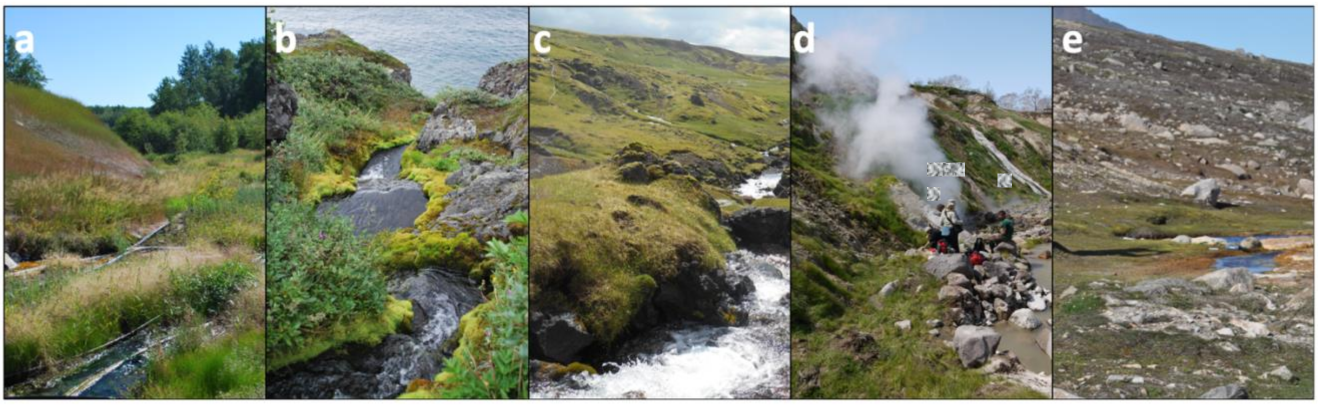
Regional impacts of warming on biodiversity and biomass in high latitude stream ecosystems across the Northern Hemisphere

Jackson et al. **Supporting Information**

Supplementary Note 1: STUDY SYSTEM

Geothermal regions offer ideal testbeds for investigating how warming can alter ecosystems. Hengill, a geothermal region in Iceland (hereafter, Iceland), has been used as a model system for conducting such "natural experiments" over the past decade to make predictions about future climate change over multiple organisational levels, from individuals to ecosystems[1]. Here, freshwater invertebrate abundance increases with temperature, while richness increases about to about 10^{o}C above ambient[2]. Diatoms decrease in abundance with temperature, but in general biomass stocks across all tropic levels and key ecosystem processes such as primary and secondary production, nutrient cycling and decomposition rates increase with this level of warming[3–5]. In the current paper we tested the generalities of these findings by expanding these model systems to include analogues across the Norther Hemisphere in four other high-latitude regions - Alaska (USA), Disko Island (Greenland), Kamchatka (Russia), and Svalbard - which vary in biogeography and biome type (Supplementary Figure 1, Supplementary Table 1). A paired paper (Clark et al., in prep) considers how microbial communities vary in a subset of these streams across the five regions (Supplementary Table 1). Clark et al. also have 5 streams from Iceland which were not sampled for our paper.

Supplementary Figure 1: *Site photos. Alaska **(a)**, Disko Island **(b)**, Iceland **(c)**, Kamchatka **(d)**, and Svalbard **(e)**. Photos by Nikolai Friberg and Eoin O'Gorman. Researcher faces were edited from d to maintain anonymity.*

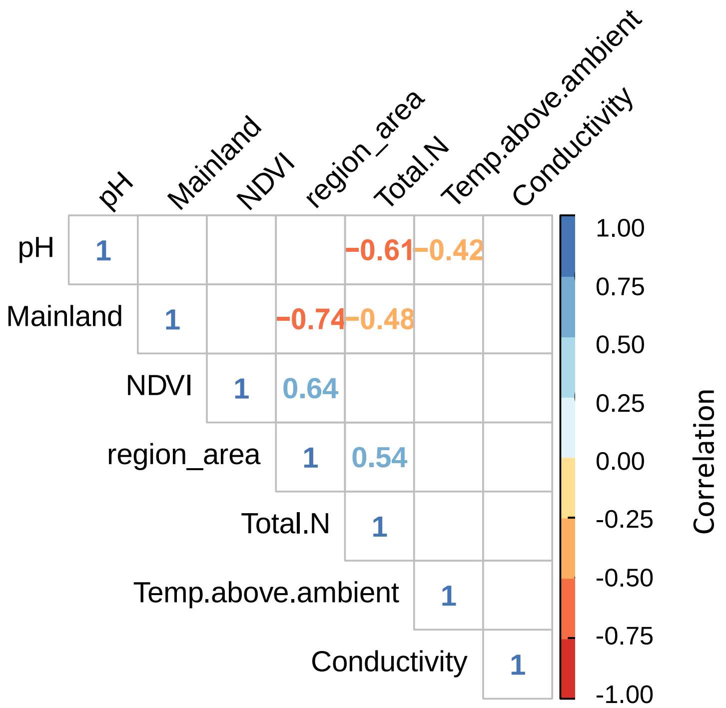


Supplementary Table 1: *Site details*

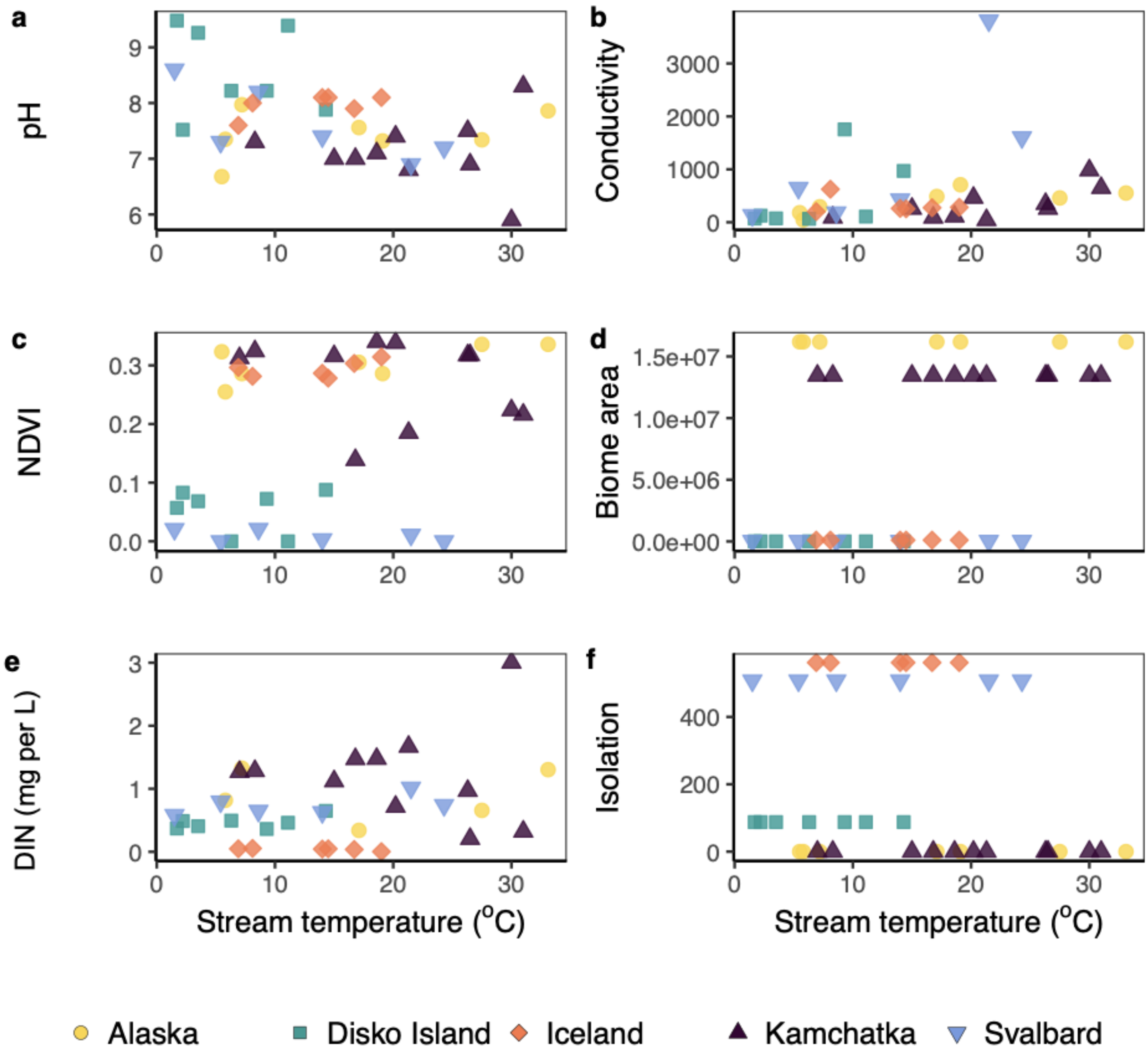
Code	Location	Stream temperature (ºC)	NDVI	pH	Conductivity (uS/cm)	Dissolved Inorganic Nitrogen (ug/ml)	Total Phosphorus (ug/ml)	DOC (ug/ml)	Width (m)	Depth (m)	Latitude	Longitude	Included in paired microbial paper?
A1	Alaska	33.1	0.34	7.86	552.00	1.30	0.036		1.75	0.4	65.0046	-150.6321	
A13	Alaska	5.5	0.32	6.68	179.90				2	0.9	65.0618	-150.6049	
A2	Alaska	27.5	0.34	7.34	459.00	0.66	0.084		0.9	0.1	65.0044	-150.6308	Yes
A6	Alaska	5.8	0.25	7.35	45.20	0.82	0.026		1	0.3	64.9952	-150.6544	Yes
A7	Alaska	17.1	0.31	7.56	487.00	0.34	0.107		0.5	0.15	65.0018	-150.6376	Yes
A8	Alaska	19.1	0.29	7.32	709.00				1	0.1	65.0065	-150.6191	Yes
A9	Alaska	7.2	0.29	7.97	292.00	1.33	0.035		1	0.2	65.0065	-150.6191	
G1	Disko Island	3.5	0.07	9.26	73.50	0.41	0.025		1.5	0.1	69.2647	-53.4397	
G12	Disko Island	11.1	0.00	9.39	107.10	0.46	0.018		1	0.2	69.4431	-53.8956	Yes
G14	Disko Island	1.7	0.06	9.48	70.90	0.37	0.020		0.35	0.3	69.2506	-53.5216	
G2	Disko Island	14.3	0.09	7.88	970.00	0.65	0.008		0.5	0.05	69.2594	-53.5686	Yes
G5	Disko Island	2.2	0.08	7.52	125.10	0.49	0.115		0.5	0.1	69.5747	-53.9897	Yes
G8	Disko Island	6.3	0.00	8.22	64.40	0.50	0.025		2.3	0.1	69.5539	-53.5244	Yes
G9	Disko Island	9.3	0.07	8.22	1755.0	0.36	0.003		1.5	0.1	69.5561	-53.6058	
K1	Kamchatka	31	0.22	8.30	650.00	0.32	1.060	3.88	0.35	0.03	54.4383	160.1411	
K10	Kamchatka	20.2	0.34	7.40	464.00	0.72	0.260	1.80	0.75	0.12	52.9	158.2	Yes
K11	Kamchatka	7	0.31			1.27	0.210	1.72	0.8	0.13	52.8	158.1656	Yes
K14	Kamchatka	8.3	0.32	7.30	90.00	1.28	0.162	1.40	0.75	0.008	52.79	158.1639	
K15	Kamchatka	15	0.32	7.00	256.00	1.12	0.179	1.68			52.84	158.1653	Yes
K18	Kamchatka	16.8	0.14	7.00	89.00	1.47	0.164	2.03	0.3	0.04	52.7	158.1	
K19	Kamchatka	18.6	0.34	7.10	110.00	1.48	0.148	1.23	0.6	0.06	52.85	158.15	
K20	Kamchatka	26.3	0.32	7.50	348.00	0.97	0.159	1.80	0.5	0.075	52.8236	158.14	Yes
K4	Kamchatka	21.3	0.19	6.80	42.00	1.67	0.129	2.19	0.75	0.035	54.4	160.1414	
K5	Kamchatka	30	0.22	5.90	982.00	3.00	0.420	0.98	1.25	0.1	54.39	160.1436	
K6	Kamchatka	26.5	0.32	6.90	256.00	0.21	0.520	2.74	20	1.25	52.1075	157.655	
S1	Svalbard	21.5	0.01	6.90	3810.0	1.02	0.015		0.5	0.03	79.3972	13.4408	Yes
S2	Svalbard	8.6	0.02	8.20	184.00	0.65	0.008		0.3	0.05	79.3931	13.4	Yes
S4	Svalbard	14	0.00	7.40	430.00	0.63	0.012		0.25	0.03	79.38	13.4414	Yes
S6	Svalbard	1.5	0.02	8.60	134.00	0.58	0.005		0.4	0.05	79.4011	13.4414	Yes
S7	Svalbard	24.3	0.00	7.20	1604.0	0.74	0.006		0.75	0.08	79.46	13.2902778	Yes
S8	Svalbard	5.4	0.00	7.30	648.00	0.80	0.006		0.3	0.07	79.46	13.2847	Yes
I11_12	Iceland	8.1	0.28	8.00	624.00	0.05			0.46	0.06	64.0574	-21.3115	
I13_12	Iceland	6.9	0.30	7.60	201.00	0.05			1.47	0.08	64.0467	-21.2865	
I14_12	Iceland	14.5	0.28	8.10	254.00	0.05			1.27	0.12	64.0593	-21.3187	
I3_12	Iceland	16.7	0.30	7.90	275.00	0.04					64.0555	-21.3038	Yes
I6_12	Iceland	19	0.31	8.10	283.00	0.00			0.8	0.11	64.0558	-21.3066	
I9_12	Iceland	14	0.29	8.10	262.00	0.04			0.63	0.06	64.0569	-21.3081	

In each location we sampled 6-11 streams in August 2012 (Iceland) or 2013 (all other sites). The maximum distance between streams in each location was 850m in Iceland, 2000m in Alaska, 3500m in Greenland, 5000m in Svalbard, and 300km in Russia (the only site with streams in 2 catchments). A Pearson's correlation revealed an overall significant relationship between temperature and pH (correlation -0.43; Supplementary Figure 2), but this was largely driven by Svalbard as an outlier (Supplementary Figure 3) and all other sites had similar pH across the temperature gradient. However, we did not use pH in any of our models (Supplementary Figure 2). We also checked for collinearity between all of our predictor variables, including our biogeographical variables (Supplementary Figure 2). There was a strong correlation between biome area and isolation (-0.74, Supplementary Figure 2), so we did not use these two variables together in any models.

Supplementary Figure 2: *Correlation matrix for our predictor variables. region_area = area occupied by biome; NDVI = normalized vegetation index (terrestrial productivity); Mainland = distance from mainland as a measure of isolation. Only significant correlations (p<0.05) are shown, with colour indicating if the relationship is positive or negative.*



Supplementary Figure 3: *Relationship between stream temperature (above ambient) and other characteristics:* ***(a)*** *pH,* ***(b)*** *conductivity,* ***(c)*** *dissolved inorganic nitrogen (DIN),* ***(d)*** *NDVI,* ***(e)*** *biome area, and* ***(f)*** *isolation.*

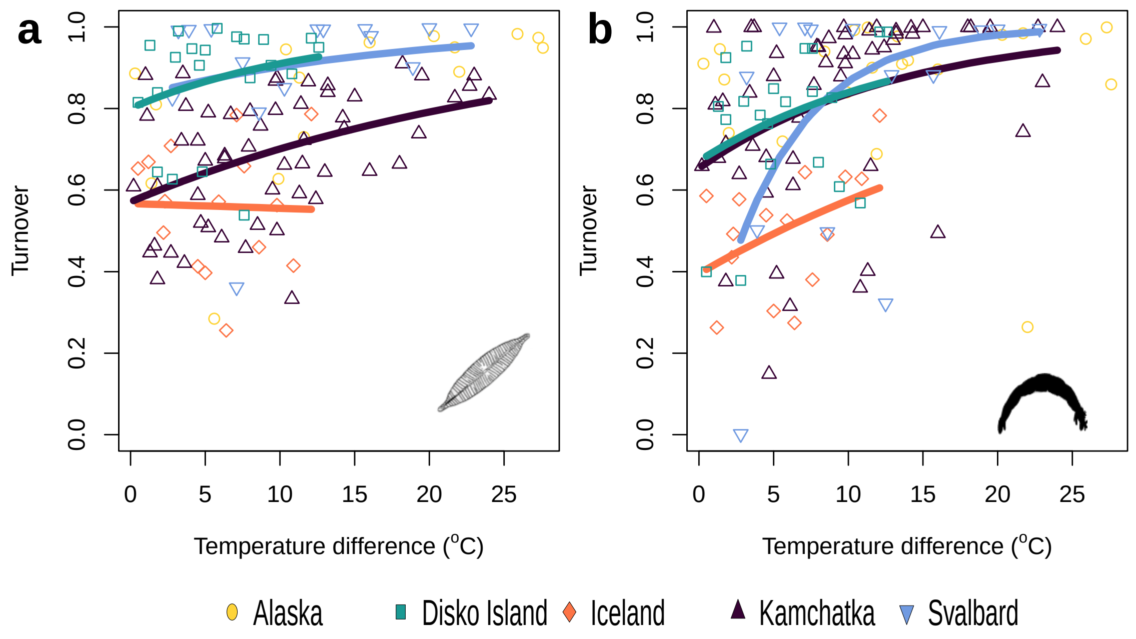


FURTHER RESULTS

Supplementary Table 2: *Best fit model selection for the effect of temperature and biogeography on stream species richness (alpha diversity). The best model is highlighted in blue.*

Alpha diversity	Predictors	AICc	RSE	R^2(adj)
Diatoms	Intercept only	44.730	0.430	NA
	Temperature above ambient	40.115	0.396	0.153
	Nitrogen	46.883	0.442	0.000
	NDVI	37.290	0.381	0.217
	Biome Area	43.461	0.404	0.115
	Isolation	44.838	0.423	0.034
	Temperature*Nitrogen	42.394	0.397	0.171
	Temperature*NDVI	29.845	0.329	0.415
	Temperature*Biome	31.512	0.337	0.387
	Temperature*Isolation	40.168	0.380	0.221
	Nitrogen*NDVI	42.675	0.398	0.164
	Nitrogen*Biome	40.642	0.387	0.211
	Nitrogen*Isolation	41.033	0.389	0.202
	NDVI*Biome	38.206	0.369	0.262
	NDVI*Isolation	40.539	0.382	0.014
	Temperature*Nitrogen*NDVI	35.336	0.318	0.465
	Temperature*Nitrogen*Biome	37.587	0.329	0.430
	Temperature*NDVI*Biome	**29.489**	**0.292**	**0.538**
	Temperature*NDVI*Isolation	37.256	0.327	0.001
Invertebrates	Intercept only	47.515	0.472	NA
	Temperature above ambient	40.084	0.413	0.234
	Nitrogen	46.898	0.477	0.000
	NDVI	46.396	0.455	0.073
	Biome Area	49.128	0.479	0.000
	Isolation	48.135	0.467	0.023
	Temperature*Nitrogen	40.748	0.410	0.247
	Temperature*NDVI	**28.154**	**0.329**	**0.516**
	Temperature*Biome	34.114	0.360	0.420
	Temperature*Isolation	37.416	0.378	0.359
	Nitrogen*NDVI	44.230	0.433	0.158
	Nitrogen*Biome	43.145	0.426	0.187
	Nitrogen*Isolation	38.888	0.398	0.291
	NDVI*Biome	51.518	0.468	0.017
	NDVI*Isolation	41.896	0.405	0.266
	Temperature*Nitrogen*NDVI	30.154	0.298	0.602
	Temperature*Nitrogen*Biome	30.039	0.297	0.604
	Temperature*NDVI*Biome	38.755	0.338	0.487
	Temperature*NDVI*Isolation	38.667	0.338	0.489

Supplementary Figure 4: Trends in beta diversity. *Turnover in the **(a)** diatom and **(b)** invertebrate communities with increasing temperature difference between streams within each region. Symbols represent a single stream, and coloured lines are negative exponential GLMs for each region.*



Supplementary Table 3: *Analysis of bootstrapped temperature-turnover relationships for each region. Models were specified as negative exponential equations.*

Region	Group	df	Slope	*P*	R^2
Alaska	Diatoms	1,13	0.057	0.055	0.293
	Invertebrates	1,19	0.000	0.991	0.000
Disko Island	Diatoms	1,19	0.079	0.270	0.069
	Invertebrates	1,19	0.072	0.212	0.090
Iceland	Diatoms	1,13	-0.003	0.930	0.001
	Invertebrates	1,13	0.035	0.030	0.196
Kamchatka	Diatoms	1,53	0.036	0.001	0.194
	Invertebrates	1,53	0.075	0.010	0.135
Svalbard	Diatoms	1,13	0.059	0.439	0.060
	Invertebrates	1,13	0.190	0.130	0.236

Supplementary Table 4: *Comparison of models of temperature-turnover slopes as a function of taxonomic group and biogeographic variables.*

Model	**Variable**	**df**	**F-value**	***P***	**AICc**
Slope ~ Biome*Group	Biome	1	0.776	0.412	-9.34
	Group	1	0.655	0.449	
	Biome*Group	1	0.929	0.372	
	Residuals	6			
Slope ~ NDVI*Group	NDVI	1	5.703	0.054	-14.40
	Group	1	1.086	0.338	
	NDVI*Group	1	1.078	0.339	
	Residuals	6			
Slope ~ Isolation*Group	Isolation	1	0.177	0.689	-9.28
	Group	1	0.651	0.451	
	Isolation*Group	1	1.482	0.270	
	Residuals	6			

***Supplementary* Table 5:** Results of our Detrended Correspondence Analysis (DCA) showing which environment variables correspond with each axis.

Group	**Variable**	**DCA1**	**DCA2**	**r^2**	**P**
Diatoms	Temperature	-0.053	-0.999	0.678	0.001
	pH	0.094	0.996	0.341	0.003
	Conductivity	0.006	-1.000	0.133	0.099
	NDVI	0.587	-0.810	0.346	0.001
	Isolation	0.965	0.262	0.473	0.001
	Area	-0.458	-0.889	0.296	0.002
	Nitrogen	-0.788	-0.616	0.267	0.012
Invertebrates	Temperature	-0.936	0.353	0.288	0.01
	pH	0.881	-0.473	0.124	0.153
	Conductivity	-0.304	0.953	0.121	0.116
	NDVI	-0.128	-0.992	0.075	0.295
	Isolation	0.641	0.767	0.182	0.047
	Area	-0.908	-0.419	0.254	0.023
	Nitrogen	-0.860	0.511	0.244	0.013

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