Oikos

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Appendix 1

Table A1. Overview of the sampling schedule for plant leaf collection. In total, seven sampling occasions have been performed throughout the summer season of 2015 in all 96 plots, spanning from the end of June soon after snowmelt (28–30 of June, days of the year [DOY]: 179–181) to mid September before the first snowfall (8–10 of September, DOY: 251–253). Day of the year (DOY, i.e. seasonality) has been used as continuous predictor of plant leaf nitrogen and phosphorus contents in data analysis (see main text for details).

Sampling occasion	**Sample collection (fieldwork)**	**Day of the year (DOY)**
1	28 - 30 June	179 - 181
2	10 - 12 July	191 - 193
3	23 - 25 July	204 - 206
4	3 - 5 August	215 - 217
5	13 - 15 August	225 - 227
6	26 - 28 August	238 - 240
7	8 - 10 September	251 - 253

Table A2. Overview of the plant leaf samples collected from the main species/genera within the experiment. In total, 2831 plant leaf samples were collected from 34 species/genera and utilized in the present study to assess the effects of small-rodent winter disturbance, reindeer summer herbivory, and seasonality on plant leaf nitrogen and phosphorus contents within tundra-grasslands. Number of plant leaf samples are given for each species/genera and further summarized within each plant functional type (PFT). Plant leaf samples for each species/genera are grouped by grassland-types (i.e. forb-dominated and grass-dominated tundra-grasslands) and sampling occasion (from one to seven, Supplementary material Appendix 1 Table A1).

Plant functional type (PFT)	Species	Forb-dominated grasslands							Grass-dominated grasslands						
		1	2	3	4	5	6	7	1	2	3	4	5	6	7
Forbs	*Alchemilla* spp.	14	12	17	12	17	16	15	0	1	0	1	3	3	3
	Astragalus spp.	2	2	0	2	1	4	3	0	0	0	0	0	0	1
	Bistorta vivipara	19	17	7	15	18	12	4	32	33	25	17	45	34	15
	Cirsium spp.	0	0	2	0	0	1	0	0	0	0	0	0	0	0
	Geranium sylvaticum	13	18	17	18	16	13	7	1	0	0	0	0	0	0
	Gnaphalium supinum	1	0	0	0	1	2	0	0	0	0	0	0	1	0
	Hieracium spp.	0	0	0	0	1	1	0	0	0	0	0	0	8	0
	Leontodon spp.	2	0	0	0	0	0	0	3	0	0	0	0	0	0
	Omalotheca norvegica	0	2	0	2	2	2	2	1	0	0	0	0	1	1
	Potentilla spp.	0	0	0	0	0	0	0	0	0	0	0	1	2	0
	Pyrola spp.	1	2	2	2	2	4	1	0	0	0	2	2	0	1
	Ranunculus spp.	0	1	1	4	3	1	2	7	7	6	4	9	8	14
	Rumex acetosa	7	11	5	15	17	16	10	2	11	3	4	14	15	7
	Saussurea spp.	4	2	0	6	8	3	3	0	0	0	0	0	0	1
	Sibbaldia spp.	1	4	0	5	8	5	4	0	2	0	0	3	2	2
	Solidago virgaurea	4	24	17	26	33	24	19	0	4	2	1	11	14	6
	Taraxacum spp.	0	4	1	2	2	2	3	0	2	0	6	15	11	12
	Trientalis europaea	1	3	0	1	5	5	1	1	2	1	0	3	6	2
	Trollius spp.	13	11	10	17	15	20	8	4	2	5	3	4	5	4
	Vicia spp.	0	0	2	1	4	0	0	0	0	0	0	0	0	0
	Viola spp.	26	20	14	14	30	20	5	4	8	4	7	14	25	10
	TOTAL FORBS	**108**	**133**	**95**	**142**	**183**	**151**	**87**	**55**	**72**	**46**	**45**	**124**	**135**	**79**
Grasses	*Avenella flexuosa*	3	0	6	0	18	34	33	1	0	4	1	5	7	12
	Calamagrostis phragmitoides	7	11	6	12	15	12	14	14	19	25	25	37	30	25
	Deschampsia cespitosa	4	0	10	2	1	1	2	6	8	6	6	8	3	3
	Nardus stricta	0	1	0	0	0	1	0	34	23	25	31	34	34	37
	Poa spp.	34	40	36	41	34	37	28	26	37	36	28	19	42	35
	TOTAL GRASSES	**48**	**52**	**58**	**55**	**68**	**85**	**77**	**81**	**87**	**96**	**91**	**103**	**116**	**112**
Sedges	*Carex* spp.	3	6	2	7	2	2	6	5	7	4	8	10	12	16
Deciduous shrubs	*Salix herbacea*	0	2	2	8	2	2	9	2	10	0	0	10	1	7
	Salix spp.	2	2	2	11	0	9	5	3	0	0	1	0	7	3
Evergreen shrubs	*Empetrum nigrum*	0	0	0	0	0	0	1	0	0	0	0	0	0	0
	Vaccinium myrtillus	1	2	1	0	1	1	2	0	0	0	0	0	0	0
	Vaccinium vitis-idaea	2	2	1	2	3	2	3	1	0	0	2	1	2	0
Rushes	*Luzula* spp.	0	0	0	0	0	0	0	0	0	0	0	0	2	0
Horsetails	*Equisetum* spp.	0	6	2	6	1	1	0	3	3	1	1	1	0	0

Table A3. Plant functional type (PFT) above-ground biomass and soil environmental characteristics within tundra-grasslands. Summary statistics for (a) PFT above-ground biomass (g m^{-2}) and (b) soil environmental characteristics in forb-dominated and grass-dominated tundra-grasslands. Mean, standard deviation [SD], and number of sampled plots [n] are shown. (a) Above-ground biomass for forbs, grasses, sedges, and deciduous shrubs is presented (overall, 98% of the above-ground biomass across our tundra-grasslands). Above-ground biomass for evergreen shrubs, rushes, and horsetails (overall, 2% of the above-ground biomass across our tundra-grasslands) is not shown. (b) Soil moisture data were collected in three random spots within each plot at each sampling occasion (except occasion one, 28–30 of June) using a SM150 soil moisture sensor (Delta-T Devices, Cambridge, UK). Measurements were firstly registered as millivolt units (mV) and later converted to soil moisture (m^3H_2O/m^3Soil or %vol) using the polynomial conversion for a generalized organic soil (SM150 manual). First, we took the average of the three soil moisture measurements in each plot to obtain a soil moisture average per plot at each sampling occasion. We then averaged plot-mean soil moisture across sampling occasions in order to obtain a single soil moisture value per plot that was representative for the whole growing season (i.e. seasonal-average soil moisture, which is represented here). Given the high correlation between seasonal-average soil moisture and average soil moisture at each sampling occasion (Supplementary material Appendix 1 Fig. A6), seasonal-average soil moisture is used in Supplementary material Appendix 1 Fig. A3 because more likely biologically relevant in determining a differentiation between tundra-grassland plant communities in the long-term. In sampling occasion five (13–15 of August), three samples of organic soil were collected from all plots using a soil sample cylinder (25 mm Ø and 30-50 mm deep). However, due to logistic constraints, only half of the reindeer-exclusion plots were sampled. Within maximum 16 hours after collection, soil samples were transported to the laboratory and stored in a refrigerator at 3−4°C until further analyses. Immediately after collection and during the transport to the laboratory, soil samples were placed in a Styrofoam box with ice to maintain low temperatures. The three samples of organic soil belonging to each plot were pooled together prior to analyses. Half of the material was used to assess soil pH, whereas the remaining soil sample was oven-dried at 60°C for 48 h. Following the same procedure applied to plant leaf samples (see main text for details), we first created near infrared reflectance spectroscopy (NIRS) prediction models for organic soil (Supplementary material Appendix 1 Fig. A7) and finally used NIRS to analyse our samples for their nitrogen (N) and phosphorus (P) contents (% of dry weight – %DW) (for a similar approach, see Viscarra Rossel et al. 2016). Soil pH, soil N-content, and soil P-content are used in Supplementary material Appendix 1 Fig. A3.

	Forb-dominated grasslands			Grass-dominated grasslands		
(a) **Plant functional type (PFT)**	mean	±SD	n	mean	±SD	n
Forbs (g/m²)	81.9	62.3	48	19.1	14.1	48
Grasses (g/m²)	100.6	68.6	48	108.8	48.5	48
Sedges (g/m²)	4.0	10.2	48	4.5	7.7	48
Deciduous shrubs (g/m²)	8.9	14.6	48	1.2	3.4	48
(b) **Soil features**	mean	±SD	n	mean	±SD	n
Moisture (%vol)	44.06	13.03	48	66.20	11.13	48
Nitrogen (%DW)	9.49	3.37	35	13.14	4.30	36
Phosphorus (%DW)	1.37	0.56	35	1.81	0.67	36
pH	4.29	0.27	35	4.25	0.26	36

Table A4. Parameter estimates for linear (mixed-effects) models for the effects of herbivores on leaf nutrient contents of sedges found in tundra-grasslands. Parameter estimates (Estimates) and their 95% confidence interval (CI – lower and upper bounds) for the most parsimonious models in which predictors are 'small-rodent winter disturbance' (two-level factor: undisturbed [Ro−] and disturbed [Ro+]), 'reindeer summer herbivory' (two-level factor: reindeer-exclusion [Re−] and reindeer-open [Re+]), and 'seasonality' (continuous variable: seven sampling occasions throughout the summer; day of the year [DOY]) and responses are (a) leaf nitrogen [N] content and (b) leaf phosphorus [P] content (% of dry weight – %DW) in sedges found across forb-dominated and grass-dominated tundra-grasslands (see main text for details). Intercept is calculated for undisturbed tundra-patches (Ro−), reindeer-exclusion plots (Re−), and first sampling occasion (DOY 180, 29 June). Estimates with bold indicate that their 95% CI does not include 0. Random effects retained in the final models are presented as standard deviations. For leaf P-content, a linear model was fitted since no random effects were retained in the most parsimonious model, thus 'residual' represents the standard error of the residuals. Observations refer to the number of plant leaf samples used in each model (3.2% of the collected plant leaf samples). Marginal R^2 represents the variance explained by the model when only fixed-effects are considered, whereas the conditional R^2 represents the variance explained by the model when both fixed- and random-effects are considered. For leaf P-content, which is described by a linear model without random-effects, the first value refers to the un-adjusted R^2, whereas the second value refers to the adjusted R^2. Specifications of the fitted models are presented in Supplementary material Appendix 2 and results are displayed in Supplementary material Appendix 1 Fig. A4.

	(a) Nitrogen (%DW)		**(b) Phosphorus (%DW)**	
Fixed effects (Predictors)	Estimates	CI (95%)	Estimates	CI (95%)
(*Intercept*) [Ro– / Re– / DOY = 180]	**3.15** ***	**2.80** ; **3.50**	**0.262** ***	**0.228** ; **0.295**
Small-rodent winter disturbance [Ro+]	**0.39** *	**0.03** ; **0.73**	0.005	–0.021 ; 0.031
Reindeer summer herbivory [Re+]	–0.14	–0.38 ; 0.10	–0.012	–0.039 ; 0.014
Seasonality [+1 DOY]	**–0.017** ***	**–0.022** ; **–0.013**	**–0.0016** ***	**–0.0021** ; **–0.0010**
Random effects	SD		SD	
Grassland site : Tundra-patch	0.36			
Residual	0.48		0.061	
Observations	90		90	
Marginal R^2 / Conditional R^2	0.381 / 0.600		0.290 / 0.265	

* p<0.05 ** p<0.01 *** p<0.001

Table A5. Parameter estimates for linear (mixed-effects) models for the effects of herbivores on leaf nutrient contents of deciduous shrubs found in tundra-grasslands. Parameter estimates (Estimates) and their 95% confidence interval (CI – lower and upper bounds) for the most parsimonious models in which predictors are small-rodent winter disturbance (two-level factor: undisturbed [Ro−] and disturbed [Ro+]), reindeer summer herbivory (two-level factor: reindeer-exclusion [Re−] and reindeer-open [Re+]), and seasonality (continuous variable: seven sampling occasions throughout the summer; day of the year [DOY]) and responses are (a) leaf nitrogen [N] content and (b) leaf phosphorus [P] content (% of dry weight – %DW) in deciduous shrubs found across forb-dominated and grass-dominated tundra-grasslands (see main text for details). Intercept is calculated for undisturbed tundra-patches (Ro−), reindeer-exclusion plots (Re−), and first sampling occasion (DOY 180, 29th of June). Estimates with bold indicate that their 95% CI does not include 0. Random effects retained in the final models are presented as standard deviations. Empty cells indicate that a predictor was not statistically significant, thus it was removed from the model. For leaf P-content, a linear model was fitted since no random effects were retained in the most parsimonious model, thus 'residual' represents the standard error of the residuals. Observations refer to the number of plant leaf samples used in each model (3.5% of the collected plant leaf samples). Marginal R^2 represents the variance explained by the model when only fixed-effects are considered, whereas the conditional R^2 represents the variance explained by the model when both fixed- and random-effects are considered. For leaf P-content, which is described by a linear model without random effects, the first value refers to the un-adjusted R^2, whereas the second value refers to the adjusted R^2. Specifications of the fitted models are presented in Supplementary material Appendix 2 and results are displayed in Supplementary material Appendix 1 Fig. A5.

	(a) Nitrogen (%DW)		**(b) Phosphorus (%DW)**	
Fixed effects (Predictors)	Estimates	CI (95%)	Estimates	CI (95%)
(*Intercept*) [Ro– / Re– / DOY = 180]	**2.60** ***	**2.32** ; **2.89**	**0.242** ***	**0.214** ; **0.272**
Small-rodent winter disturbance [Ro+]	**0.91** ***	**0.57** ; **1.25**	**0.042** **	**0.018** ; **0.067**
Reindeer summer herbivory [Re+]	0.21	–0.05 ; 0.47	–0.004	–0.029 ; 0.021
Seasonality [+1 DOY]	**–0.009** ***	**–0.013** ; **–0.005**	**–0.0017** ***	**–0.0022** ; **–0.0012**
Herbivore interaction [Ro+ × Re+]	**–0.55** **	**–0.93** ; **–0.17**		
Random effects	SD		SD	
Grassland site : Tundra-patch	0.28			
Residual	0.44		0.061	
Observations	100		99	
Marginal R^2 / Conditional R^2	0.358 / 0.548		0.328 / 0.307	

* p<0.05 ** p<0.01 *** p<0.001

Table A6. Summary statistics for leaf nutrient contents of evergreen shrubs, rushes, and horsetails found in tundra-grasslands under different herbivore-treatment combinations. Summary statistics for (a) leaf nitrogen [N] content and (b) leaf phosphorus [P] content (% of dry weight, %DW) in evergreen shrubs, rushes, and horsetails (2% of the collected plant leaf samples), for which the sample sizes did not allow us to perform statistical analyses for the effects of herbivores on leaf nutrient contents at the plant functional type (PFT) level. For both (a) leaf N-content and (b) leaf P-content, the mean, standard deviation [SD], and number of samples [n] for each PFT are presented according to herbivore-treatment combinations: 1) Ro−/Re−: small-rodent undisturbed/reindeer-exclusion plots, 2) Ro−/Re+: small-rodent undisturbed/reindeer-open plots,3) Ro+/Re−: small-rodent disturbed/reindeer-exclusion plots, and 4) Ro+/Re+: small-rodent disturbed/reindeer-open plots (see main text for details). When the number of samples for a given herbivore-treatment combination was n < 3, the actual nutrient values for each sample are presented and the calculation of mean and SD has not been performed. Empty cells indi cate that no samples for a given herbivore-treatment combination were available.

Plant functional type (PFT)	**(A) Nitrogen %DW (±SD) [n]**			
	Ro−/Re−	Ro−/Re+	Ro+/Re−	Ro+/Re+
Evergreen shrubs	2.16 (0.79) [16]	1.69 (0.61) [9]	0.85;2.69	2.52 (0.14) [3]
Rushes	1.26		1.20	
Horsetails	3.56 (0.62) [10]	3.22 (0.37) [5]	3.96 (0.50) [7]	4.11 (0.34) [3]
	(B) Phosphorus %DW (±SD) [n]			
	Ro−/Re−	Ro−/Re+	Ro+/Re−	Ro+/Re+
Evergreen shrubs	0.140 (0.066) [15]	0.150 (0.083) [8]	0.088;0.270	0.209 (0.053) [3]
Rushes			0.128	
Horsetails	0.233 (0.087) [10]	0.252 (0.055) [5]	0.270 (0.086) [7]	0.299 (0.104) [3]

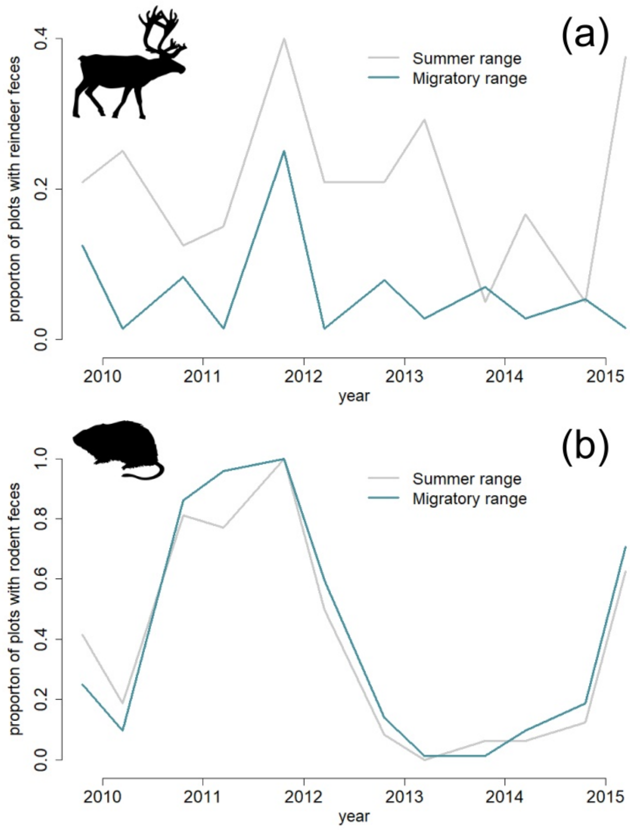

Figure A1. Time-series of faeces counts for small rodents and reindeer in the study area. Time-series (2010−2015) of faeces counts for (a) reindeer and (b) small rodents at permanent plots within tundra-grassland sites found in the study area. Nine grassland sites are monitored in the migratory range (i.e. in forb-dominated grasslands) and seven grassland sites are monitored in the summer range (i.e. in grass-dominated grasslands). At each grassland site, 8 permanent plots (50 × 50 cm) are cleaned from faeces twice a year; early July (1−3 July – spring/summer count) and early September (1−3 September – autumn count). The method was modified in 2013; since then small-rodent faeces were not removed at each count, and the presence of small rodents was recorded based on fresh faeces and/or other fresh signs of activity. Data are presented as the mean proportion of plots with herbivore presence, separately for summer (i.e. grass-dominated grasslands) and migratory (i.e. forb-dominated grasslands) ranges.

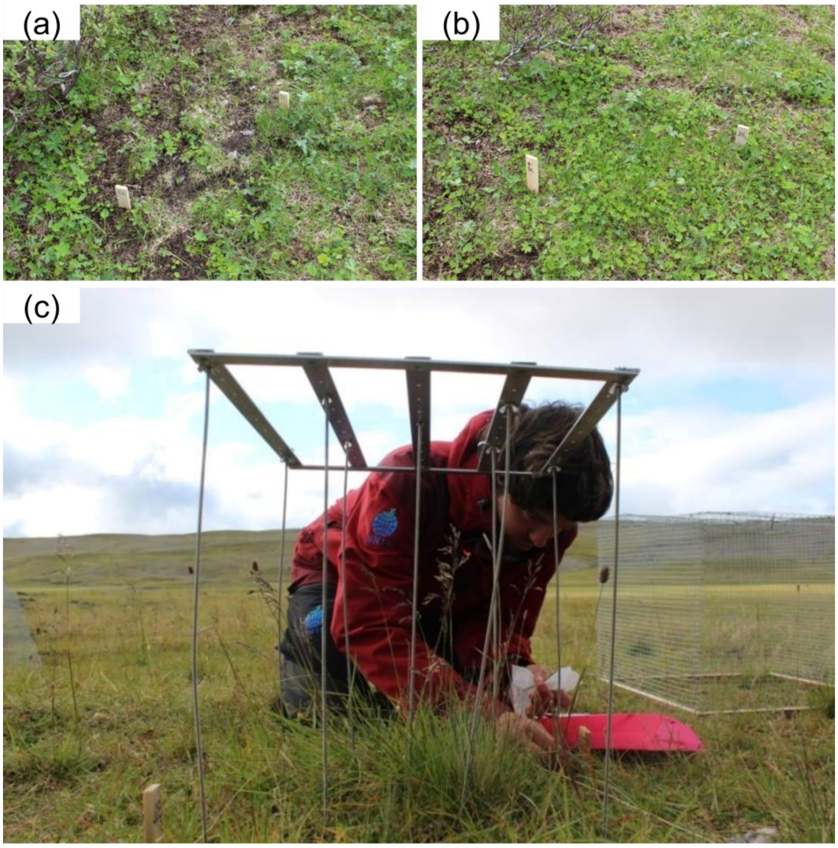

Figure A2. Contrast between (a) small-rodent disturbed (Ro+) and (b) small-rodent undisturbed (Ro−) tundra-patches, as selected for the present study, in one of the forb-dominated tundra-grasslands. Woody sticks marked one of the diagonal of each plot (photos: 10−12 of July 2015). (c) A metal frame with nine randomly-distributed pins is being utilized for conducting leaf sampling in an experimental plot in one of the grass-dominated tundra-grasslands (photos: 3−5 of August).

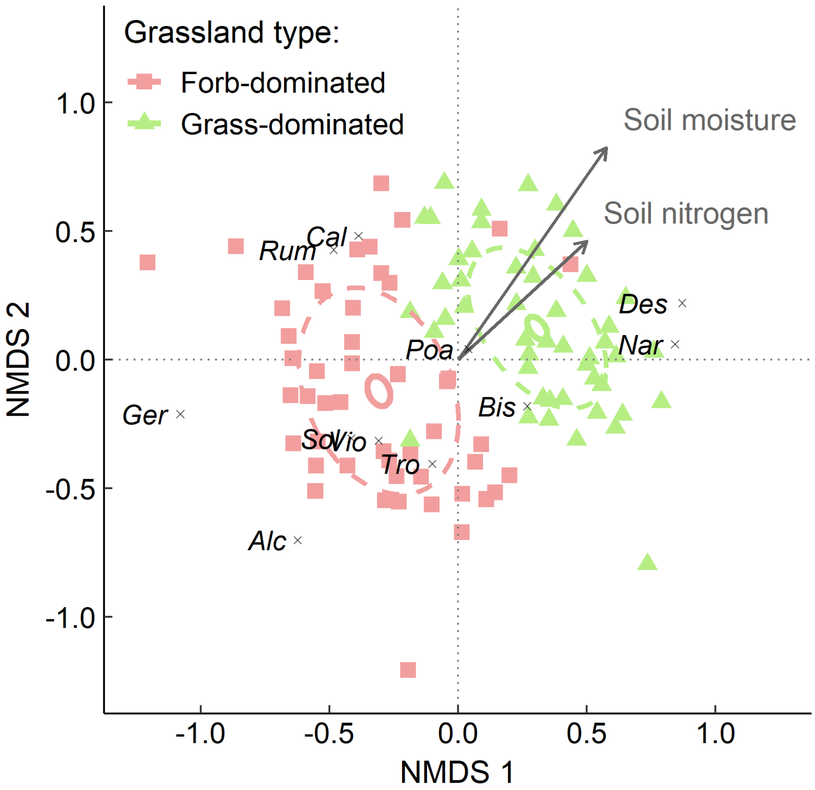

Figure A3. Plant species composition in tundra-grasslands. Two-dimensional NMDS ordination (based on Bray-Curtis dissimilarity index) of plot plant species/genera above-ground biomass (log-transformed [g m^{-2}]+1) within forb-dominated and grass-dominated tundra-grasslands (n = 96, stress = 0.25, Non-metric fit $r^2 = 0.94$, Linear fit $r^2 = 0.68$). Ellipses represent the 95% confidence interval for the mean (i.e. grassland-type centroids – solid lines) and for the standard deviation of the mean (dashed lines): Grassland-type: $R^2 = 0.18$, F-statistics = 20.1, $p < 0.001$ (via vegan package: ordiellipse-function and adonis-function run with 10 000 restricted permutations to account for the hierarchical spatial structure of the study design; see main text for details). Fit of the environmental parameters (i.e. soil environmental variables, Supplementary material Appendix 1 Table A3) when a posteriori regressed on the two axes of the biplot: Soil moisture: $r^2 = 0.45$, p = 0.01; Soil nitrogen-content: $r^2 = 0.21$, p = 0.04; Soil pH and soil phosphorus content did not significantly correlate with the NMDS ordination ($p > 0.1$) and thus are not displayed (envfit-function via vegan package run with 10 000 restricted permutations to account for the hierarchical spatial structure of the study design; see main text for details). The ordination shows only the main species/genera characterizing our tundra-grassland communities (species names abbreviated as follow: *Alc*: *Alchemilla* spp.; *Bis*: *Bistorta vivipara*; *Cal*: *Calamagrostis phragmitoides*; *Des*: *Deschampsia cespitosa*; *Ger*: *Geranium sylvaticum*; *Nar*: *Nardus stricta*; *Poa*: *Poa* spp.; *Rum*: *Rumex acetosa*; *Sol*: *Solidago virgaurea*; *Tro*: *Trollius* spp.; *Vio: Viola* spp. – see Supplementary material Appendix 1 Table A2). Specifications on the implementation of the NMDS ordination and details on statistical analyses of plant species composition and soil environmental variables are described in Supplementary material Appendix 2.

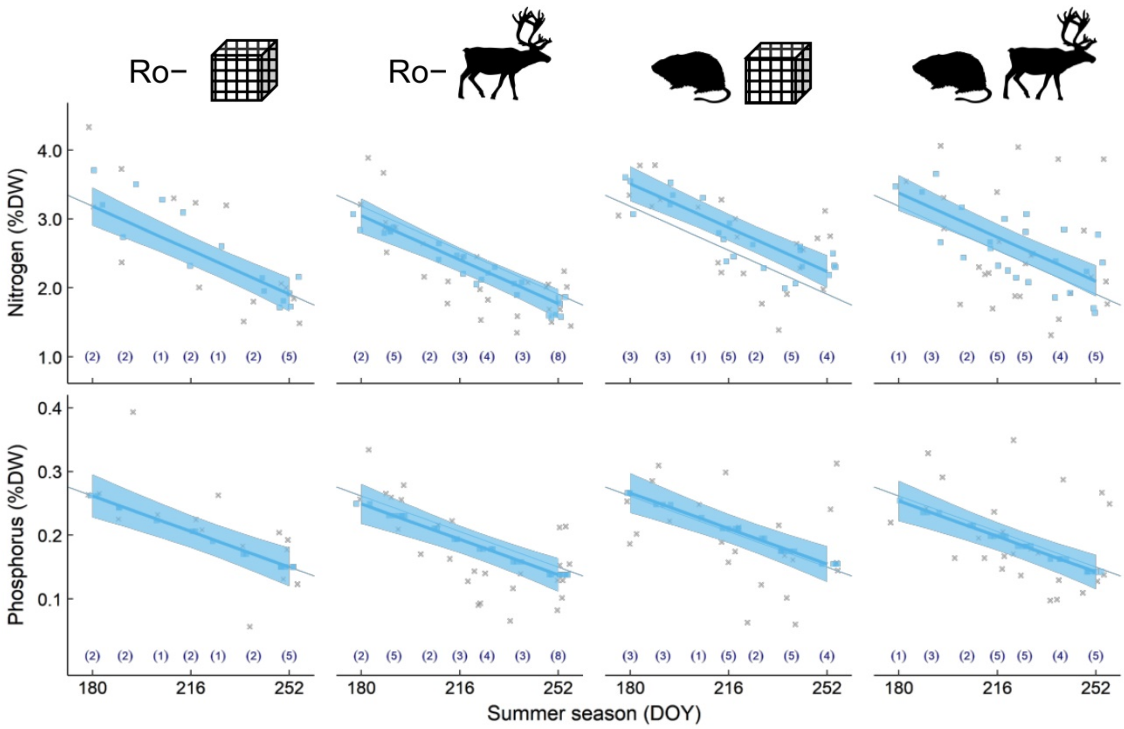

Figure A4. Effects of herbivores on leaf nutrient levels of sedges found in tundra-grasslands. ffects of small-rodent winter disturbance, reindeer summer herbivory, and seasonality on leaf nitrogen [N] content (upper panel) and leaf phosphorus [P] content (lower panel) (% of dry weight − %DW) in sedges found across forb-dominated and grass-dominated tundra-grasslands (see main text for details). Thick lines and bands represent regression lines for the fitted values and their 95% confidence intervals (CIs). Fitted values were acquired from the prediction models on sedge N- and P-content. The reference line (thin line) in absence of herbivores [Ro−/Re−] is maintained in each panel to facilitate the visualization of the effects of herbivores on sedge nutrient levels. Coloured dots represent fitted values for each plant leaf sample, whereas grey dots represent raw values. All dots were spaced apart within each of the seven sampling occasions to reduce overlapping. Numbers in parentheses represent the number of plant leaf samples collected at each sampling occasion (Supplementary material Appendix 1 Table A1) in each herbivore-treatment combination. Specifications of the fitted models are presented in Supplementary material Appendix 2. Parameter estimates and their CI are provided in Supplementary material Appendix 1 Table A4.

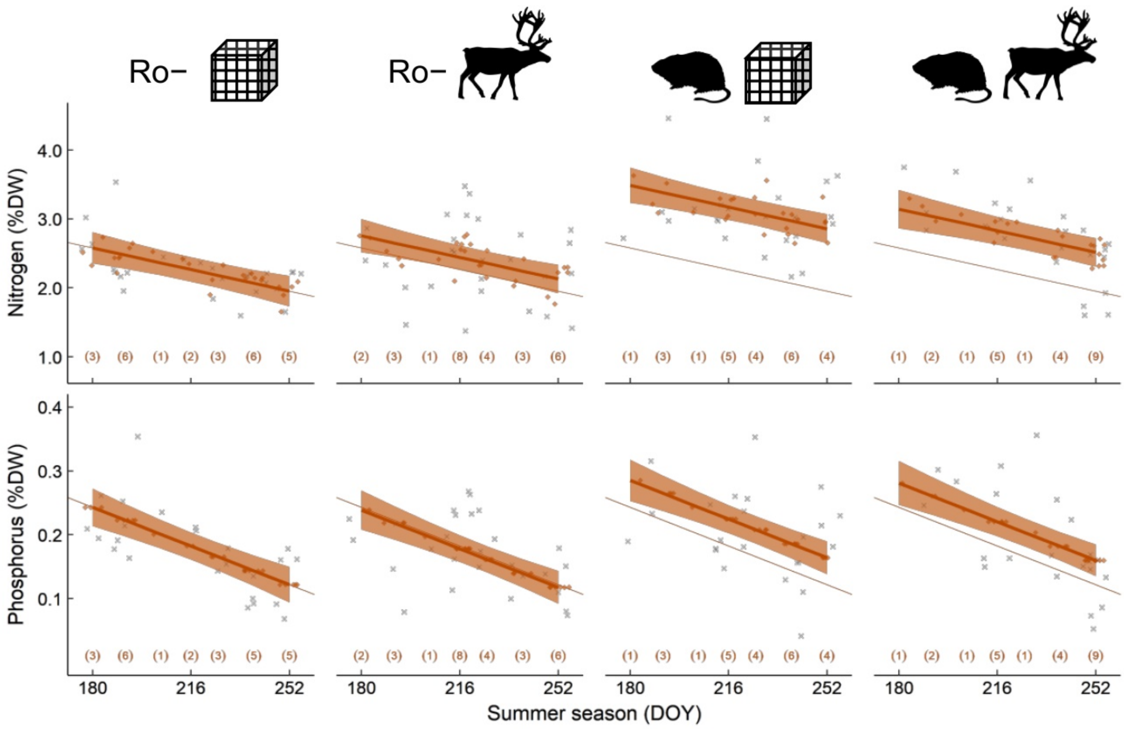

Figure A5. Effects of herbivores on leaf nutrient levels of deciduous shrubs found in tundra-grasslands. Effects of small-rodent winter disturbance, reindeer summer herbivory, and seasonality on leaf nitrogen [N] content (upper panel) and leaf phosphorus [P] content (lower panel) (% of dry weight − %DW) in deciduous shrubs found across forb-dominated and grass-dominated tundra-grasslands (see main text for details). Thick lines and bands represent regression lines for the fitted values and their 95% confidence intervals (CIs). Fitted values were acquired from the prediction models on deciduous-shrub N- and P-content. The reference line (thin line) in absence of herbivores [Ro−/Re−] is maintained in each panel to facilitate the visualization of the effects of herbivores on deciduous-shrub nutrient levels. Coloured dots represent fitted values for each plant leaf sample, whereas grey dots represent raw values. All dots were spaced apart within each of the seven sampling occasions to reduce overlapping. Numbers in parentheses represent the number of plant leaf samples collected at each sampling occasion (Supplementary material Appendix 1 Table A1) in each herbivore-treatment combination. Specifications of the fitted models are presented in Supplementary material Appendix 2. Parameter estimates and their CI are provided in Supplementary material Appendix 1 Table A5.

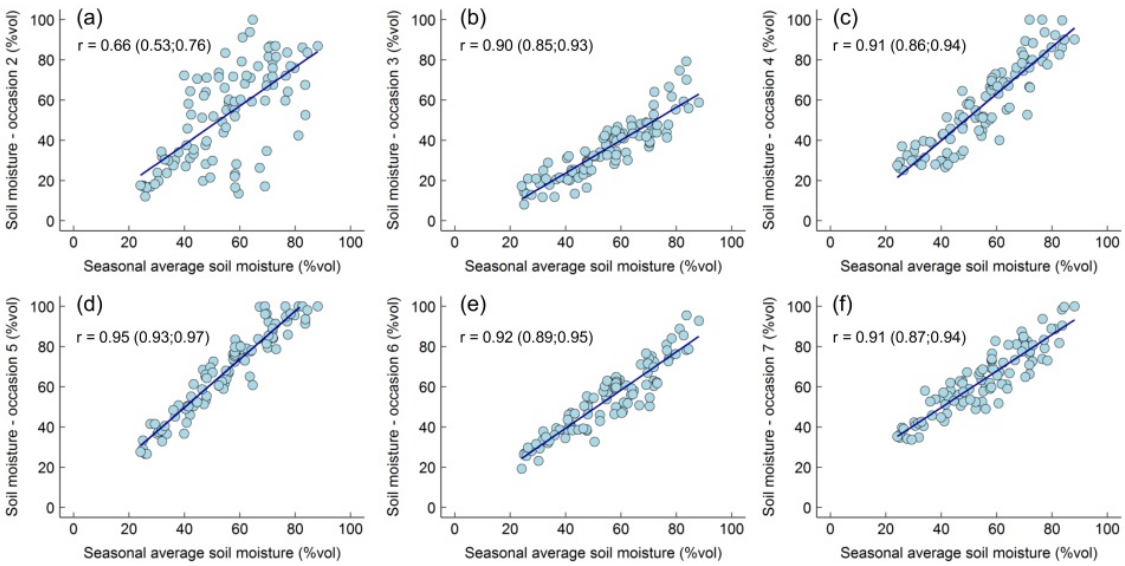

Figure A6. Correlations between seasonal-average soil moisture and average soil moisture at each sampling occasion. Correlations between plot seasonal-average soil moisture (*x* axis) and plot average soil moisture at each sampling occasion (*y* axis) (panels [a–f] correspond to sampling occasions 2–7, respectively; notice that we did not measure soil moisture in sampling occasion one, Supplementary material Appendix 1 Table A3). Pearson correlation coefficients (r) and their 95% confidence interval for each relationship are given in each panel of the figure. Soil moisture data were collected at each sampling occasion following the schedule for plant leaf sampling (Supplementary material Appendix 1 Table A1).

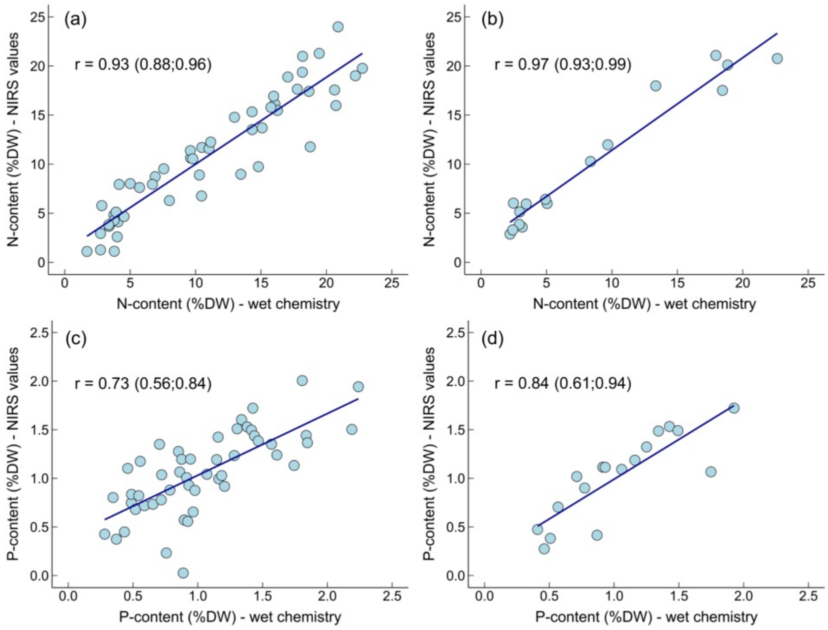

Figure A7. Correlations between soil nutrient levels obtained using wet chemistry and using near infrared reflectance spectroscopy (NIRS) methodology. Correlations between nutrient values obtained with wet chemistry and nutrient values obtained with NIRS in the (a,c) calibration sample sets and (b,d) validation sample sets for nitrogen [N] content [upper panels] and phosphorus [P] content [lower panels] in the organic soil. Pearson correlation coefficients (r) and their 95% confidence interval for each relationship are given in each panel of the figure. Calibration models derived from (a,c) the calibration sample sets and further validated using (b,d) the validation sample sets have been used to predict N- and P-content in the organic soil samples used in this study to characterize the abiotic component of our forb-dominated and grass-dominated tundra-grasslands (Supplementary material Appendix 1 Table A3, Fig. A3).

Appendix 2

Details on statistical analyses

All statistical analyses were conducted in the R environment ver. 3.6.1 (<www.r-project.org>).

<u>Plant-community composition in forb- and grass-dominated grasslands</u>

A nonmetric multidimensional scaling (NMDS) based on Bray-Curtis dissimilarity index (Legendre and Legendre 2012) was implemented using the metaMDS-function via vegan package (Oksanen et al. 2018) to explore the overall plant community composition of our tundra-grasslands. The NMDS was based on the *log-transformed+1* above-ground biomass values (g m^{-2}) of the species/genera at each plot. A visual screening of the plant communities clearly showed that species composition varied widely between the two grassland-types (Supplementary material Appendix 1 Fig. A3). All forb species (except *Bistorta vivipara*) displayed higher biomass in forb-dominated tundra-grasslands, whereas silica-rich grasses such as *Nardus stricta* and *Deschampsia cespitosa* were the main species prevailing in grass-dominated tundra-grasslands. *Poa* spp. biomass was approximately the same in all our tundra-grassland communities.

We statistically tested differences in species composition between forb- and grass-dominated tundra-grassland communities by implementing permutational multivariate analysis of variance (PERMANOVA) (adonis-function via vegan package) based on the Bray-Curtis distance matrix of species composition. We run PERMANOVA with 10 000 restricted permutations (defined a priori using the how-function via permute package; Simpson et al. 2019) to account for the hierarchical spatial structure of the study design. In particular, 'Plots' were allowed to permute only within the 'Tundra-patch' they belonged to (see main text for details). Results are reported in Supplementary material Appendix 1 Fig. A3.

Finally, the statistical significance of soil environmental characteristics (Supplementary material Appendix 1 Table A3) when a posteriori fitted onto the NMDS ordination was evaluated by using 10 000 restricted permutations to account for the hierarchical spatial structure of the study design (envfit-function via vegan package). In particular, 'tundra-patches' nested within 'grassland sites' were allowed to permute only within the 'grassland-type' (i.e. forb- and grass-dominated tundra-grasslands) they belonged to (see main text for details). The interpretation of significant soil environmental characteristics (vectors) is that they significantly correlate with the Bray-Curtis distance matrix of species composition. As such, the direction of the vectors in the NMDS ordination space indicates towards which direction these vectors change most rapidly and the direction to which they have maximal correlations with the ordination configuration. The projections of points (i.e. experimental plots) onto vectors have maximum correlation with corresponding soil environmental characteristics. Results are reported in Supplementary material Appendix 1 Fig. A3.

<u>Linear mixed-effects models (LMMs) presented in the main text</u>

Given the fervent debate around the simplification of the random-effects structure (Barr et al. 2013, Bates et al. 2015a), we also performed all the statistical analyses maintaining the maximal random-effects structure (i.e. all the random intercepts) in each linear mixed-effects model (LMM). Since the selected random-effects structure did not significantly influence the final estimates for the fixed-effects, we decided to present the LMMs with the simplest random-effects structure (Bates et al. 2015a).

The selection of the better random-effects structure for each LMM was accomplished by using a combination of two alternative computationally-intensive methods:

1) Parametric bootstrapping with 10 000 replicates with the confint-function (base R package) applied to lmer-objects (i.e. LMMs fitted by lmer-function via lme4 package – see main text for details).
2) Simulations (i.e. permutations) with 10 000 replicates with the simulate- and refit- functions (base R package), as suggested by Gałecki and Burzykowski (2013).

Although the ratio of the total sample size to the number of fixed-effects levels being tested and the number of random-effects levels were large enough for likelihood ratio (LR) tests (Bolker et al. 2009), we repeated the selection of the better fixed-effects structure using two alternative methods:

1) Computationally-efficient analysis of variance (ANOVA) with the anova-function (base R package).
2) Computationally-intensive parametric bootstrapping with 10 000 replicates with the PBmodcomp-function via pbkrtest package (Halekoh and Højsgaard 2014).

The two methods led to identical results (i.e. the final most parsimonious LMMs were the same independently of the methodology used to select their better fixed-effects structure), further confirming the robustness of our LMMs.

Fixed- and random-effects (i.e. model structure) retained in the most parsimonious LMMs are presented below (as specified by using the lmer-function via lme4 package in R):

Model for plant-community leaf nitrogen content across tundra-grasslands:

Fixed-effects structure: (‘Small-rodent winter disturbance’ + ‘Reindeer summer herbivory’ + ‘Seasonality’ + ‘Small-rodent winter disturbance × Reindeer summer herbivory’)

Random-effects structure: (‘Grassland site’ + ‘Grassland site : Tundra-patch’ + ‘Plant species’)

Model for plant-community leaf phosphorus content across tundra-grasslands:

Fixed-effects structure: (‘Small-rodent winter disturbance’ + ‘Reindeer summer herbivory’ + ‘Seasonality’)

Random-effects structure: (‘Grassland site’ + ‘Grassland site : Tundra-patch’ + ‘Plant species’)

Model for plant functional type (PFT) leaf nitrogen content in forb-dominated grasslands:

Fixed-effects structure: (‘Grassland site’ + ‘PFT’ + ‘Small-rodent winter disturbance’ + ‘Reindeer summer herbivory’ + ‘Seasonality’ + ‘PFT × Small-rodent winter disturbance’ + ‘PFT × Seasonality’)

Random-effects structure: (‘Grassland site : Tundra-patch’ + ‘PFT : Plant species’)

Model for plant functional type (PFT) leaf phosphorus content in forb-dominated grasslands:

Fixed-effects structure: ('Grassland site' + 'PFT' + 'Small-rodent winter disturbance' + 'Reindeer summer herbivory' + 'Seasonality' + 'PFT × Small-rodent winter disturbance' + 'PFT × Seasonality')

Random-effects structure: ('Grassland site : Tundra-patch' + 'PFT : Plant species')

<u>Model for plant functional type (PFT) leaf nitrogen content in grass-dominated grasslands</u>:

Fixed-effects structure: ('PFT' + 'Small-rodent winter disturbance' + 'Reindeer summer herbivory' + 'Seasonality' + 'PFT × Small-rodent winter disturbance' + 'PFT × Reindeer summer herbivory' + 'PFT × Seasonality' + 'PFT × Small-rodent winter disturbance × Reindeer summer herbivory')

Random-effects structure: ('Grassland site : Tundra-patch' + 'PFT : Plant species')

<u>Model for plant functional type (PFT) leaf phosphorus content in grass-dominated grasslands</u>:

Fixed-effects structure: ('PFT' + 'Small-rodent winter disturbance' + 'Reindeer summer herbivory' + 'Seasonality' + 'PFT × Seasonality' + 'PFT × Small-rodent winter disturbance × Reindeer summer herbivory')

Random-effects structure: ('Grassland site : Tundra-patch' + 'PFT : Plant species')

<u>Linear models (LMs) and linear mixed-effects models (LMMs)for the analyses of sedges and deciduous shrubs (Supplementary material Appendix 1 Table A4-A5 and Fig. A4-A5)</u>

We proceeded by analysing the data obtained for sedges (n = 90) and deciduous shrubs (n = 100) (6.7% of the collected plant samples) by using LMs fitted by lm-function via base R package and LMMs fitted by lmer-function via lme4 package (Bates et al. 2015b). The influence of herbivores on sedges and deciduous shrub leaf nutrient levels was evaluated across tundra-grasslands (i.e. encompassing both forb- and grass-dominated tundra-grasslands). Differences in model structure between these models and the models presented in the main text for forbs and grasses were due to too low sample sizes for sedges and deciduous shrubs in order to fit separate models for forb- and grass-dominated tundra-grasslands.

We fitted a separate model for the two plant functional types (PFTs) and for the two response variables of interest (plant nitrogen [N] and phosphorus [P] contents %DW), for a total of 4 models. We first created full LMMs with a basic fixed-effects structure including the three-way interaction between 'small-rodent winter disturbance' (two-level factor: undisturbed [Ro−] and disturbed [Ro+]), 'reindeer summer herbivory' (two-level factor: reindeer-exclusion [Re−] and reindeer-open [Re+]), and 'seasonality' (continuous variable: seven sampling occasions throughout the summer). In all full LMMs, the hierarchical spatial structure of the study design was entered as nested random factors, with 'plots' nested within 'tundra-patches', and subsequently nested within 'grassland sites'. 'Plots' accounted for both the nested design of our study and the repeated measures over the summer. We only fitted full random-intercept LMMs and avoid random-slope LMMs to prevent over-parameterization and convergence problems, as suggested by Bates et al. (2015a).

Selection of the better random- and fixed-effects structure for each model (i.e. most parsimonious models) was performed following the methodology applied for the main analyses presented in the main text. As for the analyses presented in the main text, we also performed all the analyses maintaining the maximal random-effects structure in each model. Since the selected random-effects structure did not significantly influence the final estimates for the fixed-effects, we decided to present the models with the simplest random-effects structure. When the variance of all random factors in a model was estimated as 0, we fitted simple linear models.

Fixed- and random-effects (i.e. model structure) retained in the most parsimonious LMs/LMMs are presented below (as specified by using the lm-function via basic R and the lmer-function via lme4 package):

<u>Model for leaf nitrogen content in sedges</u>:

Fixed-effects structure: ('Small-rodent winter disturbance' + 'Reindeer summer herbivory' + 'Seasonality')

Random-effects structure: ('Grassland site : Tundra-patch')

Model for leaf phosphorus content in sedges:

Fixed-effects structure: (‘Small-rodent winter disturbance’ + ‘Reindeer summer herbivory’ + ‘Seasonality’)

Random-effects: No random-effects were retained

Model for leaf nitrogen content in deciduous shrubs:

Fixed-effects structure: (‘Small-rodent winter disturbance’ + ‘Reindeer summer herbivory’ + ‘Seasonality’ + ‘Small-rodent winter disturbance × Reindeer summer herbivory’)

Random-effects structure: (‘Grassland site : Tundra-patch’)

Model for leaf phosphorus content in deciduous shrubs:

Fixed-effects structure: (‘Small-rodent winter disturbance’ + ‘Reindeer summer herbivory’ + ‘Seasonality’)

Random-effects structure: No random-effects were retained

Model validation process and definition of statistically significant effects was performed following the methodology applied for the main analyses presented in the main text. All graphs presented in Supplementary material Appendix 1 were made using the ggplot2 package (Wickham 2016).

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