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Riverine particulate C and N generated at the permafrost thaw front: case study of western Siberian rivers across a 1700 km latitudinal transect

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Table S1. The physico-geographical characteristics of the catchments as determined by digitalizing available soil, vegetation, lithology and geocryology maps.

No on map	N	E	Description	Sarea, km²	runoff mm.yr	bogs, %	forest, %	lakes, %	PF, %	Type of permafrost
24	65˚06'48.8"	77˚47'58.8"	Tydylyakha	7.5	185	49.4	37.4	12.7	49	Discontinuous
2	56˚43'15.0"	83˚55'35.1"	Chybyr'	8.1	44.8	19.9	28.4	1.01	0	Absent
11	61˚50'28.6"	70˚50'28.2"	Vachinguriyagun	9.5	192	78.7	9.4	11.9	0	Isolated
13	62˚37'08.4"	74˚10'15.9"	Petriyagun	9.7	192	57.2	6.7	36.1	5	Isolated
21	64˚32'07.9"	76˚54'21.3"	Seryareyakha	15.2	186	61.2	19.4	19.4	60	Sporadic
19	64˚09'06.4"	75˚22'18.1"	Apoku-Yakha	18.8	186	75.5	12.8	11.7	38	Sporadic
14	62˚33'39.8"	74˚00'29.5"	Pintyr'yagun	33.5	192	61	0	39	8	Isolated
16	63˚36'48.2"	74˚35'28.6"	Khatytayakha	34.6	194	75.3	13.2	10.8	38	Sporadic
20	64˚17'31.9"	75˚44'33.4"	Etu-Yakha	71.6	186	23.4	71.5	1.96	23	Sporadic
31	67°09'24,81"	78°57'31,76"	Sambotoyakha	75.0	N.D.	26.3	0.45	2.3	71	Continuous
25	65˚23'34.1"	77˚45'46.7"	Ponie-yakha	78.9	185	66	17.7	16.3	70	Discontinuous
10	61˚29'11.1"	74˚09'42.9"	Vach-Yagun	98.9	192	77.9	17.2	1.7	0	Isolated
17	63˚47'04.5"	75˚37'06.8"	Lymbyd'yakha	115	194	59.3	6.1	34.6	30	Sporadic
6	58˚40'46.5"	84˚27'56.6"	Vyalovka	117	127	37	48.4	0.19	0	Absent
30	66°59'25,84"	79°22'30,02"	Malaya Kheyaha	137	N.D.	23.4	43.4	1.4	75	Continuous
15	63˚22'01.6"	74˚31'53.2"	Kamgayakha	175	194	23.7	76.2	0.1	12	Sporadic
3	57˚36'43.3"	83˚37'02.1"	Malyi Tatosh	302	63.4	7.89	66.9	0.09	0	Absent
28	65˚59'14.7"	78˚32'25.2"	Malaya Khadyr-Yakha	513	278	14.8	84.9	0.3	85	Discontinuous
32	67°10'54,8"	78°51'04,5"	Nuny-Yakha	656	312	24.3	37	3.05	72	Continuous
29	66˚17'10.8"	79˚15'06.1"	Ngarka Khadyta-Yakha	1970	277	22	76	2	50	Continuous
5	58˚26'06.9"	82˚05'43.6"	Shudelka	3460	211	68.2	31.8	0.0	0	Absent
26	65˚41'51.1"	78˚01'05.0"	Yamsovey	4030	309	53.7	38.7	7.5	54	Discontinuous
22	64˚40'14.0"	77˚05'27.2"	Purpe	5110	309	48	34	15	48	Sporadic
18	63°49'54.2"	75°22'47.1"	Pyakupur	9881	324	45	40	12	34	Sporadic
12	62°07'50.0"	73°44'05.6"	Tromyegan	10770	263	51.9	35.6	12.6	10	Isolated
23	64˚55'55.1"	77˚56'08.2 "	Aivasedapur	26100	309	40.1	45.5	14.4	20	Sporadic
9	58˚04'20.8"	82˚49'19.7"	Chaya	27622	291	46.9	42.5	10.6	5	Absent
4	61°26'13.6"	74°47'39.7"	Agan	27600	291	46.9	42.5	10.6	5	Isolated
8	60°55'41.0"	76°53'49.3"	Vakh	75090	298	35	61	4	5	Absent
27	65˚57'05.5"	78˚18'59.1"	Pur	112000	298	56.9	34.4	8.7	34	Discontinuous
33	67˚22'13.28"	79˚00'25.9"	Taz	150000	330	38	59	3	59	Continuous
1	59°03'45.5"	80°52'08.9"	Ob'	520000	N.D.	9	N.D.	N.D.	0	Absent
7	60˚40'28.8"	77˚31'29.4"	Ob'	773200	216	10	N.D.	N.D.	0	Absent

PF is for permafrost, % of watershed coverage. Full dataset of measured parameters is available at the Research gate (DOI:10.13140/RG.2.2.36650.93121); https://www.researchgate.net/publication/325334684.

Table S2. Correlation matrix of watershed physico-geographical parameters and particulate nutrient concentration. All rivers, June and August and September. Marked (bold and red) Pearson correlations R > 0.28 are significant at p < 0.09. Lat and Permaf. are for Latitude (° N) and permafrost coverage of the watershed, %. The runoff is in mm y^{-1} and bogs, forest and lakes represent the % coverage in the watershed

		Lat	S, km²	runoff	Bogs	Forest	Lakes	Permaf
Spring 2016								
permafrost-free (N=8)	RSM, mg/l	**0.87**	**0.91**	0.67	0.12	0.62	**0.79**	-
	N, %	-0.61	-0.38	-0.44	-0.33	-0.60	-0.12	-
	C, %	-0.65	-0.47	-0.46	-0.34	-0.59	-0.23	-
	% C_{RSM} of total C	0.44	0.49	0.53	-0.38	0.36	0.58	-
	P	-0.19	-0.37	-0.18	-0.28	0.51	-0.49	-
	% P_{RSM} of P total	**0.95**	**0.88**	**0.87**	0.03	0.62	**0.80**	-
permafrost-bearing (N=24)	RSM, mg/l	**0.55**	-0.004	0.11	-0.39	0.19	-0.24	**0.52**
	N, %	**-0.55**	-0.16	**-0.53**	**0.66**	**-0.69**	**0.72**	**-0.50**
	C, %	**-0.55**	-0.21	**-0.56**	**0.66**	**-0.72**	**0.78**	**-0.48**
	% C_{RSM} of total C	-0.29	-0.16	-0.38	**0.47**	**-0.61**	**0.75**	-0.25
	P	-0.28	0.05	-0.13	0.33	-0.24	-0.10	-0.36
	% P_{RSM} of P total	-0.24	-0.15	**-0.44**	0.34	**-0.51**	**0.40**	-0.27
Summer 2016								
permafrost-free (N=8)	RSM, mg/l	**0.76**	0.42	0.67	0.38	0.18	0.34	-
	N, %	-0.55	-0.27	-0.43	-0.53	-0.39	-0.01	-
	C, %	**-0.81**	-0.66	**-0.76**	-0.54	-0.41	-0.43	-
	% C_{RSM} of total C	**0.92**	0.63	**0.87**	0.05	0.57	0.56	-
	P	-0.54	**-0.81**	-0.57	-0.44	0.21	**-0.82**	-
	% P_{RSM} of P total	0.53	0.01	0.52	0.20	0.41	-0.15	-
permafrost-bearing (N=24)	RSM, mg/l	**-0.43**	**-0.38**	**-0.40**	**0.55**	-0.30	-0.05	-0.28
	N, %	-0.35	0.06	-0.10	**0.60**	**-0.67**	**0.50**	**-0.41**
	C, %	**-0.53**	-0.24	**-0.61**	**0.63**	**-0.78**	**0.76**	**-0.52**
	% C_{RSM} of total C	**-0.53**	**-0.45**	**-0.58**	**0.38**	-0.26	0.20	**-0.50**
	P	0.29	0.24	0.34	-0.24	0.32	**-0.46**	0.05
	% P_{RSM} of P total	-0.27	-0.28	-0.16	0.35	-0.21	-0.17	-0.22
Autumn 2016								
permafrost-free (N=8)	RSM, mg/l	0.29	0.52	0.45	0.41	-0.01	0.40	-
	N, %	-0.13	0.20	-0.09	-0.39	-0.31	0.45	-
	C, %	-0.51	-0.20	-0.43	-0.44	-0.47	0.08	-
	% C_{RSM} of total C	0.74	**0.88**	**0.78**	0.12	0.37	**0.83**	-
	P	-0.45	-0.74	-0.46	0.01	-0.12	**-0.88**	-
	% P_{RSM} of P total	0.29	0.52	0.45	0.41	-0.01	0.40	-
permafrost-bearing (N=24)	RSM, mg/l	**0.51**	-0.12	0.09	-0.17	0.19	-0.34	**0.61**
	N, %	**-0.55**	0.17	-0.23	**0.70**	**-0.64**	**0.60**	**-0.61**
	C, %	**-0.69**	-0.18	**-0.50**	**0.60**	**-0.66**	**0.78**	**-0.67**
	% C_{RSM} of total C	-0.16	-0.13	-0.21	0.12	-0.02	0.17	-0.12
	P	0.17	0.05	0.28	**-0.36**	**0.60**	-0.36	0.26
	% P_{RSM} of P total	**-0.42**	-0.23	**-0.43**	**0.37**	-0.29	0.32	-0.28
All seasons								
perm	RSM, mg/l	0.41	0.35	0.37	0.14	0.36	0.27	-

	N, %	**-0.47**	-0.25	-0.39	**-0.53**	-0.42	-0.03	-
	C, %	**-0.61**	-0.42	**-0.51**	**-0.52**	**-0.55**	-0.19	-
	% C_{RSM} of total C	**0.62**	**0.58**	**0.64**	-0.01	**0.50**	**0.54**	-
	P	-0.25	**-0.50**	-0.20	0.24	-0.26	**-0.56**	-
	% P_{RSM} of P total	**0.48**	0.32	**0.56**	0.33	0.31	0.20	-
permafrost-bearing (N=70)	RSM, mg/l	0.18	-0.18	-0.09	0.03	0.01	-0.20	**0.26**
	N, %	**-0.44**	0.01	**-0.27**	**0.60**	**-0.62**	**0.55**	**-0.47**
	C, %	**-0.57**	**-0.21**	**-0.54**	**0.60**	**-0.69**	**0.74**	**-0.54**
	% C_{RSM} of total C	**-0.29**	**-0.23**	**-0.36**	**0.29**	**-0.25**	**0.32**	**-0.26**
	P	0.12	0.11	0.19	-0.15	**0.28**	**-0.32**	0.03
	% P_{RSM} of P total	**-0.28**	**-0.21**	**-0.32**	**0.33**	**-0.31**	0.15	**-0.24**

Correlation matrix of watershed physico-geographical parameters and particulate nutrient concentration. All rivers, all seasons, $p < 0.05$

		Latitude	**S, km²**	**runoff**	**Bogs**	**Forest**	**Lakes**	**Permaf**
permafrost-free (N=24)	RSM. mg/l	0.41	0.35	0.37	0.14	0.36	0.27	-
	N. %	-0.47	-0.25	-0.39	**-0.53**	-0.42	-0.03	-
	C. %	**-0.61**	-0.42	-0.51	**-0.52**	**-0.55**	-0.19	-
	% C_{RSM} of total C	**0.62**	**0.58**	**0.64**	-0.01	0.50	**0.54**	-
	P	-0.25	-0.50	-0.20	0.24	-0.26	**-0.56**	-
	% P_{RSM} of P total	0.48	0.32	**0.56**	0.33	0.31	0.20	-
permafrost-bearing (N=70)	RSM. mg/l	0.18	-0.18	-0.09	0.03	0.01	-0.20	**0.26**
	N. %	**-0.44**	0.01	**-0.27**	**0.60**	**-0.62**	**0.55**	**-0.47**
	C. %	**-0.57**	-0.21	**-0.54**	**0.60**	**-0.69**	**0.74**	**-0.54**
	% C_{RSM} of total C	**-0.29**	-0.23	**-0.36**	**0.29**	**-0.25**	**0.32**	**-0.26**
	P	0.12	0.11	0.19	-0.15	**0.28**	**-0.32**	0.03
	% P_{RSM} of P total	**-0.28**	-0.21	**-0.32**	**0.33**	**-0.31**	0.15	**-0.24**

Table S3. Compilation of statistical parameters for the differences in RSM, C, N and P concentration (N=32) among watersheds of different size (<100, 100-1000, 1000-50000, >50000 km²)

Table S3-A: Non-parametric H-criterion Kruskal Wallis for un-paired data, at $p < 0.05$

Season	Variable	H	p-level
Spring	**RSM**	-	-
	C	10.98	**0.0118**
	N	10.55	**0.0145**
	P	-	-
Summer	**RSM**	-	-
	C	15,74	**0.0013**
	N	-	-
	P	-	-
Autumn	**RSM**	-	-
	C	11,02	**0,0116**
	N	10,72	**0,0133**
	P	-	-

Table S3-B: Impact of the watershed area ($S_{watershed}$) on RSM and nutrient concentration. Mann-Whitney U test, statistically significant (at $p < 0.05$) differences are in bold red. (N=32)

Watershed, km²	Variable	Spring			Summer			Autumn		
		U	Z	p-level	U	Z	p-level	U	Z	p-level
<100/100-1000	RSM, mg/l	20.0	-1.415	0.1571	28.0	0.906	0.365	37.00	0.091	0.928
	C, %	11.0	**2.294**	**0.0218**	10.0	**2.537**	**0.011**	12.00	**2.355**	**0.019**
	N, %	10.0	**2.391**	**0.0168**	16.0	**1.992**	**0.046**	9.00	**2.626**	**0.009**
	P,%	25.0	-0.635	0.525	23.0	-1.359	0.174	32.00	-0.543	0.587
100-1000/1000-50000	RSM, mg/l	26.0	0.174	0.862	21.0	-1.059	0.290	22.50	-0.900	0.368
	C, %	23.0	-0.521	0.603	27.0	0.423	0.672	25.00	-0.635	0.525
	N, %	22.0	-0.637	0.524	24.0	-0.741	0.459	17.00	-1.481	0.138
	P,%	26.0	0.174	0.862	31.0	0.0000	1.000	29.00	-0.212	0.832
1000-50000/>50000	RSM, mg/l	8.00	-1.683	0.092	21.0	0.133	0.894	22.50	-0.900	0.368
	C, %	10.0	1.391	0.164	13.0	1.200	0.230	25.00	-0.635	0.525
	N, %	13.00	0.952	0.341	20.00	0.267	0.790	17.00	-1.482	0.138
	P,%	13.00	0.952	0.341	11.00	1.4667	0.1425	29.00	-0.212	0.832

Table S3-C. Non-parametric H-criterion Kruskal Wallis for un-paired data, at $p < 0.05$. Difference between parameters depending on type of permafrost (Absent, Isolated, Sporadic, Discontinuous, Continuous)

Season	Variable	H	p-level
Spring	**RSM**	-	-
	C	12.07	**0.017**
	N	10.59	**0.031**
	P	-	-
Summer	**RSM**	15.81	**0.0033**
	C	14.77	**0.0052**
	N	11.33	**0.0230**
	P	-	-
Autumn	**RSM**	18.28	**0.0004**
	C	10.68	**0.014**
	N	7.86	**0.049**
	P	-	-

Table S3-D. Mann-Whitney U test of the difference in nutrient concentration between two adjacent permafrost zones. Statistically significant (at $p < 0.05$) differences are in bold red. (N=32)

	Variable	Spring			Summer			Autumn		
		U	Z	p-level	U	Z	p-level	U	Z	p-level
Permafrost/ Absent	RSM, mg/l	61.0	-1.266	0.205	63.5	1.414	0.157	22.0	**-3.22**	**0.001**
	C, %	82.0	-0.281	0.778	33.0	**-2.74**	**0.006**	48.0	**-2.09**	**0.037**
	N, %	81.0	-0.328	0.743	34.0	**-2.70**	**0.007**	68.0	-1.22	0.223
	P,%	70.0	0.683	0.495	71.0	1.088	0.277	61.0	1.52	0.128
Absent/ Isolated	RSM, mg/l	19.0	-0.073	0.942	14.5	1.162	0.245	14.0	-1.226	0.220
	C, %	11.0	-1.244	0.213	4.0	**-2.52**	**0.012**	3.0	**-2.647**	**0.008**
	N, %	11.0	-1.244	0.213	2.0	**-2.77**	**0.006**	5.0	**-2.388**	**0.017**
	P,%	20.0	0.452	0.651	13.0	1.356	0.175	11.0	1.614	0.107
Sporadic/ Discontinious	RSM, mg/l	13.0	0.0	1.0	2.0	**2.39**	**0.017**	16.0	-1.221	0.222
	C, %	5.0	1.479	0.139	7.0	1.620	0.105	28.0	0.053	0.958
	N, %	6.0	1.294	0.196	10.0	1.157	0.247	23.0	-0.478	0.633
	P,%	6.5	1.697	0.090	18.0	-0.077	0.939	18.0	-1.009	0.313
Discontinuous/ Continious	RSM, mg/l	6.0	-0.298	0.766	4.0	1.347	0.178	6.0	0.857	0.391
	C, %	5.0	0.596	0.551	9.0	-0.122	0.903	3.0	1.592	0.111
	N, %	5.0	0.596	0.551	10.0	0.122	0.903	4.0	1.347	0.178
	P,%	9.0	-0.122	0.903	4.0	-1.347	0.178	3.0	1.592	0.111

Table S3-E. Mann-Whitney U test for the impact of bog coverage of the watershed on RSM and nutrient concentration, for < 10% and > 10% of lake coverage. Statistically significant (at p < 0.05) differences are in bold red. (N=30)

Variable	Spring			Summer			Autumn		
	U	Z	p-level	U	Z	p-level	U	Z	p-level
RSM, mg/l	90.0	0.0	1.0	100.5	-0.863	0.388	103.5	-0.748	0.454
C, %	44.0	**-2.22**	**0.026**	30.0	**-3.568**	**0.0004**	24.0	**-3.799**	**0.0001**
N, %	44.0	**-2.22**	**0.026**	32.0	**-3.492**	**0.0005**	43.0	**-3.070**	**0.0021**
P,%	76.0	-0.386	0.700	63.0	**2.302**	**0.0213**	104.0	0.729	0.4660

Table S3-F. Mann-Whitney U test for the impact of bog coverage of the watershed on RSM and nutrient concentration, for < 50% and > 50% of bog coverage. Statistically significant (at p < 0.05) differences are in bold red (N=30)

Variable	Spring			Summer			Autumn		
	U	Z	p-level	U	Z	p-level	U	Z	p-level
RSM, mg/l	83.0	0.904	0.366	93.5	-1.132	0.258	119.0	-0.153	0.878
C, %	58.0	**-1.980**	**0.048**	63.0	**-2.30**	**0.021**	71.0	**-1.995**	**0.046**
N, %	62.0	-1.808	0.0707	70.0	**-2.03**	**0.042**	68.0	**-2.110**	**0.035**
P,%	77.0	-0.967	0.334	94.0	1.11	0.266	97.0	0.998	0.318

Table S3-G. Mann-Whitney U test for the impact of bog coverage of the watershed on RSM and nutrient concentration, for < 30% and > 30% of forest coverage. Statistically significant (at p < 0.05) differences are in bold red. (N=30)

Variable	Spring			Summer			Autumn		
	U	Z	p-level	U	Z	p-level	U	Z	p-level
RSM, mg/l	76.0	-0.443	0.658	87.0	0.550	0.582	68.0	-1.386	0.166
C, %	31.0	**2.656**	**0.0079**	11.0	**3.893**	**0.0001**	29.0	**3.102**	**0.0019**
N, %	33.0	**2.558**	**0.0105**	38.0	**2.705**	**0.007**	31.0	**3.014**	**0.0026**
P,%	80.0	0.0258	0.9795	57.0	-1.869	0.062	46.0	**-2.354**	**0.0186**

Table S4. Mean C:N values in soils and lake sediments of WSL river watersheds.

Site	Mean ± SD
Cryosols in Tazovsky, south tundra, mineral soils	14.0±7.0
Cryic Histosols, polygonal southern tundra in Tazovsky, (СкTz15)	24.3±5.7
Cryic Histosols, polygonal southern tundra in Tazovsky (СкTz14-2)	28.4±10.7
Cryic Histosols, depression over permafrost, southern tundra (СкTz14-3)	39.5±20.1
Soil of recently drained lakes, south tundra, Tazovsky, 2016	22.4±3.0
Sediments of thermokarst lake in Tazovsky, continuous permafrost	27.3±8.1
Fluvisols in Taz River flood zone, south tundra, continuous permafrost	14.9±2.2
Cryic Histosols, frozen mound in Pangody, forest-tundra (СкP15)	50.0±16.3
Thermokarst lake sediment Pangody, August 2015	27.7±7.3
Cryic Histosols, frozen mound in northern taiga Khanymey (X17-9)	43.6±19.6
Cryic Histosols, frozen mound in northern taiga Khanymey (X14-4)	57.1±16.8
Albic Alisol, light color soil, Khanymey, northern taiga Khanymey	13.0±6.4
Thermokarst lake sediment Khanymey, August 2015	24.0±3.0
Histosols, bog, ridge, northern taiga, Kogalym , sporadic perm. (Kg16-1)	65.4±21.1
Thermokarst lake sediment Kogalym, August 2015	26.8±2.5
Histosols, bog, depression, middle taiga (Stepanova et al., 2015)	36.3±18.8
Histosols, bog, ridge, middle taiga (Stepanova et al., 2015)	79.4±25.5
Fluvisols in floodzone of the Ob River, southern taiga, Kaibasovo, 2017	11.0±1.4

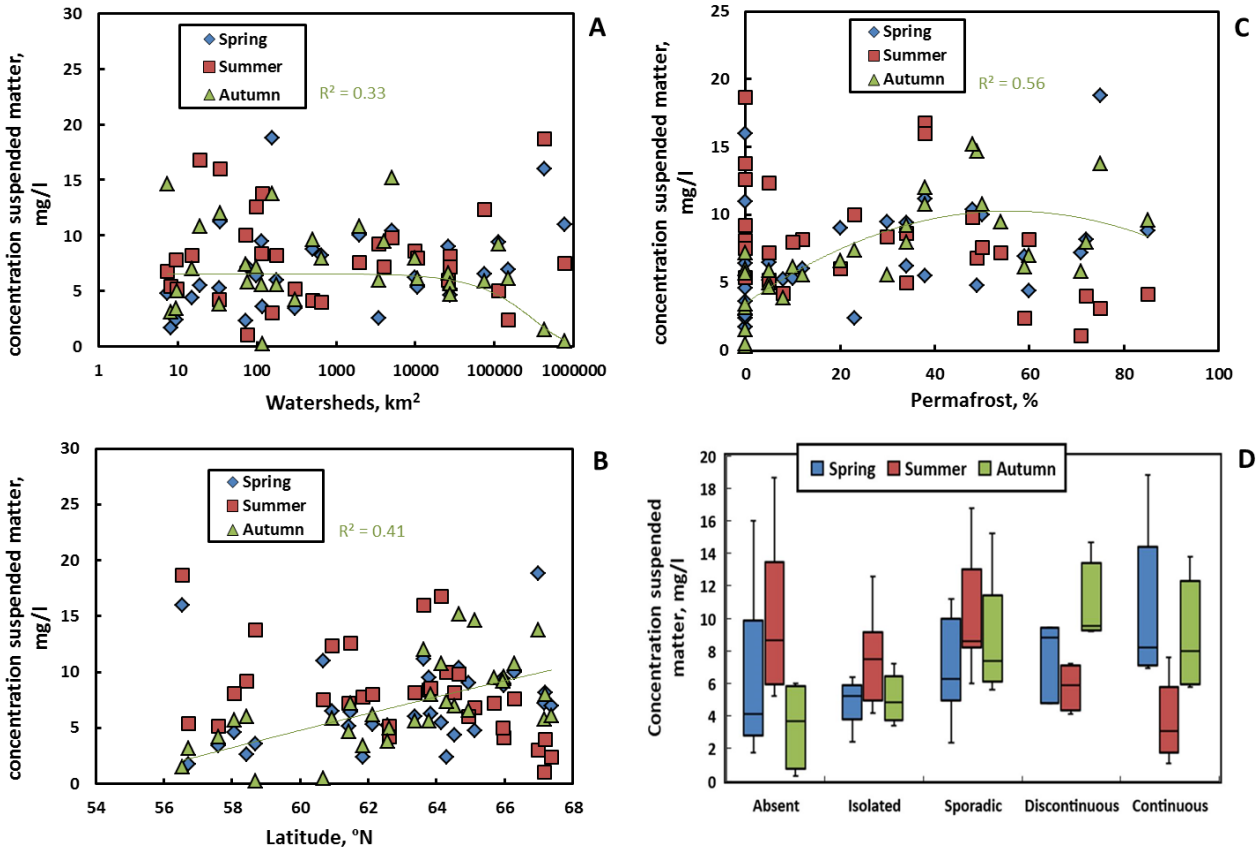

Fig. S1. Effect of watershed size (**A**), latitude (**B**), permafrost coverage (**C**) and box-plot of permafrost type (**D**) on RSM concentration in WSL rivers.

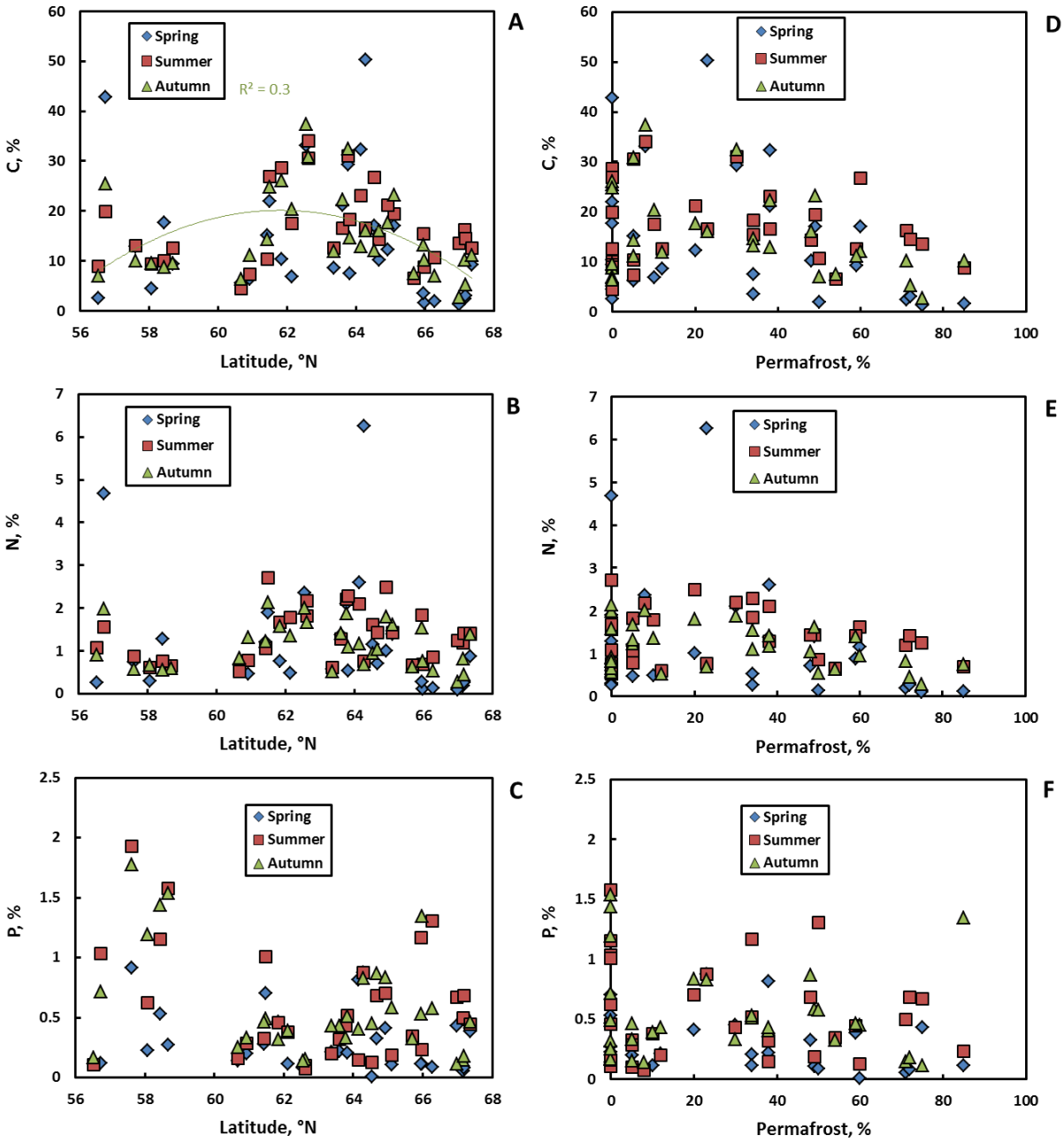

Fig. S2. Latitudinal dependences of C (**A**), N (**B**) and P (**C**) concentrations in RSM. A maximum in C concentrations is observed at 62-64°N, of the isolated to sporadic permafrost zone, where the maximal thawing of permafrost occurs (**A**). C (**D**), N (**E**) and P (**F**) concentration in RMS of WSL rivers as a function of permafrost coverage of the watershed. There is a general decrease of C and N concentration with an increase in permafrost coverage, consistent with maximal nutrient concentration at the beginning of permafrost appearance.

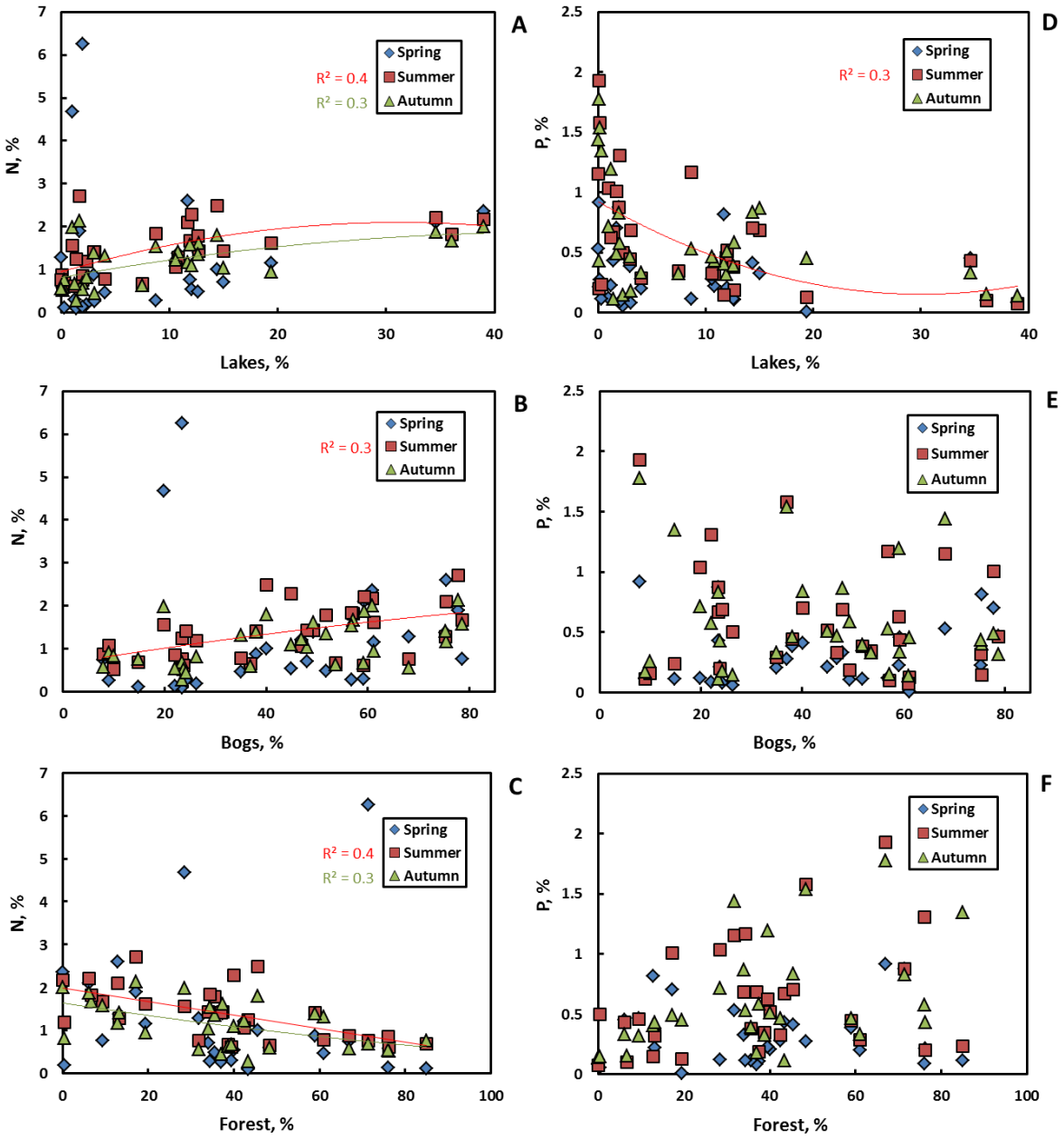

Fig. S3. N (A-C) and P (D-F) concentration in RSM (mass %) of WSL rivers as a function of lakes (A, D), bogs (B, E) and forest (C, F) coverage of the watershed during different seasons.

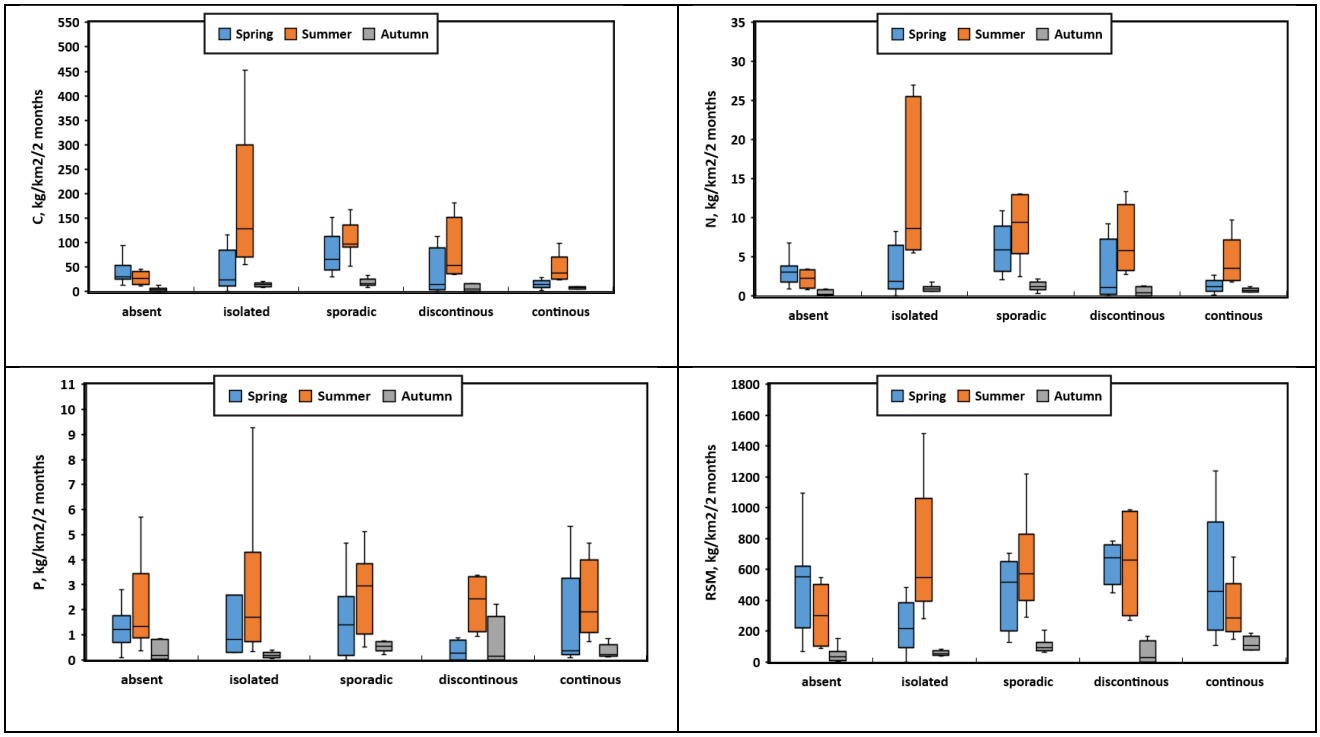

Fig. S4. Seasonally-resolved export fluxes of particulate C, N, P and RSM from WSL rivers during spring (May and June), summer (July and August) and autumn (September and October) for permafrost-free region and 4 distinct permafrost zones.

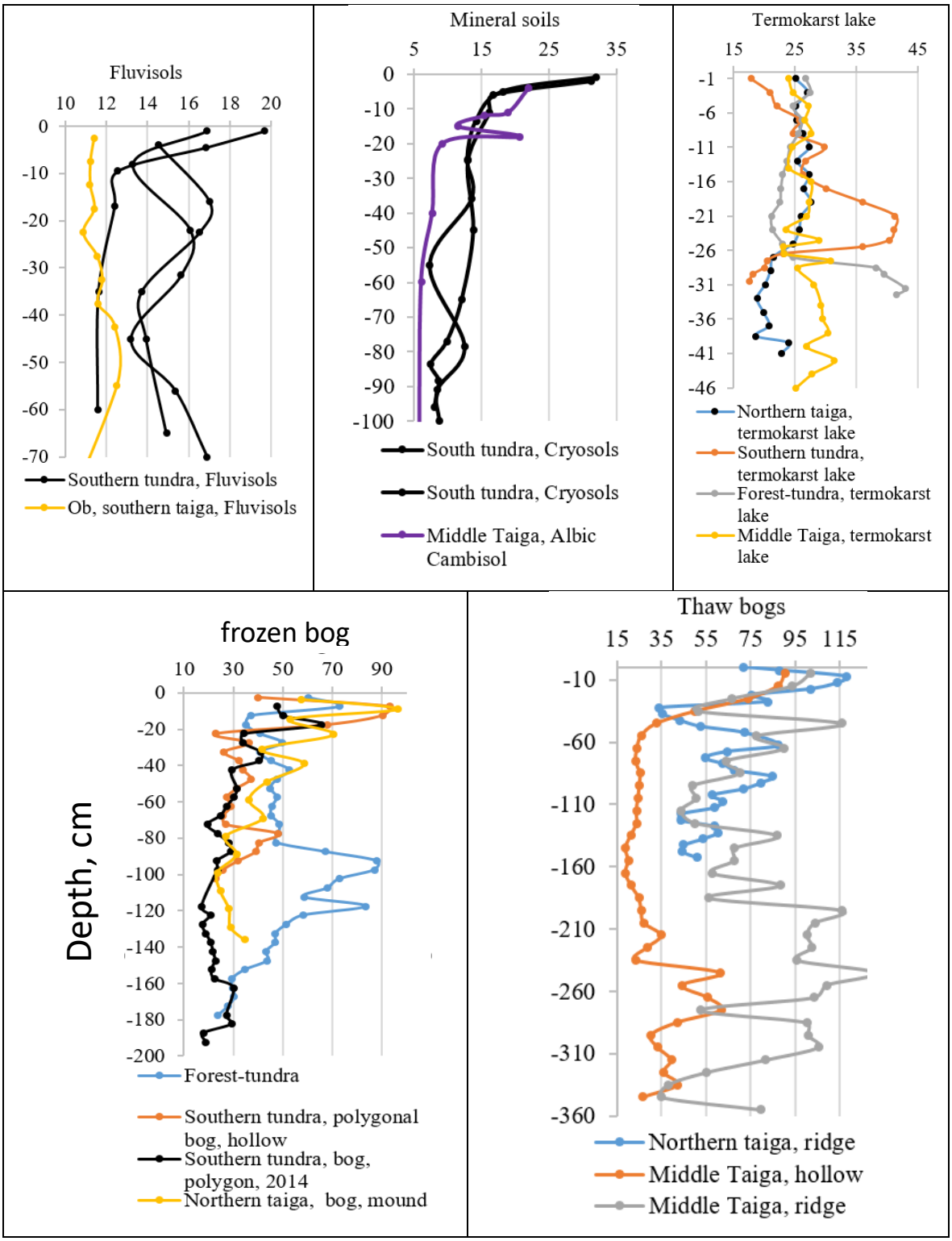

Fig. S5. C:N in peat profile across the latitudinal transect of WSL, corresponding to four main regions (permafrost-free region of Ob, southern taiga; isolated/sporadic permafrost at Kogalym; discontinuous permafrost at Khanymey and continuous permafros at Tazovsky). Authors' unpublished data.