

Supplementary Information for

Warming reverses top-down effects of predators on belowground ecosystem function in arctic tundra

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Supplementary Information Text

Comparison of wolf vs. wolf spider biomass

We did a back of the envelope calculation of wolf vs. wolf spider biomass to highlight the high biomass of wolf spiders in the arctic tundra relative to mammalian predators. We estimate that the biomass of wolf spiders is roughly 80 times more than the biomass of grey wolves within the vicinity of our study site near the Toolik Field Station on the North Slope of Alaska.

Calculation of wolf spider biomass km⁻²

In order to estimate wolf spider density km⁻², we assumed that field densities would be similar to the average wolf spider density within our control density plots at the end of the experiment (1.8 wolf spiders per 1.5 m-diameter mesocosm = 1.019 wolf spiders m⁻²). We then estimated the average biomass of a single wolf spider by creating a size-mass model using 38 wolf spiders that we collected near our study site during the 2012 summer growing season. For each of these spiders, we measured the carapace width (1, 2) using digital calipers (Diesella, Kolding, Denmark) and then dried the spiders at 60°C for three days before weighing them to the nearest 0.001 mg. We fit a linear model with no intercept ($y=mx+0$) to these biomass and size data, whereby y was the square root transformed measure of biomass, m was the model coefficient, and x was carapace width ($y = (0.99304x + 0)^2$; $R^2 = 0.958$). We fit this carapace width-biomass model to an additional 400 wolf spiders that we had collected during the same period and whose carapace widths we had also measured. We calculated the average dry biomass of an individual wolf spider (across all life stages) as 4.279 mg and therefore estimate that wolf spider dry biomass in the general area around Toolik Field Station is approximately 4360 g km⁻².

Calculation of grey wolf biomass/km²

Our estimate of the density of grey wolves on the North Slope of Alaska comes from a 2008 aerial survey that was done by Alaska Fish and Wildlife, from which there was evidence of 4.4 wolves per 1000 km² (3). We took a conservative approach by recalculating wolf density in the actual suitable habitat over the same area by removing the area that was occupied by major rivers and water bodies using the USGS National Hydrography Dataset (<http://nhd.usgs.gov/data.html>). After accounting for these major water bodies, the density of grey wolves becomes approximately 4.4 wolves per 975.7 km² of terrestrial habitat. Assuming that average biomass for a wolf is 40 kg (4) and that the dry weight of terrestrial mammals is approximately 30% of the wet weight, our estimate of grey wolf dry biomass on the Alaskan tundra is 54.12 g km⁻².

Table S1. Mixed effects model results of ecosystem function response variables at the soil surface, as predicted by wolf spider density, warming, and litter moisture content. Decomposition rate is expressed as percent litter mass remaining in proportion to the initial mass. Litter N is percent N remaining in litter in relation to initial N content of litter. Litter bags were on the soil surface for 14 months of experimental treatment. The reference category for the wolf spider density treatment in the models is low density; results were qualitatively similar to models with the reference as control wolf spider density (shown in Table S5).

Response	Fixed effects terms	Estimate	SE	df	<i>t</i>	<i>P</i>
% mass remaining	Intercept	73.83	2.46	19	29.99	0.000
	Litter % moisture content	-0.06	0.04	19	-1.41	0.175
	Control SD	6.75	3.23	19	2.09	0.051
	High SD	1.89	3.38	19	0.56	0.582
	Warming	1.81	3.22	19	0.56	0.581
	Control SD x warming	-5.32	4.54	19	-1.17	0.256
	High SD x warming	0.07	4.56	19	0.01	0.988
% N remaining	Intercept	92.59	6.65	19	13.93	0.000
	Litter % moisture content	-0.07	0.12	19	-0.57	0.572
	Control SD	-2.33	9.19	19	-0.25	0.803
	High SD	-0.05	9.58	19	0.00	0.996
	Warming	-7.10	9.14	19	-0.78	0.447
	Control SD x warming	5.03	12.90	19	0.39	0.701
	High SD x warming	6.36	12.97	19	0.49	0.630

Table S2. Means and standard errors of measured community and ecosystem function response variables across all of the wolf spider density x warming treatment combinations. For densities of Collembola, oribatid mites, predatory mites, and soil-dwelling intermediate predators, we used the average densities from the June and July sampling dates (see main text); these densities are expressed as the number of individuals per cm³ soil. Surface-active intermediate predators are the average total abundance per plot from several bouts of live-trapping over the summer. Fungal and bacterial biomass were sampled from the upper organic soil layer in July at the conclusion of the experiment and are expressed as mg biomass per g soil. Decomposition rates for surface and belowground litter bags are expressed as percent litter mass remaining in proportion to initial mass of the litter. Litter N is the percent N remaining in litter in relation to the initial N content of the litter, and soil N, P, and K (mg per 10 cm²) are the total available nutrients as measured from ion exchange membranes (Plant Root Simulator (PRS)TM probes; Western Ag Innovations Inc., Saskatoon, Canada) over the peak 6-week summer season.

Response variable	Wolf spider density	Warming treatment	Mean	SE
<i>Organisms</i>				
Collembola	Low	Ambient temp.	0.192	0.051
	Control	Ambient temp.	0.117	0.049
	High	Ambient temp.	0.116	0.043
	Low	Warmed	0.097	0.032
	Control	Warmed	0.145	0.043
	High	Warmed	0.158	0.045
Oribatid mites	Low	Ambient temp.	2.007	0.279
	Control	Ambient temp.	2.052	0.330
	High	Ambient temp.	1.334	0.170
	Low	Warmed	1.479	0.332
	Control	Warmed	2.111	0.361
	High	Warmed	1.507	0.155
Predatory mites	Low	Ambient temp.	0.282	0.051
	Control	Ambient temp.	0.184	0.018
	High	Ambient temp.	0.239	0.045
	Low	Warmed	0.212	0.012
	Control	Warmed	0.207	0.023
	High	Warmed	0.276	0.025
Soil-dwelling intermediate predators	Low	Ambient temp.	0.005	0.001
	Control	Ambient temp.	0.004	0.001
	High	Ambient temp.	0.005	0.002
	Low	Warmed	0.003	0.001
	Control	Warmed	0.002	0.001
	High	Warmed	0.005	0.001
Surface-active intermediate predators	Low	Ambient temp.	0.018	0.004
	Control	Ambient temp.	0.031	0.007
	High	Ambient temp.	0.007	0.003
	Low	Warmed	0.018	0.007
	Control	Warmed	0.008	0.004
	High	Warmed	0.004	0.003
Bacterial biomass	Low	Ambient temp.	0.009	0.004
	Control	Ambient temp.	0.011	0.002
	High	Ambient temp.	0.012	0.002

	Low	Warmed	0.010	0.001
	Control	Warmed	0.008	0.002
	High	Warmed	0.065	0.025
Fungal biomass	Low	Ambient temp.	4.678	1.011
	Control	Ambient temp.	4.543	1.836
	High	Ambient temp.	6.168	0.935
	Low	Warmed	7.100	1.416
	Control	Warmed	3.778	0.851
	High	Warmed	2.949	0.567
<i>Litter bag measures</i>				
Belowground decomposition	Low	Ambient temp.	71.579	2.918
	Control	Ambient temp.	72.474	1.430
	High	Ambient temp.	61.889	0.609
	Low	Warmed	61.193	2.024
	Control	Warmed	68.427	1.285
	High	Warmed	69.052	1.033
%N remaining-buried litter	Low	Ambient temp.	86.536	3.381
	Control	Ambient temp.	85.276	2.308
	High	Ambient temp.	91.540	2.993
	Low	Warmed	94.657	3.174
	Control	Warmed	86.196	3.320
	High	Warmed	85.956	3.458
Surface decomposition	Low	Ambient temp.	72.945	1.245
	Control	Ambient temp.	78.942	1.786
	High	Ambient temp.	73.271	0.942
	Low	Warmed	74.172	2.304
	Control	Warmed	75.550	1.450
	High	Warmed	75.529	2.177
%N remaining-surface litter	Low	Ambient temp.	91.587	5.115
	Control	Ambient temp.	88.406	5.627
	High	Ambient temp.	89.765	3.590
	Low	Warmed	83.830	5.612
	Control	Warmed	86.471	2.341
	High	Warmed	89.460	3.510
<i>Soil available nutrients</i>				
Total N	Low	Ambient temp.	16.160	1.247
	Control	Ambient temp.	23.040	1.691
	High	Ambient temp.	25.820	2.352
	Low	Warmed	22.460	1.179
	Control	Warmed	19.580	1.031
	High	Warmed	25.520	2.673
NH₄⁺	Low	Ambient temp.	10.440	0.655
	Control	Ambient temp.	14.700	2.172
	High	Ambient temp.	16.940	2.392
	Low	Warmed	13.360	1.263
	Control	Warmed	12.360	1.286
	High	Warmed	18.220	2.291
NO₃⁻	Low	Ambient temp.	6.650	0.677
	Control	Ambient temp.	8.300	1.063
	High	Ambient temp.	8.500	1.014
	Low	Warmed	9.060	0.777

	Control	Warmed	7.040	0.805
	High	Warmed	7.280	0.993
P	Low	Ambient temp.	2.040	0.230
	Control	Ambient temp.	1.880	0.457
	High	Ambient temp.	2.650	0.499
	Low	Warmed	3.500	1.001
	Control	Warmed	4.440	1.607
	High	Warmed	2.240	0.312
K	Low	Ambient temp.	102.580	13.148
	Control	Ambient temp.	106.040	24.557
	High	Ambient temp.	116.060	12.373
	Low	Warmed	121.780	32.898
	Control	Warmed	118.880	18.944
	High	Warmed	109.560	19.306

Table S3. Mixed effects model results of altered wolf spider densities and warming on total soil availability of N, P, and K, as measured by two successive three-week-long incubations of three ion exchange membranes (Plant Root Simulator (PRS)TM probes; Western Ag Innovations Inc., Saskatoon, Canada) that were deployed in each research plot. For each nutrient, we began with a fully parameterized model and proceeded to simplify it by excluding non-significant interaction terms followed by non-significant main effects one at a time. Model results are first shown with the reference category for wolf spider density (SD) as low spider density (Table S3a) and then with wolf spider density as control density (Table S3b). Significant results are those for which $p < 0.0167$ (Bonferroni correction used, whereby $P_{\text{critical}} = 3/0.05 = 0.01\bar{6}$).

S3a. Reference category for wolf spider density (SD) treatment: Low density

Response	Fixed effects terms	Est.	SE	df	<i>t</i>	<i>P</i>
Total N	Intercept	12.944	2.461	22	5.259	<0.0001
	Control spider density	1.100	2.086	22	0.527	0.603
	High spider density	4.960	2.109	22	2.352	0.028
	Warming	-	-	-	-	n.s.
	Soil moisture content	0.199	0.057	22	3.479	0.0021
	High spider density x warming	-	-	-	-	n.s.
	Low spider density x warming	-	-	-	-	n.s.
NH ₄ ⁺	Intercept	4.513	2.181	22	2.070	0.0504
	Control spider density	0.586	1.533	22	0.382	0.706
	High spider density	4.056	1.556	22	2.607	0.0161
	Warming	-	-	-	-	n.s.
	Soil moisture content	0.231	0.049	22	4.708	0.0001
	High spider density x warming	-	-	-	-	n.s.
	Low spider density x warming	-	-	-	-	n.s.
NO ₃ ⁻	Intercept	-	-	-	-	n.s.
	Control spider density	-	-	-	-	n.s.
	High spider density	-	-	-	-	n.s.
	Warming	-	-	-	-	n.s.
	Soil moisture content	-	-	-	-	n.s.
	High spider density x warming	-	-	-	-	n.s.
	Low spider density x warming	-	-	-	-	n.s.
P	Intercept	5.261	1.015	23	5.185	<0.0001
	Control spider density	-	-	-	-	n.s.
	High spider density	-	-	-	-	n.s.
	Warming	-	-	-	-	n.s.
	Soil moisture content	-0.071	0.026	23	-2.694	0.0129
	High spider density x warming	-	-	-	-	n.s.
	Low spider density x warming	-	-	-	-	n.s.
K	Intercept	-	-	-	-	n.s.
	Control spider density	-	-	-	-	n.s.

High spider density	-	-	-	-	n.s.
Warming	-	-	-	-	n.s.
Soil moisture content	-	-	-	-	n.s.
High spider density x warming	-	-	-	-	n.s.
Low spider density x warming	-	-	-	-	n.s.

S3b. Reference category for wolf spider density (SD) treatment: Control density

Response	Fixed effects terms	Est.	SE	df	<i>t</i>	<i>P</i>
Total N	Intercept	14.044	2.659	22	5.281	0
	Soil moisture	0.199	0.057	22	3.479	0.002
	Low SD	-1.100	2.086	22	-0.527	0.603
	High SD	3.860	2.075	22	1.860	0.0763
	Warming	-	-	-	-	n.s.
	Low SD x warming	-	-	-	-	n.s.
	High SD x warming	-	-	-	-	n.s.
NH ₄ ⁺	Intercept	5.099	2.345	22	2.174	0.0407
	Soil moisture	0.231	0.049	22	4.708	0.0001
	Low SD	-0.586	1.533	22	-0.382	0.706
	High SD	3.470	1.522	22	2.280	0.0326
	Warming	-	-	-	-	n.s.
	Low SD x warming	-	-	-	-	n.s.
	High SD x warming	-	-	-	-	n.s.
NO ₃ ⁻	Intercept	-	-	-	-	n.s.
	Soil moisture	-	-	-	-	n.s.
	Low SD	-	-	-	-	n.s.
	High SD	-	-	-	-	n.s.
	Warming	-	-	-	-	n.s.
	Low SD x warming	-	-	-	-	n.s.
	High SD x warming	-	-	-	-	n.s.
P	Intercept	5.816	1.259	21	4.618	0.0001
	Soil moisture	-0.073	0.027	21	-2.653	0.0149
	Low SD	-0.719	1.083	21	-0.664	0.514
	High SD	-0.830	1.106	21	-0.750	0.461
	Warming	-	-	-	-	n.s.
	Low SD x warming	-	-	-	-	n.s.
	High SD x warming	-	-	-	-	n.s.
K	Intercept	-	-	-	-	n.s.
	Soil moisture	-	-	-	-	n.s.
	Low SD	-	-	-	-	n.s.
	High SD	-	-	-	-	n.s.
	Warming	-	-	-	-	n.s.
	Low SD x warming	-	-	-	-	n.s.
	High SD x warming	-	-	-	-	n.s.

Table S4. Results of mixed effects models of altered wolf spider densities under ambient temperature vs. under warming for those response variables that showed interactive treatment effects in the full models (Collembola, intermediate surface-active predators and belowground litter decomposition; see main text and Table 1). Model results shown here are with the reference categories for wolf spider density (SD) as either low density (Table S4a) or control density (Table S4b). Significant results are those for which $P \leq 0.0167$ (Bonferroni correction used, whereby $P_{\text{critical}} = 3/0.05 = 0.01\bar{6}$).

S4a. Reference category for wolf spider density (SD) treatment: Low density

Response	Temperature treatment	Fixed effects terms	Est.	SE	df	<i>t</i>	<i>P</i>
Collembola	Ambient	Intercept	0.262	0.037	28	7.107	0.000
		Soil moisture	-0.001	0.001	11	-1.837	0.093
		Control SD	-0.045	0.036	11	-1.247	0.238
		High SD	-0.043	0.037	11	-1.171	0.267
		Poduromorpha	-0.013	0.035	28	-0.370	0.714
		Symphyleona	-0.169	0.035	28	-4.850	0.000
Collembola	Warmed	Intercept	0.145	0.048	28	3.000	0.006
		Soil moisture	0.000	0.001	11	-0.457	0.657
		Control SD	0.038	0.035	11	1.077	0.305
		High SD	0.051	0.035	11	1.448	0.176
		Poduromorpha	0.024	0.027	28	0.911	0.370
		Symphyleona	-0.141	0.027	28	-5.293	0.000
Intermediate predators (surface-active)	Ambient	Intercept	1.012	0.005	7	221.259	0.000
		Soil moisture	0.000	0.000	7	-1.178	0.277
		Control SD	0.008	0.005	7	1.618	0.150
		High SD	-0.003	0.005	7	-0.654	0.534
Intermediate predators (surface-active)	Warmed	Intercept	1.018	0.006	7	178.470	0.000
		Soil moisture	0.000	0.000	7	-1.775	0.119
		Control SD	-0.006	0.004	7	-1.341	0.222
		High SD	-0.007	0.004	7	-1.693	0.134
% Litter mass remaining (Belowground)	Ambient	Intercept	97.202	9.006	7	10.793	0.000
		Litter moisture	-0.352	0.120	7	-2.926	0.022
		Control SD	3.493	2.986	7	1.170	0.280
		High SD	-6.446	3.059	7	-2.107	0.073
% Litter mass remaining (Belowground)	Warmed	Intercept	89.929	7.163	7	12.554	0.000
		Litter moisture	-0.364	0.089	7	-4.091	0.005
		Control SD	8.394	2.003	7	4.191	0.004
		High SD	8.665	1.993	7	4.349	0.003

S4b. Reference category for wolf spider density (SD) treatment: Control density

Response	Temperature treatment	Fixed effects terms	Estimate	SE	df	<i>t</i>	<i>P</i>
Collembola	Ambient	Intercept	0.217	0.043	28	5.050	0.000
		Soil moisture	-0.001	0.001	11	-1.837	0.093
		Low SD	0.045	0.036	11	1.247	0.238
		High SD	0.002	0.035	11	0.069	0.946
		Poduromorpha	-0.013	0.035	28	-0.370	0.714
		Symphyleona	-0.169	0.035	28	-4.850	0.000
Collembola	Warmed	Intercept	0.183	0.045	28	4.078	0.000
		Soil moisture	0.000	0.001	11	-0.457	0.657
		Low SD	-0.038	0.035	11	-1.077	0.305
		High SD	0.013	0.035	11	0.361	0.725
		Poduromorpha	0.024	0.027	28	0.911	0.370
		Symphyleona	-0.141	0.027	28	-5.293	0.000
Intermediate predators (surface-active)	Ambient	Intercept	1.021	0.006	7	180.815	0.000
		Soil moisture	0.000	0.000	7	-1.178	0.277
		Low SD	-0.008	0.005	7	-1.618	0.150
		High SD	-0.012	0.005	7	-2.385	0.049
Intermediate predators (surface-active)	Warmed	Intercept	1.012	0.005	7	192.671	0.000
		Soil moisture	0.000	0.000	7	-1.775	0.119
		Low SD	0.006	0.004	7	1.341	0.222
		High SD	-0.001	0.004	7	-0.341	0.743
% Litter mass remaining (Belowground)	Ambient	Intercept	100.696	9.872	7	10.200	0.000
		Litter moisture	-0.352	0.120	7	-2.926	0.022
		Low SD	-3.493	2.986	7	-1.170	0.280
		High SD	-9.939	2.860	7	-3.476	0.010
% Litter mass remaining (Belowground)	Warmed	Intercept	98.323	7.442	7	13.213	0.000
		Litter moisture	-0.364	0.089	7	-4.091	0.005
		Low SD	-8.394	2.003	7	-4.191	0.004
		High SD	0.271	1.985	7	0.137	0.895

Table S5. Results of mixed effects models of wolf spider density and warming treatments on community and ecosystem response variables with the reference category for wolf spider density (SD) as control density. See Tables 1, 2, and S3 for model results with low wolf spider density as the reference variable.

Response	Fixed effects terms	Estimate	SE	df	<i>t</i>	<i>P</i>
Collembola	Intercept	0.193	0.034	58	5.740	0.000
	Soil moisture	-0.001	0.001	23	-1.887	0.072
	Low SD	0.050	0.033	23	1.520	0.142
	High SD	0.002	0.032	23	0.058	0.954
	Warming	0.022	0.032	23	0.679	0.504
	Poduromorpha	0.006	0.023	58	0.249	0.804
	Symphyleona	-0.155	0.023	58	-6.832	0.000
	Low SD x warming	-0.085	0.046	23	-1.843	0.078
	High SD x warming	0.013	0.045	23	0.285	0.778
Oribatid mites	Intercept	1.089	0.236	19	4.613	0.000
	Soil moisture	-0.008	0.004	19	-1.936	0.068
	Low SD	-0.107	0.251	19	-0.425	0.675
	High SD	-0.310	0.245	19	-1.264	0.222
	Warming	-0.006	0.245	19	-0.024	0.981
	Low SD x warming	-0.180	0.355	19	-0.509	0.617
	High SD x warming	0.105	0.347	19	0.304	0.765
Predatory mites	Intercept	0.039	0.051	19	0.755	0.459
	Soil moisture	0.001	0.001	19	1.118	0.278
	Low SD	0.095	0.055	19	1.730	0.100
	High SD	0.044	0.053	19	0.821	0.422
	Warming	0.024	0.054	19	0.449	0.659
	Low SD x warming	-0.093	0.077	19	-1.202	0.244
	High SD x warming	0.013	0.076	19	0.176	0.863
Intermediate predators (soil-dwelling)	Intercept	0.005	0.002	19	2.420	0.026
	Soil moisture	0.000	0.000	19	-0.505	0.620
	Low SD	0.000	0.002	19	-0.035	0.972
	High SD	0.000	0.002	19	0.219	0.829
	Warming	-0.003	0.002	19	-1.331	0.199
	Low SD x warming	0.002	0.003	19	0.677	0.506
	High SD x warming	0.003	0.003	19	1.110	0.281
Intermediate predators (surface-active)	Intercept	0.043	0.009	19	4.817	0.000
	Soil moisture	0.000	0.000	19	-2.003	0.060
	Low SD	-0.017	0.009	19	-1.806	0.087
	High SD	-0.023	0.009	19	-2.500	0.022
	Warming	-0.024	0.009	19	-2.575	0.019

	Low SD x warming	0.028	0.013	19	2.113	0.048
	High SD x warming	0.020	0.013	19	1.509	0.148
Fungal biomass	Intercept	1.154	2.109	16	0.547	0.592
	Soil moisture	0.121	0.047	16	2.563	0.021
	Low SD	0.513	2.210	16	0.232	0.819
	High SD	1.186	2.330	16	0.509	0.618
	Warming	-1.590	2.228	16	-0.714	0.486
	Low SD x warming	2.266	3.051	16	0.743	0.468
	High SD x warming	-2.064	3.207	16	-0.644	0.529
Bacterial biomass	Intercept	-0.017	0.021	18	-0.801	0.434
	Soil moisture	0.001	0.000	18	1.838	0.083
	Low SD	0.008	0.021	18	0.379	0.709
	High SD	0.006	0.022	18	0.275	0.786
	Warming	0.000	0.020	18	-0.002	0.998
	Low SD x warming	-0.009	0.030	18	-0.295	0.772
	High SD x warming	0.049	0.030	18	1.626	0.121
% mass remaining (belowground)	Intercept	101.60	6.27	19	16.20	0.000
	Litter % moisture	-0.36	0.08	19	-4.84	0.0001
	Low SD	-3.58	2.54	19	-1.41	0.175
	High SD	-9.92	2.48	19	-4.00	0.0008
	Warming	-3.32	2.48	19	-1.34	0.196
	Low SD x warming	-4.82	3.51	19	-1.37	0.186
	High SD x warming	10.19	3.51	19	2.91	0.009
% N remaining (belowground)	Intercept	113.11	15.24	19	7.42	0.000
	Litter % moisture	-0.35	0.18	19	-1.90	0.073
	Low SD	-1.30	5.98	19	-0.22	0.830
	High SD	6.90	5.84	19	1.18	0.252
	Warming	1.61	5.838	19	0.28	0.785
	Low SD x warming	8.66	8.28	19	1.05	0.309
	High SD x warming	-7.48	8.26	19	-0.91	0.376
% mass remaining (surface)	Intercept	80.58	2.65	19	30.42	0.000
	Litter % moisture	-0.06	0.04	19	-1.41	0.175
	Low SD	-6.75	3.23	19	-2.09	0.051
	High SD	-4.86	3.24	19	-1.50	0.151
	Warming	-3.51	3.19	19	-1.10	0.285
	Low SD x warming	5.32	4.54	19	1.17	0.256
	High SD x warming	5.39	4.52	19	1.19	0.248
% N remaining (surface)	Intercept	90.26	7.18	19	12.57	0.000
	Litter % moisture	-0.07	0.12	19	-0.57	0.572
	Low SD	2.33	9.19	19	0.25	0.803
	High SD	2.28	9.21	19	0.25	0.807

Warming	-2.07	9.07	19	-0.23	0.822
Low SD x warming	-5.03	12.90	19	-0.39	0.701
High SD x warming	1.33	12.84	19	0.10	0.918

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