the source and number of data for each sampling station of all

9 rivers is given in the file providing supplementary material. Note that we corrected accordingly small errors on the total number of data (n):

Page 13401 (line 8): "We compiled riverine nitrate (n = 2436), SRP (n = 1618), silicate (n = 1683), DOC (n = 509), DON (n = 380), POC (n = 160) and PON (n = 160) 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))."

9) "Table 1. The caption for table 1 indicates that the number of months accounted for in various estimates is shown in brackets, but the numbers in the brackets seem to show number of months as well as some percentage values that don't make sense. Revise to show only number of months. The percentage of the annual flux that is not accounted for as a consequence of the missing months is unknown for the climatology estimates."

With respect to comment #1 on the need to interpolate concentrations data, we present in Table 1 the fluxes computed from monthly-binned interpolated nutrients concentrations. We hence removed the numbers in the brackets.

Please also note the supplement to this comment:
http://www.biogeosciences-discuss.net/9/C7710/2013/bgd-9-C7710-2013-supplement.pdf

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