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Distinct changes in carbon, nitrogen, and phosphorus cycling in the litter layer across two contrasting forest–tundra ecotones

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S1 Study sites

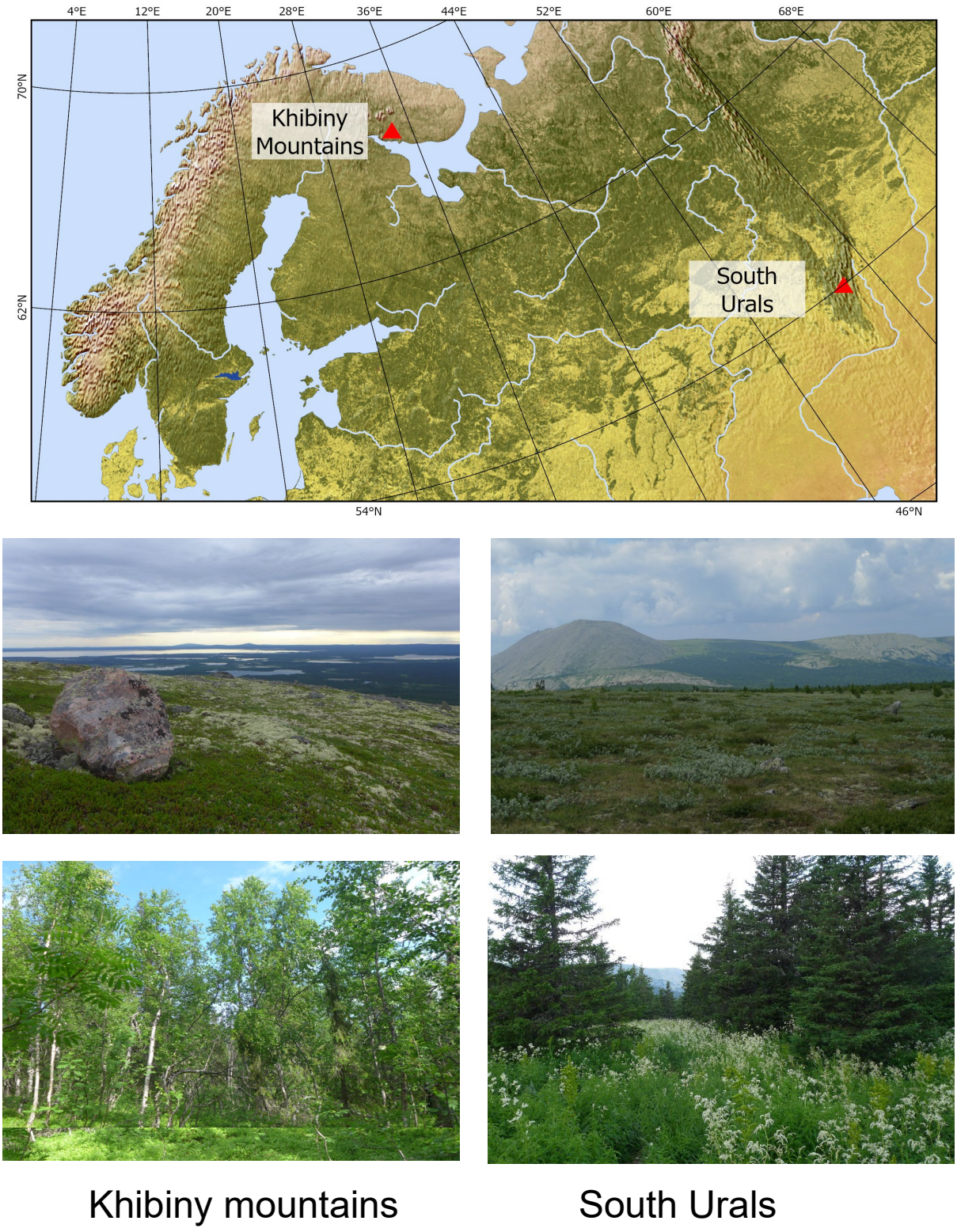

Figure S1: Location of the study sites and photographs of the studied tundra ecosystems (two upper photos) and the forest ecosystem (two lower photos) in the Khibiny mountains and South Urals. The map was created with Natural Earth under CC0 license. Photos: Frank Hagedorn.

S2 Formula to calculate potential activities of extracellular enzymes

The potential activities of litter extracellular enzymes were presented in units of nmol g^{-1} dry soil h^{-1} and calculated using the following formulas (German et al., 2011):

$$Activity\ (nmol\ g^{-1}\ h^{-1}) = \frac{Net\ Fluorescence \times Buffer\ volume\ (ml)}{Emission\ coefficient \times Homogenate\ volume\ (ml) \times Time\ (h) \times Soil\ mass\ (g)} \quad \text{[Eq. 1]}$$

$$Net\ Fluorescence\ = \left(\frac{Assay - Homogenate\ control}{Quench\ coefficient}\right) - Substrate\ control \quad \text{[Eq. 2]}$$

$$Emission\ coefficient\ (fluorescence\ nmol^{-1})\ = \frac{Standard\ fluorescence}{\left[\frac{Standard\ concentration\ (nmol) \times Assay\ volume\ (ml)}{Volume\ of\ standard\ (ml)}\right]} \quad \text{[Eq. 3]}$$

$$Quench\ coefficient\ = \frac{Quench\ control - Homogenate\ control}{Standard\ fluorescence} \quad \text{[Eq. 4]}$$

S 3 Litter characteristics

Table S1: Concentrations of Ca, Fe, K, Mg, and Mn in the litter layer of treeline ecotones in the Khibiny mountains and South Urals. Means of three replicates per site type.

Region	Elevation	Vegetation	Ca (mg/kg)	Mg (mg/kg)	K (mg/kg)	Fe (mg/kg)	Mn (mg/kg)
Khibiny	Tundra	Open	5256	823	2464	3694	607
	Treeline	Open	4843	766	2183	3395	198
		Tree	10239	1281	2679	2952	1012
	Forest	Open	9187	950	1741	2002	962
		Tree	14057	1972	2595	2626	3291
South Urals	Tundra	Open	1729	595	1550	1277	233
	Treeline	Open	2294	684	1893	1282	277
		Tree	5874	1053	1627	1106	1627
	Forest	Open	8469	1551	2831	3980	1072
		Tree	10135	1205	2862	3267	1239
	Significance						
	Region		<0.0001	0.13	0.16	0.0008	0.78
	Elevation		<0.0001	<0.0001	0.17	0.95	0.0001
	Vegetation		<0.0001	0.0004	0.1	0.01	0.019
	Region x Elevation		0.23	0.23	0.2	0.76	0.23
	Elevation x Vegetation		0.13	0.53	0.29	0.31	0.63

S 4: Fourier-transformed infrared spectroscopy of litter layer material

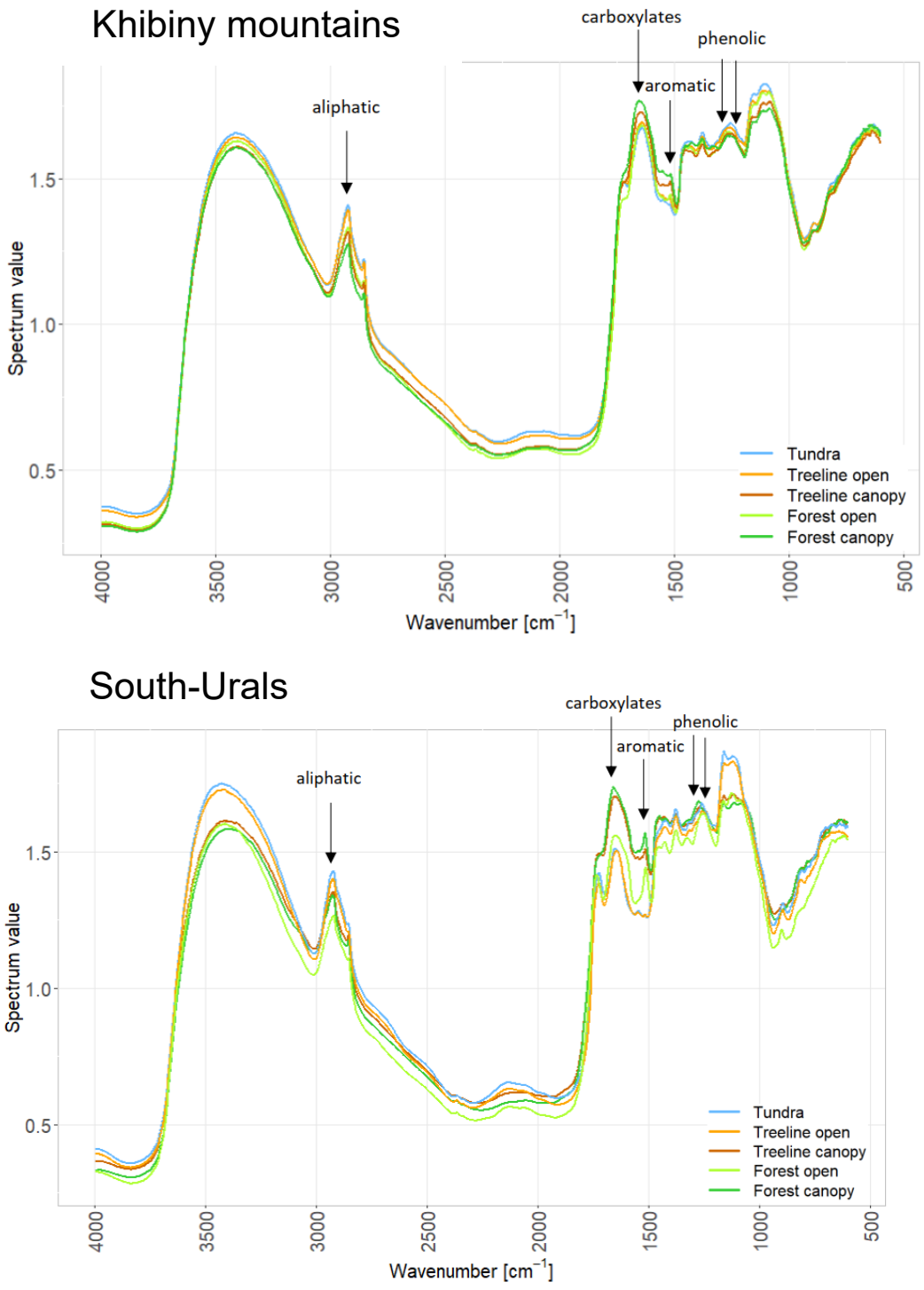

Figure S2: FT-IR spectra showing mean absorbance of three replicates per ecosystem type (tundra, treeline open, treeline canopy, forest open, forest canopy), for each of which duplicate measurements were taken (n=6).

S 5: Carbon mineralization rates of litter layer material at 5°C and 15°C

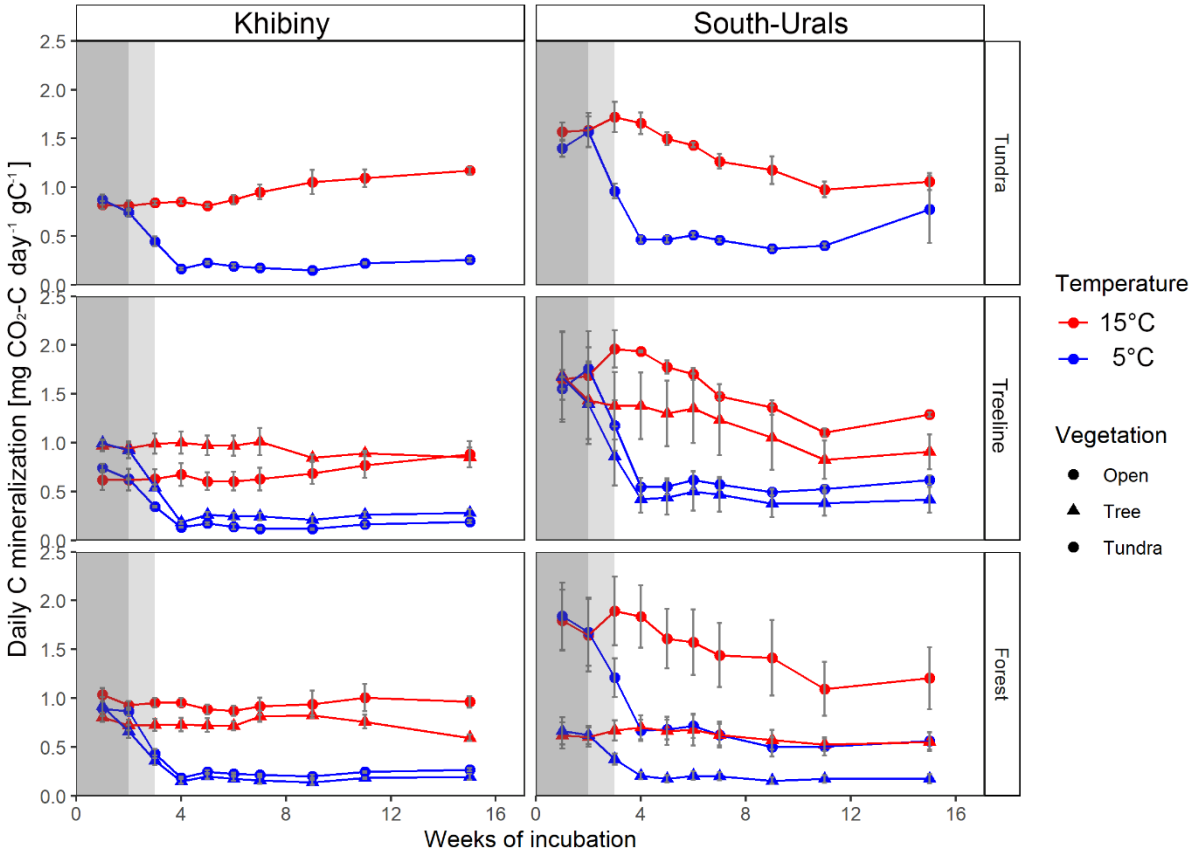

Figure S3: Daily carbon (C) mineralization (in mg CO_2-C per day and g C) of litter layer material at the two study sites Khibiny (left panel) and the South-Urals (right panel) for the five vegetation types (tundra, open and closed forest patches at the treeline, open and closed forest patches in the established forest) at two temperatures (5°C, blue line, 15°C, red line). The dark grey area indicates the precondition phase of two weeks at 15°C, the light grey area the transition phase. Means and standard error of three replicates. Cumulative values had been estimated for the period following the 4th week, when C mineralization rates had 'acclimatized' to the colder temperatures.

S 6: Activity of extracellular enzymes in the litter layer

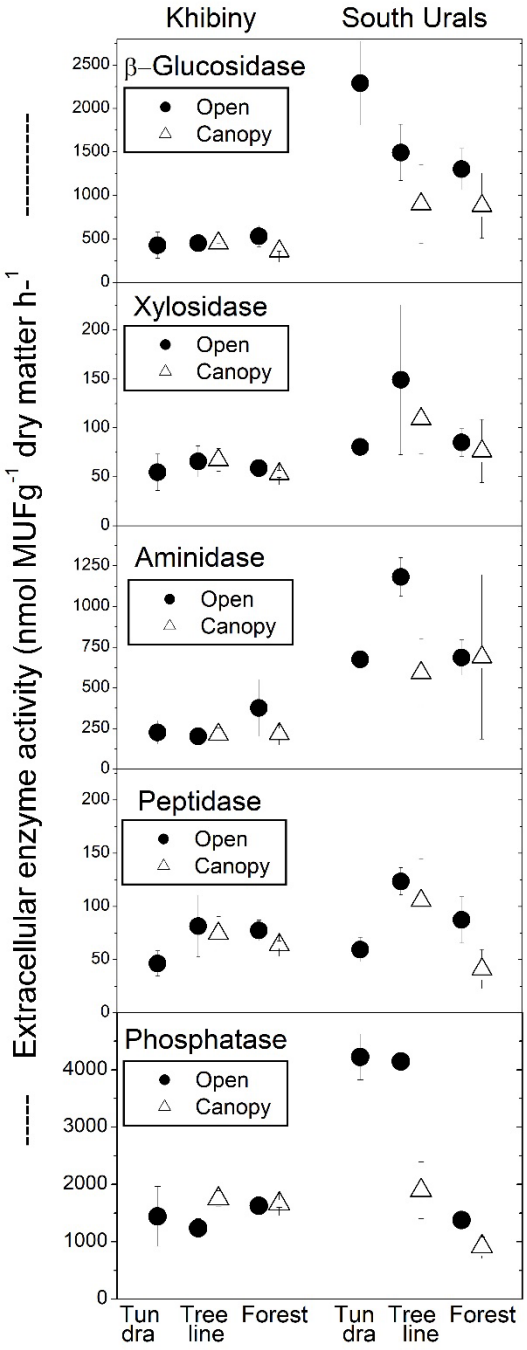

Figure S4: Potential activity of element acquiring extracellular enzymes across the forest-tundra ecotones in Khibiny and South Urals. Tundra, treeline, and forest span distinct elevation gradients. Samples at treeline and forest were sampled under tree canopy and adjacent open areas. Means and standard error of three plots after a 12-week long incubation at 15°C.

S 7: Tracking ^{13}C labelled glucose-6-phosphate to estimate substrate-use efficiency

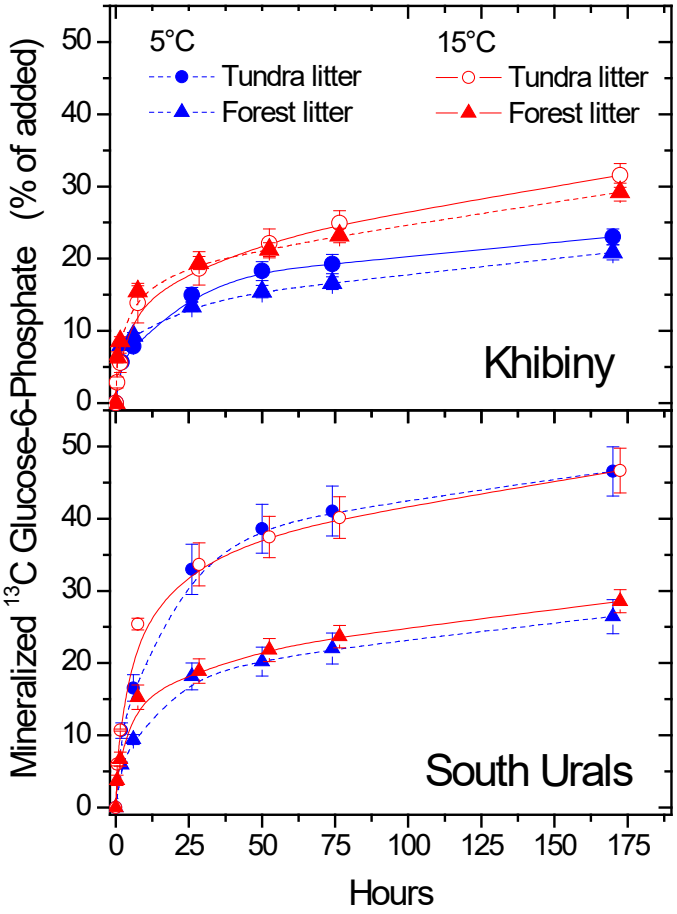

Figure S5: Mineralization of ^{13}C labelled glucose-6-phosphate from the litter layer in the tundra (50 m above species line) and under the forest canopy (100 m below species line) in the in the Khibiny mountains and South Urals. Means and standard error of three replicates incubated at 5°C and 15°C.

S 8: Release of inorganic phosphorus from added glucose-6-phosphate

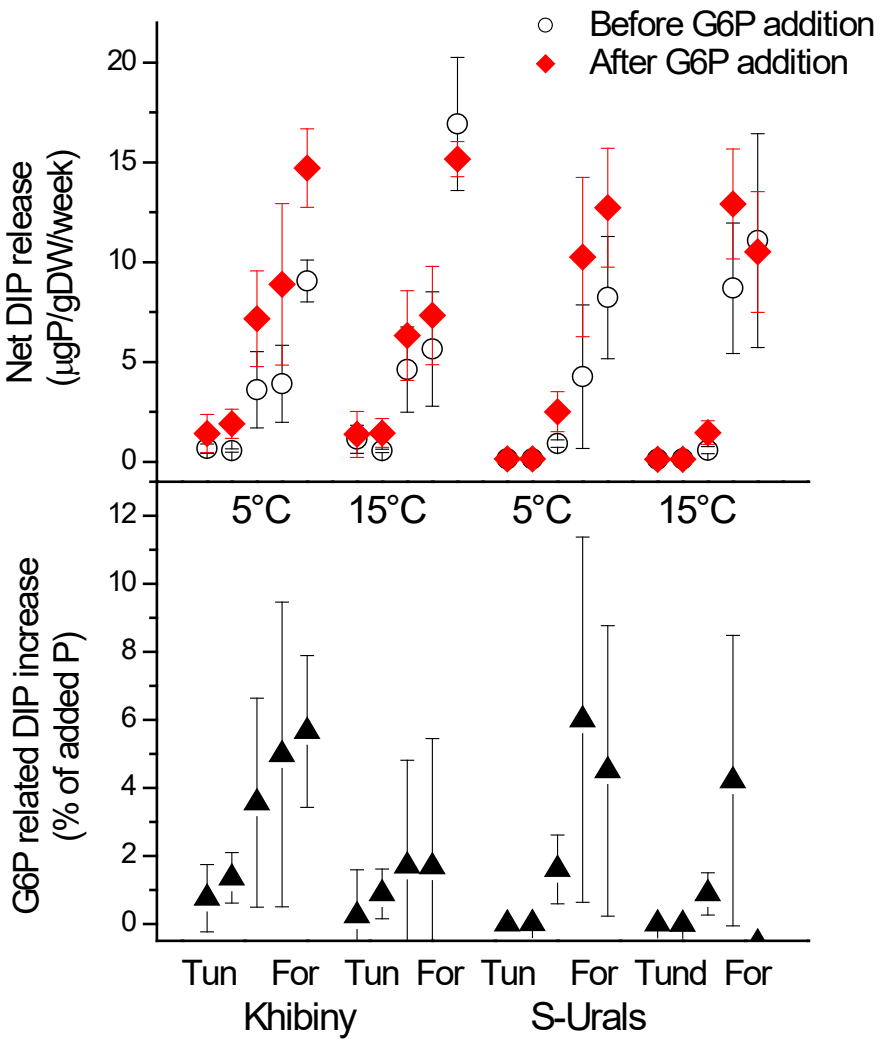

Figure S6: Release of dissolved inorganic phosphorus (DIP) from the litter layer across the treeline ecotone at Khibiny and the South Urals at 5°C and 15°C following the addition of 0.175 mg glucose-6-phosphate-P (G6P). Means and standard errors of three replicates per sample type.

S 9: Relation of C:N and C:P ratios with substrate use efficiency

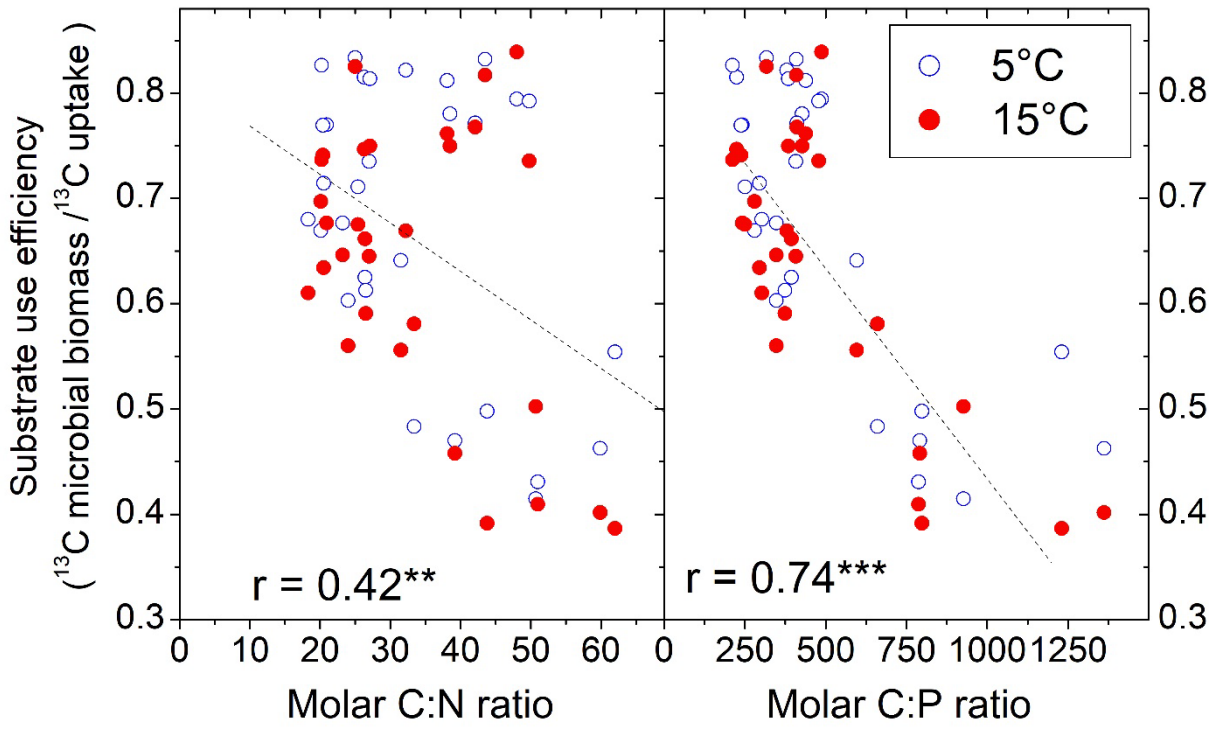

Figure S7: Relationship of molar C:N and C:P ratios in the litter layer with the substrate use efficiency (SUE) relating incorporation of ^{13}C labelled glucose-6-phosphate into microbial biomass to the total amount of ^{13}C label taken up by microorganisms.

S 10: 'Plant available' extractable N and P

Table S2: `Plant-available` nitrogen (N; $NH_4^+ + NO_3^-$) and phosphorus (P) from 0-20 cm across the forest-tundra ecotone in the Khibiny mountains and South Urals. Means and standard errors of 6 replicates per site type.

			Mineral N [mg N * kg dry soil^{-1}]	Soil P_{Bray} [mg P * kg dry soil^{-1}]
Khibiny Mountains	Tundra		0.85 ± 0.27	5.79 ± 1.73
	Treeline	Open	1.06 ± 0.39	3.82 ± 0.69
	Treeline	Tree	4.31 ± 2.14	8.62 ± 2.78
	Forest	Open	1.00 ± 0.16	8.92 ± 2.94
	Forest	Tree	13.81 ± 4.26	21.34 ± 4.50
South Urals	Tundra		21.92 ± 4.22	11.99 ± 2.48
	Treeline	Open	26.77 ± 3.84	13.80 ± 2.67
	Treeline	Tree	40.31 ± 2.14	16.37 ± 2.22
	Forest	Open	39.59 ± 2.43	15.43 ± 1.86
	Forest	Tree	45.86 ± 4.36	19.34 ± 2.32
Significance				
Region			0.003	0.041
Elevation			<0.0001	0.0022
Vegetation			<0.0001	0.0073
Region x Elevation			0.6	0.15
Region x Vegetation			0.2	0.14