Supplement

Changing sub-Arctic tundra vegetation upon permafrost degradation: impact on foliar mineral element cycling

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Text S.1. Method to correct pXRF measurements using linear regressions between pXRF and ICP OES total element measurements he logo of Copernicus Publications.

For trueness of the total element concentrations measured by pXRF on the total set of foliar samples (n=506), we calibrated the pXRF measurements with another accurate analytical method. For 90 foliar and litter samples, we compared the total elemental concentrations (Al, Ca, Fe, K, Mn, P, S, Si, and Zn) measured by pXRF with the concentrations of the same elements measured by ICP-OES (iCAP 6500 ThermoFisher Scientific, Waltham, USA) after sample dissolution by alkaline fusion. For the fusion, a portion of the ground sample was mixed with lithium metaborate and lithium tetraborate and heated up to 1000°C. The fusion bead was dissolved in HNO3 2.2 N at 80°C and stirred until complete dissolution (Chao and Sanzolone, 1992). The loss on ignition was assessed at 500°C and total element content was expressed in reference to the dry weight at 60°C. Trueness of the analytical measurement by ICP-OES was validated by repeated measurements on the lichen reference material IAEA-336 Lichen (Heller-Zeisler et al., 1999). For the selected mineral elements (Al, Ca, Fe, K, Mn, P, S, Si, and Zn), the linear regressions based on the two analytical methods (pXRF and ICP-OES) presented coefficients of correlation (R^2) between the two methods higher than 0.7, except for Fe at 0.6 and S at 0.5 (Figure S1).

Figure S.1. Linear regressions between XRF and ICP OES measurements of mineral element concentration (Al, Ca, Fe, K, Mn, P, S, Si, Zn) from organic matrices (foliar tissues and soil litter).

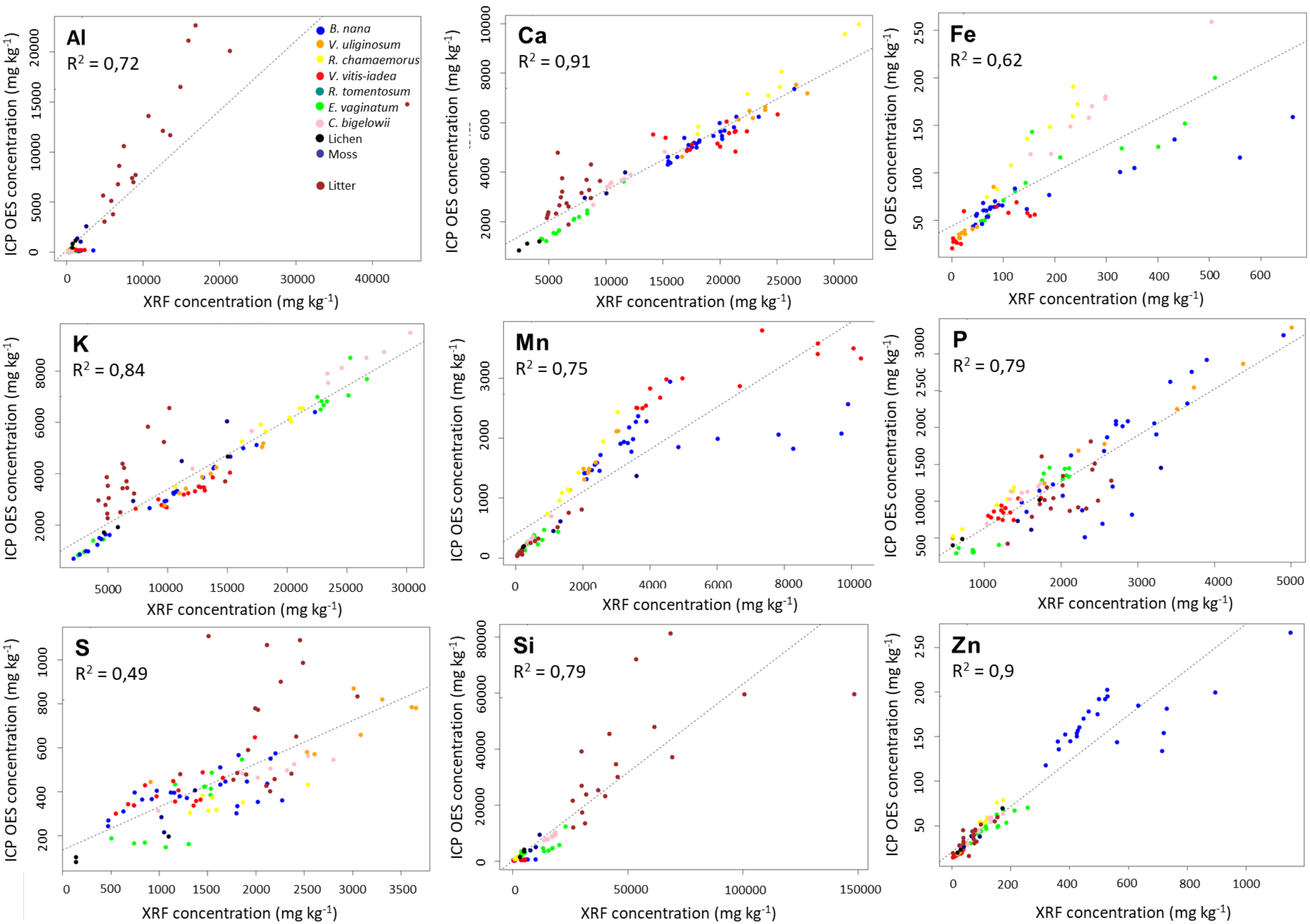

Figure S.2. Cumulative foliar stocks (mg m-2) of mineral elements (K, Al, P, S, Fe, and Zn) into typical moist acidic tundra species. At the Carbon in Permafrost Experimental Heating Research (CiPEHR), elemental content of mosses and lichens was not measure. The four treatments (Control, Summer warming, Winter warming and Annual warming) refer respectively to no artificial treatment, air warming, soil warming and both (air and soil) warming. Vegetation species are sorted by plant functional types; deciduous shrubs and forbs (green), evergreen shrubs (blue), and sedges (yellow). Letters correspond to a mixed model analysis and compare the total foliar elemental stocks between warming treatments and years. Error bars represent standard deviations.

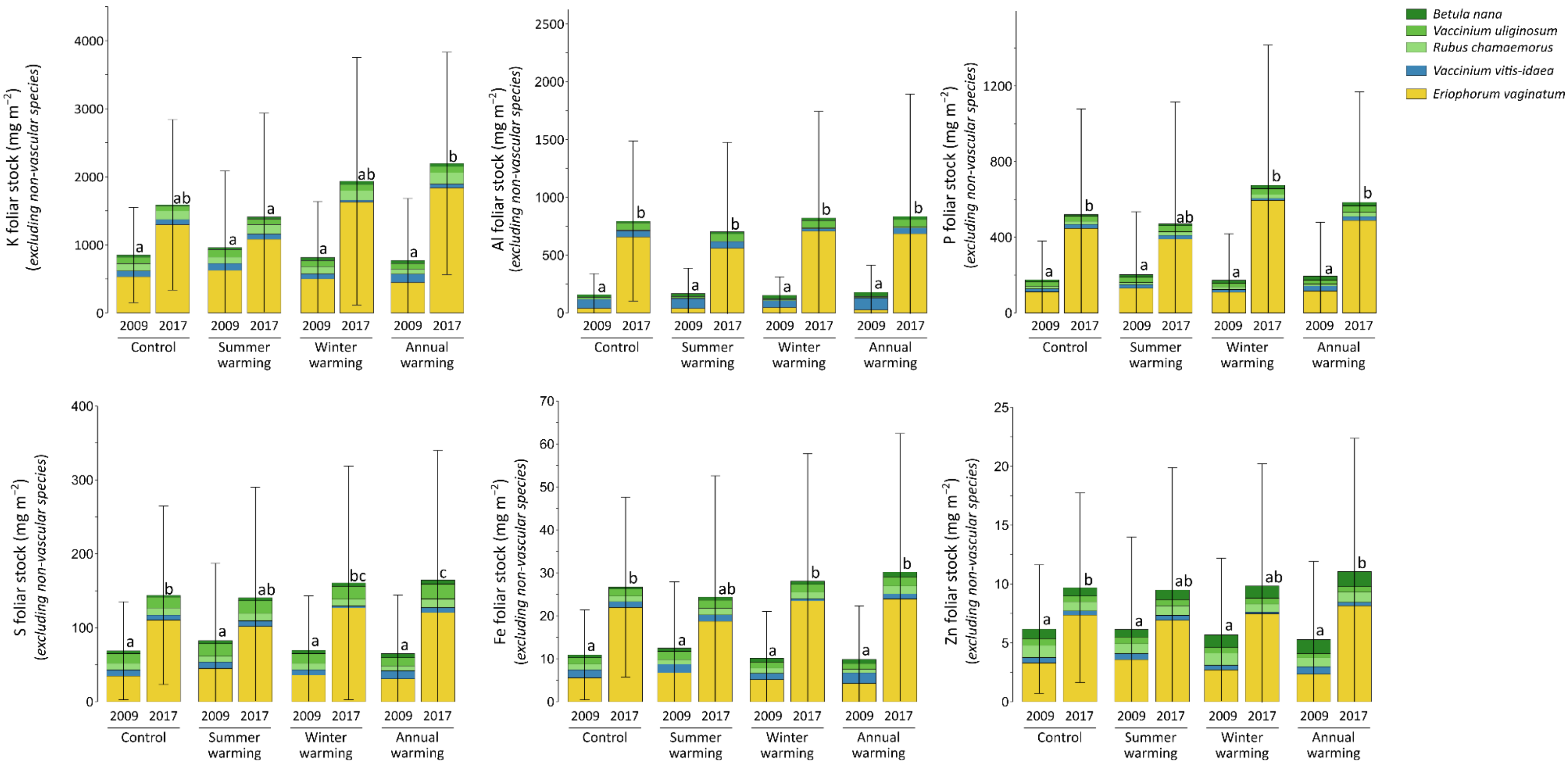

Figure S.3. Cumulative foliar stocks (mg m-2) of mineral elements (K, Al, P, S, Fe, and Zn) into typical moist acidic tundra species. The natural thermokarst gradient (Gradient site) displays three stages of permafrost degradation, classified as Minimal, Moderate and Extensive, based on permafrost thaw and subsidence rate. Vegetation species are sorted by plant functional types: deciduous shrubs and forbs (green), evergreen shrubs (blue), sedges (yellow), lichens and mosses (red). Letters correspond to a one-way ANOVA test and compare the total foliar elemental stocks between the three stages of permafrost degradation at Gradient. Error bars represent standard deviations.

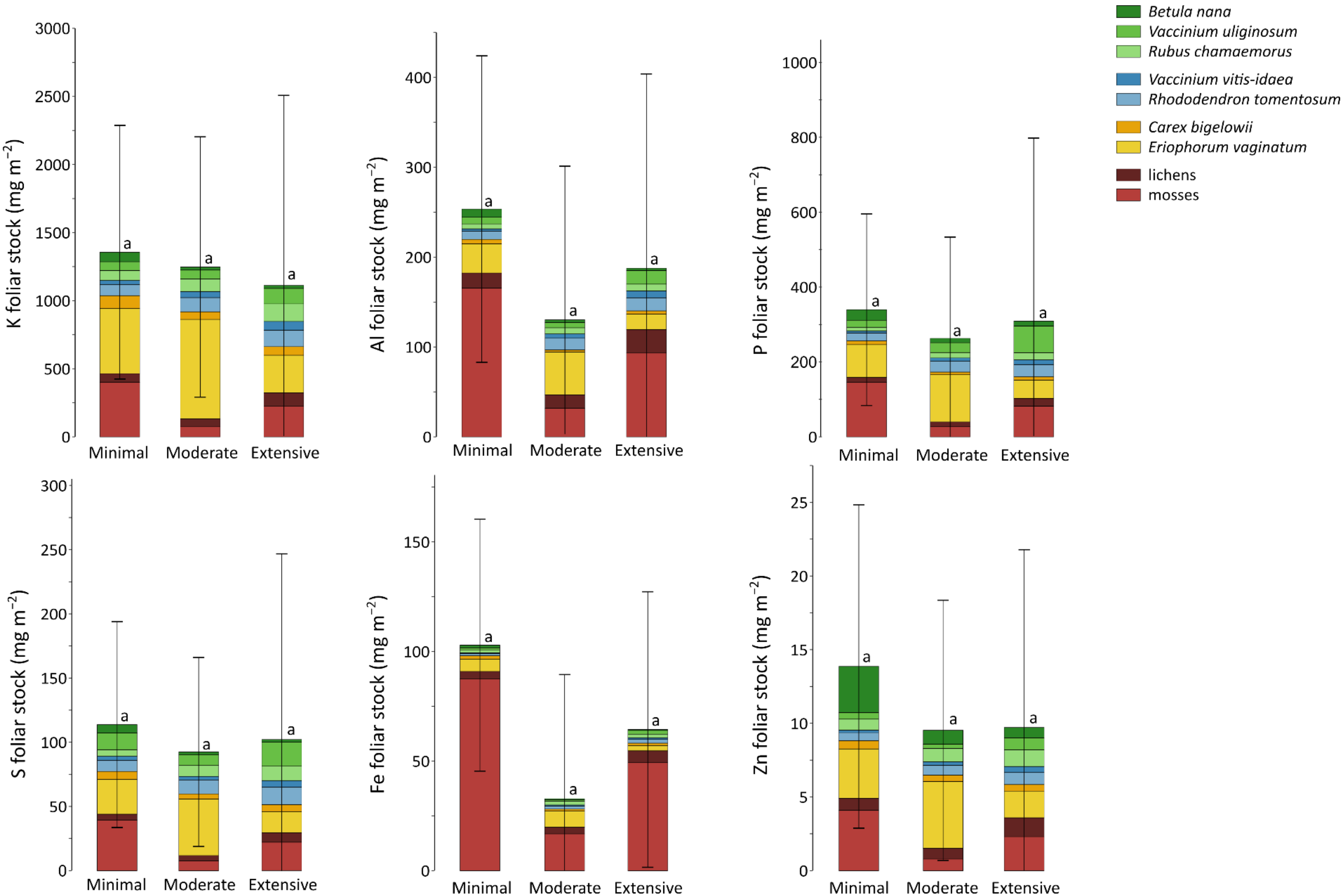

Figure S.4. Cumulative annual foliar fluxes (mg m-2 a-1) of mineral elements (K, Al, P, S, Fe, and Zn) from typical moist acidic tundra species. At the Carbon in Permafrost Experimental Heating Research (CiPEHR), the four treatments (Control, Summer warming, Winter warming and Annual warming) refer respectively to no artificial treatment, air warming, soil warming and both (air and soil) warming. Vegetation species are sorted by plant functional types: deciduous shrubs and forbs (green), and sedges (yellow). Letters correspond to a mixed model analysis and compare total foliar elemental fluxes between warming treatments and years. Error bars represent standard deviations.

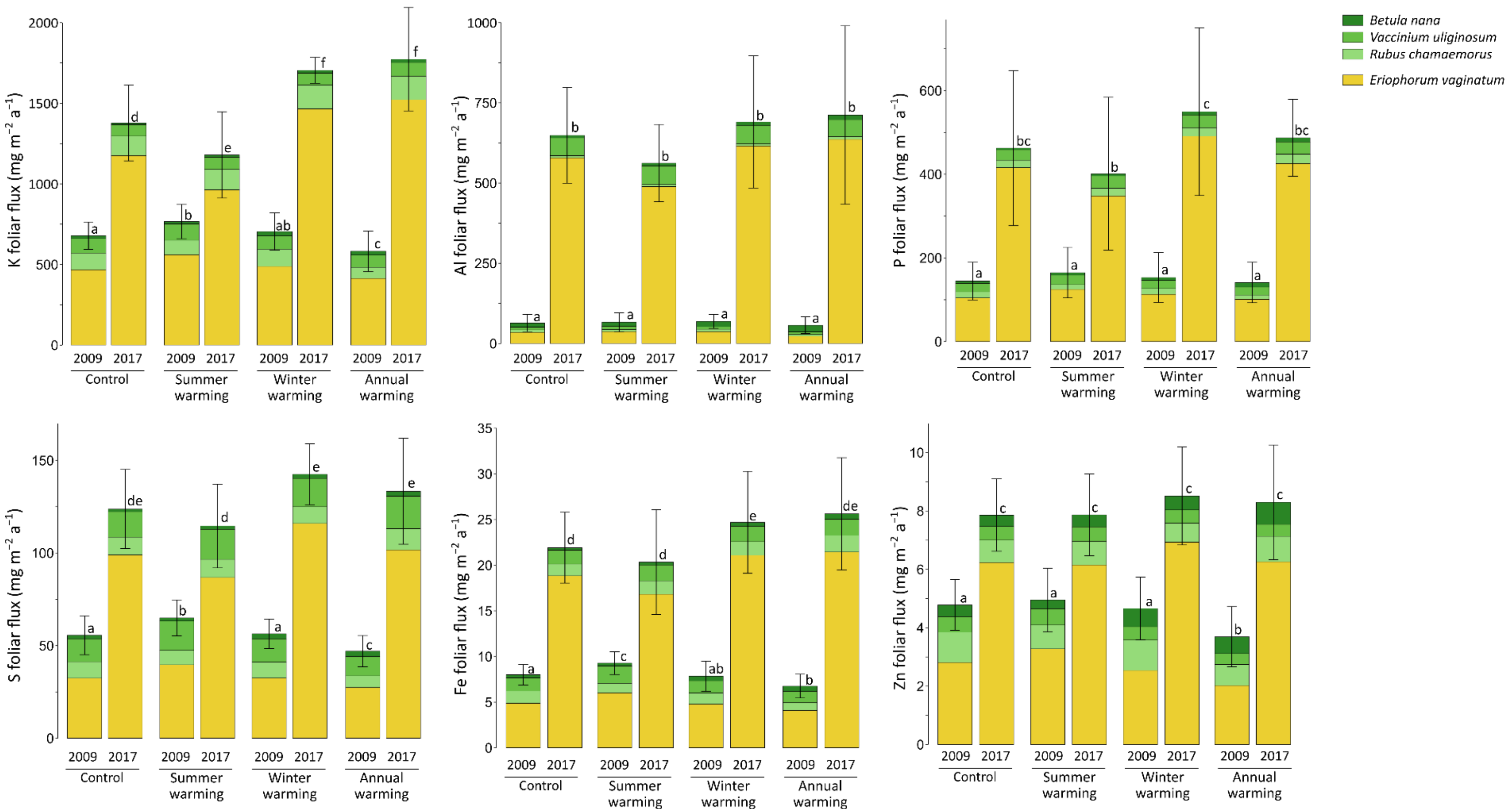

Figure S.5. Cumulative annual foliar fluxes (mg m-2 a-1) of mineral elements (K, Al, P, S, Fe, and Zn) from typical moist acidic tundra species. The natural thermokarst gradient (Gradient site) displays three stages of permafrost degradation, classified as Minimal, Moderate and Extensive, based on permafrost thaw and subsidence rate. Vegetation species are sorted by plant functional types: deciduous shrubs and forbs (green), and sedges (yellow). Letters correspond to one-way ANOVA test and compare total foliar elemental fluxes from the three stages of permafrost degradation at Gradient. Error bars represent standard deviations.

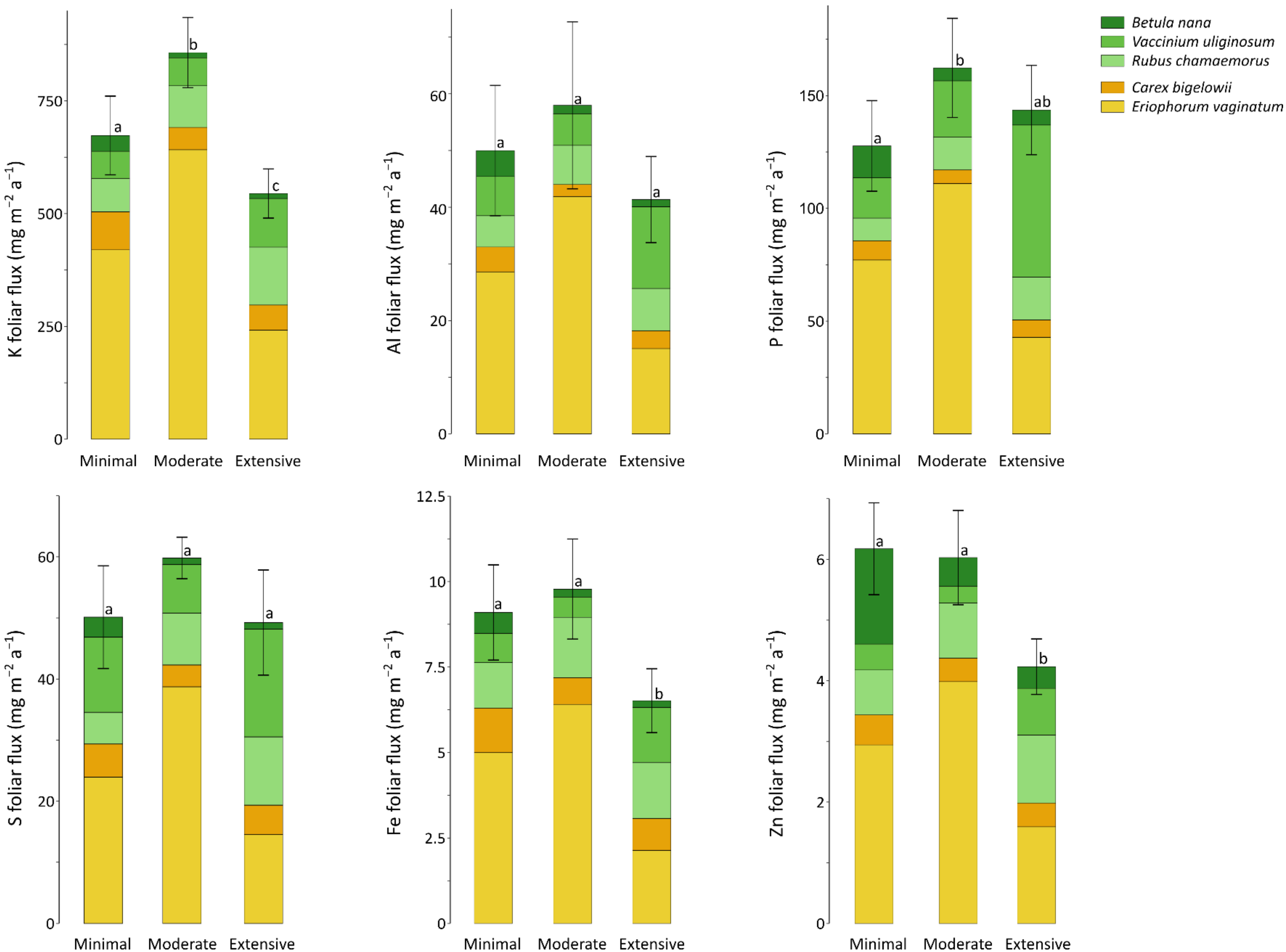

Table S.1. Number of leaf samples used for the pXRF measurements of total elements concentration, at the Carbon in Permafrost Experimental Heating Research (CiPEHR) in 2009 and 2017, and at the natural thermokarst gradient (Gradient site) in 2019.

Site	Year	Species	Number of leaf samples				
			Control	Summer warming	Winter warming	Annual warming	Total
CiPEHR	2009	*E.vaginatum*	12	12	12	12	48
CiPEHR	2009	*B. nana*	12	10	11	8	41
CiPEHR	2009	*V. uliginosum*	12	12	12	12	48
CiPEHR	2009	*R. chamaemorus*	12	12	12	12	48
CiPEHR	2009	*V. vitis-idaea*	12	12	12	12	48
CiPEHR	2017	*E.vaginatum*	12	12	9	7	40
CiPEHR	2017	*B. nana*	8	9	7	8	32
CiPEHR	2017	*V. uliginosum*	12	12	11	11	46
CiPEHR	2017	*R. chamaemorus*	10	11	12	10	43
CiPEHR	2017	*V. vitis-idaea*	12	11	9	11	43

Site	Year	Species	Number of leaf samples			
			Minimal	Moderate	Extensive	Total
Gradient	2019	*E.vaginatum*	3	3	3	9
Gradient	2019	*C. bigelowii*	3	3	3	9
Gradient	2019	*B. nana*	3	3	3	9
Gradient	2019	*V. uliginosum*	3	3	3	9
Gradient	2019	*R. chamaemorus*	3	3	3	9
Gradient	2019	*R. tomentosum*	3	3	3	9
Gradient	2019	*V. vitis-idaea*	3	3	3	9
Gradient	2019	Moss	undefined*	undefined*	undefined*	3
Gradient	2019	Lichen	undefined*	undefined*	undefined*	3

*Mosses and lichens were randomly sampled at Gradient and do not refer to a specific site. The total number of mosses and lichens corresponds to the three species sampled (for mosses: Sphagnum sp., Dicranum sp., and Brachytecium sp; for lichens: Nephroma sp., Cladonia sp., and Flavocetraria cucullata).

Table S.2. Ratios between foliar biomass and aboveground biomass for seven typical vascular plant species from moist acidic tundra (Salmon et al., 2016; Schuur et al., 2007).

Species	Plant functional type	Leave: aboveground ratio in biomass tissue allocation
E. vaginatum	Sedge	0.63
C. bigelowii	Sedge	0.79
B. nana	Dec. shrub	0.34
V. uliginosum	Dec. shrub	0.28
R. chamaemorus	Forb	0.91
R. tomentosum	Evergr. shrub	0.39
V. vitis-idaea	Evergr. shrub	0.66

Table S.3. Vascular and non-vascular foliar biomasses (means (μ), standard deviations (σ), and relative standard deviation (RDS)) from typical moist acidic tundra species, at Carbon in Permafrost Experimental Heating Research (CiPEHR) in 2009 and in 2017 (Taylor et al., 2018), and natural thermokarst gradient (Gradient site) in 2017 (Jasinski et al., 2018). The ratios between foliar and aboveground biomasses come from Salmon et al. (2016) and Schuur et al. (2007).

Site	Year	Species	Plant functional type	Foliar biomass (g m^{-2})											
				Control			Summer warming			Winter warming			Annual warming		
				Mean (μ)	SD (σ)	RSD (σ/μ)	Mean (μ)	SD (σ)	RSD (σ/μ)	Mean (μ)	SD (σ)	RSD (σ/μ)	Mean (μ)	SD (σ)	RSD (σ/μ)
CiPEHR	2009	*E. vaginatum*	Sedge	61.83	38.09	62%	75.79	76.07	100%	57.04	44.11	77%	47.28	45.38	96%
CiPEHR	2009	*C. bigelowii*	Sedge	5.54	4.39	79%	8.43	6.48	77%	9.30	6.56	71%	9.93	5.81	59%
CiPEHR	2009	*Betula nana*	Dec. shrub	4.51	4.86	108%	3.85	5.52	143%	6.21	7.77	125%	5.98	8.91	149%
CiPEHR	2009	*V. uliginosum*	Dec. shrub	15.31	4.14	27%	18.32	8.87	48%	14.28	5.78	41%	11.66	4.88	42%
CiPEHR	2009	*R. chamaemorus*	Forb	14.36	5.96	42%	12.54	4.87	39%	13.55	2.66	20%	10.13	6.60	65%
CiPEHR	2009	*R. tomentosum*	Evergr. shrub	26.06	13.96	54%	26.65	13.07	49%	31.78	14.02	44%	27.59	9.82	36%
CiPEHR	2009	*V. vitis-idaea*	Evergr. shrub	16.62	13.11	79%	18.96	11.35	60%	13.17	5.58	42%	21.36	15.70	74%
CiPEHR	2009	Mosses	Moss	44.55	16.63	37%	45.86	19.93	43%	41.03	13.37	33%	47.24	20.73	44%
CiPEHR	2009	Lichens	Lichen	39.81	30.93	78%	33.08	24.97	75%	42.06	23.80	57%	34.84	38.00	109%
CiPEHR	2009	**Total**		**228.61**			**243.48**			**228.42**			**216.02**		

Site	Year	Species	Plant functional type	Foliar biomass (g m^{-2})											
				Control			Summer warming			Winter warming			Annual warming		
				Mean (μ)	SD (σ)	RSD (σ/μ)	Mean (μ)	SD (σ)	RSD (σ/μ)	Mean (μ)	SD (σ)	RSD (σ/μ)	Mean (μ)	SD (σ)	RSD (σ/μ)
CiPEHR	2017	*E. vaginatum*	Sedge	149.14	84.64	57%	130.52	110.26	84%	161.35	98.55	61%	161.48	123.87	77%
CiPEHR	2017	*C. bigelowii*	Sedge	2.40	1.64	68%	2.84	3.15	111%	8.87	11.52	130%	4.06	1.69	42%
CiPEHR	2017	*Betula nana*	Dec. shrub	3.46	4.29	124%	4.02	6.26	156%	4.80	5.61	117%	6.03	8.78	146%
CiPEHR	2017	*V. uliginosum*	Dec. shrub	13.39	4.31	32%	14.61	4.70	32%	14.11	6.83	48%	13.88	9.97	72%
CiPEHR	2017	*R. chamaemorus*	Forb	15.16	9.93	65%	16.44	6.99	43%	14.65	8.25	56%	19.11	8.63	45%
CiPEHR	2017	*R. tomentosum*	Evergr. shrub	33.68	17.12	51%	31.97	14.84	46%	35.94	17.21	48%	33.53	17.91	53%
CiPEHR	2017	*V. vitis-idaea*	Evergr. shrub	11.26	3.87	34%	12.79	9.45	74%	3.97	5.26	132%	8.13	3.72	46%
CiPEHR	2017	Mosses	Moss	29.52	20.61	70%	23.29	25.60	110%	15.98	16.67	104%	32.41	50.78	157%
CiPEHR	2017	Lichens	Lichen	36.56	40.40	111%	21.32	30.27	142%	7.60	10.74	141%	12.20	28.60	235%
CiPEHR	2017	**Total**		**294.57**			**257.81**			**267.28**			**290.81**		

Site	Year	Species	Plant functional type	Foliar biomass (g m^{-2})								
				Minimal			Moderate			Extensive		
				Mean (μ)	SD (σ)	RSD (σ/μ)	Mean (μ)	SD (σ)	RSD (σ/μ)	Mean (μ)	SD (σ)	RSD (σ/μ)
Gradient	2017	*E. vaginatum*	Sedge	61.69	30.16	49%	89.23	33.32	37%	33.74	52.34	155%
Gradient	2017	*C. bigelowii*	Sedge	8.24	3.09	37%	5.16	2.67	52%	5.95	3.12	52%
Gradient	2017	*Betula nana*	Dec. shrub	14.77	15.01	102%	5.04	5.89	117%	4.25	5.06	119%
Gradient	2017	*V. uliginosum*	Dec. shrub	14.13	3.34	24%	11.07	4.69	42%	24.47	20.80	85%
Gradient	2017	*R. chamaemorus*	Forb	14.25	4.60	32%	19.51	3.26	17%	24.60	14.64	60%
Gradient	2017	*R. tomentosum*	Evergr. shrub	28.24	12.56	44%	35.42	14.22	40%	43.34	15.45	36%
Gradient	2017	*V. vitis-idaea*	Evergr. shrub	6.18	5.53	89%	8.51	5.14	60%	13.98	10.91	78%
Gradient	2017	Mosses	Moss	108.77	125.10	115%	20.89	19.54	94%	61.30	48.71	79%
Gradient	2017	Lichens	Lichen	20.96	16.91	81%	18.65	21.08	113%	32.67	38.63	118%
Gradient	2017	**Total**		**277.23**			**213.49**			**244.29**		

Table S.4. Foliar net primary productivity (NPP) adapted from Schuur et al. (2007), at Carbon in Permafrost Experimental Heating Research (CiPEHR) in 2009 and in 2017, and at the natural thermokarst gradient (Gradient site) in 2017.Figure 1: The logo of Copernicus Publications.

Site	Species	Plant functional type	**2009** Foliar NPP (g m^{-2} a^{-1})				**2017** Foliar NPP (g m^{-2} a^{-1})			
			Control	Summer warming	Winter warming	Annual warming	Control	Summer warming	Winter warming	Annual warming
CiPEHR	*E. vaginatum*	Sedge	57.74	70.77	53.27	44.15	139.26	121.88	150.67	150.79
CiPEHR	*C. bigelowii*	Sedge	6.63	10.08	11.12	11.87	2.87	3.40	10.61	4.85
CiPEHR	*Betula nana*	Dec. shrub	2.87	2.45	3.95	3.81	2.20	2.56	3.05	3.83
CiPEHR	*V. uliginosum*	Dec. shrub	15.98	19.11	14.90	12.17	13.97	15.25	14.72	14.48
CiPEHR	*R. chamaemorus*	Forb	12.08	10.54	11.40	8.52	12.75	13.82	12.32	16.07

Site	Species	Plant functional type	**2017** Foliar NPP (g m^{-2} a^{-1})		
			Minimal Thaw	Moderate Thaw	Extensive Thaw
Gradient	*E. vaginatum*	Sedge	57.61	83.32	31.50
Gradient	*C. bigelowii*	Sedge	9.86	6.17	7.12
Gradient	*Betula nana*	Dec. shrub	9.39	3.20	2.70
Gradient	*V. uliginosum*	Dec. shrub	14.74	11.55	25.53
Gradient	*R. chamaemorus*	Forb	11.99	16.41	20.69

Table S.5. Results of mixed model (*Lmer4* package in R 4.0.2 (R Core Team, 2020)) on foliar mineral element stocks and maximum potential litterfall fluxes at CiPEHR. We included individual plots as random factors, and year (2009 and 2017) and treatments (control, summer warming, winter warming, and annual warming) as covariates. The model includes interactions between treatments (summer × winter), and between treatments and years (2009 and 2017).

	Foliar stocks at CiPEHR						Foliar fluxes at CiPEHR					
Mineral element	Al §		Ca		Fe §		Al §		Ca		Fe §	
	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value
Intercept (Control)	4.95	***	395.23	***	2.35	***	4.12	***	276.00	***	2.08	***
Winter	0.03		-50.75		-0.12		0.07		-21.16		-0.03	
Summer	0.13		-10.49		-0.05		0.05		10.53		0.16	*
Year2017	1.50	***	61.55		0.75	***	2.33	***	104.25	***	0.99	***
*Winter*Summer*	-0.19		-64.52		-0.13		-0.19		-65.17	**	-0.29	**
Winter:Year2017	0.54		0.95		0.39		0.09		20.28		0.25	*
*Summer*Year2017*	-0.44		-14.48		-0.26		-0.17		5.52		-0.22	*
*Winter*Summer*Year2017*	0.24		264.21	*	0.45		0.09		83.74	*	0.23	
Mineral element	K		Mn §		P §		K		Mn		P §	
	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value
Intercept (Control)	852.17	***	4.86	***	5.10	***	678.20	***	70.07	***	4.96	***
Winter	-40.36		-0.15		-0.06		25.45		0.23		0.06	
Summer	-28.33		0.07		-0.27		88.87	*	14.43	**	0.12	
Year2017	743.76	**	0.11		0.96	***	623.55	***	38.54	***	1.12	***
*Winter*Summer*	-114.18		-0.23		0.09		-205.60	***	-24.04	**	-0.18	
Winter:Year2017	582.14		0.19		0.49		299.80	*	14.12		0.14	
*Summer*Year2017*	-329.54		-0.04		-0.19		-284.88	**	-9.90		-0.26	
*Winter*Summer*Year2017*	548.39		0.43		0.12		480.90	**	17.60		0.16	
Mineral element	S		Si §		Zn		S §		Si §		Zn	
	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value
Intercept (Control)	68.92	***	6.22	***	6.17	***	4.01	***	5.73	***	4.78	***
Winter	-1.34		0.06		-0.69		0.02		0.13		-0.15	
Summer	3.12		0.08		-0.84		0.17	**	0.15		0.24	
Year2017	66.65	***	1.25	***	3.17	**	0.77	***	1.77	***	2.81	***
*Winter*Summer*	-15.30		-0.03		-0.56		-0.35	***	-0.11		-1.39	*
Winter:Year2017	23.24		0.43		-0.32		0.12		0.05		0.79	
*Summer*Year2017*	-16.11		-0.39		-0.33		-0.20	*	-0.22		0.22	
*Winter*Summer*Year2017*	67.23		0.27		4.65		0.40	*	0.13		1.40	

Notes: The p-value asterisks indicate level of significance: $p < 0.05$ (*), $p < 0.01$(**), $p < 0.001$ (***), and not significant (blank). Some mineral element foliar stocks were log-transformed (§) to achieve homogeneity of variance.