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Supporting Information for: Biotic rescaling reveals importance of species interactions for variation in biodiversity responses to climate change cross landscapes

By: **Vigdis Vandvik, Olav Skarpaas, Kari Klanderud, Richard J. Telford, Aud H. Halbritter, Deborah E. Goldberg**

Corresponding author: Vigdis Vandvik
Email: vigdis.vandvik@uib.no

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Figures S1 to S3
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SI References

Other supplementary materials for this manuscript include the following:

Dataset S1
Code C1

These data can be accessed in the following OSF project: Vandvik, V., Skarpaas, O., Klanderud, K., Telford, R. J., Halbritter, A. H., & Goldberg, D. E. Data for: Biotic rescaling reveals importance of species interactions for variation in biodiversity responses to climate change (Vandvik et al. 2020). Open Science Foundation (OSF). Retrieved from osf.io/8y4mk August 7, 2020.

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Supplementary Information Text

Extended methods 1. Site selection and climate data

The study was implemented as a replicated distributed experiment over twelve calcareous grassland sites in southern Norway. The sites were chosen to fit within a climate grid reflecting the major bioclimatic variation in the study region in southern Norway, with three temperature levels (Alpine, Sub-alpine, Boreal) replicated within each of four levels of precipitation (Figure 2, Table S1). We identified potential areas for sites with a combination of topographic maps, geological maps (NGU) and interpolated maps of summer temperature and annual precipitation normals 1960-90 (100 m resolution gridded data, met.no; see (1)(Tveito *et al.* 2005) and references therein). Subsequent on-site temperature and precipitation measurements at the twelve selected sites confirmed the regular spacing of the climate grid (see Extended methods 3. Climate grid confirmation).

Approximately 200 potential sites were visited and surveyed in the summer of 2008. Careful site selection ensured that other factors such as grazing regime and history, bedrock, vegetation type and structure, slope and exposure were kept as constant as possible among the selected sites (Klanderud *et al.* 2015). Geographical distance between sites averages 15 km and ranges from 650 m to 175 km. Within each site, the experiment is situated within a total area of 75 – 200 m^2. All sites were moderately grazed prior to the experiment, but were fenced to avoid animal disturbance of the experimental installations. They were mowed annually for the duration of the experiment to mimic past disturbance regimes.

The vegetation is forb-rich semi-natural upland grassland vegetation, within the plant sociological association Potentillo-Festucetum ovinae tending towards Potentillo-Poligonium vivipara in the alpine sites and Nardo-Agrostion tenuis in some lowland sites (2)(Fremstad 1998). The most prevalent and common species in these systems are the graminoids *Agrostis capillaris, Anthoxanthum odoratum, Deschampsia cespitosa* and *Nardus stricta,* and the forbs *Achillea millefolium, Bistorta vivipara,* and *Potentilla erecta.*

Temperature was measured continuously at four heights (2 m and 30 cm above ground, at ground level, and 5 cm below ground), soil moisture was measured continuously with two replicate loggers ca. 5 cm below ground, and precipitation was measured at each site during the snow-free season at all twelve sites. For these measurements, we used Delta T GP1 loggers (Delta T devices, Cambridge, UK) equipped with two temperature probes, two SM 200 moisture sensors, and an ARG 100 tipping bucket (EML LTD, North Shields, UK) from 2009 onwards. UTL-3 version 3.0 temperature loggers (GEOTEST AG, Zollikofen, Switzerland) were used for measuring the 2 m and 30 cm temperatures. In addition, soil moisture was measured next to each turf, as the mean of four measurements taken along each side of the turf, two times during the growing season using a Delta T HH2 version 2.3 Moisture Meter with the same probe as for the GP1 logger. These data were used to assess and confirm the relevance of the climate grid for on-site climatic conditions (see Extended methods 3. climate grid confirmation).

Extended methods 2. Experimental methods and vegetation data

At each of the twelve sites we established five blocks, each containing a maximum of five 25 × 25 cm plots randomly designated to five different turf transplant treatments: transplanting to warmer, wetter, or warmer and wetter climates, transplanting within blocks (to control for the transplanting itself), and one untouched control turf. Thus, each transplanted plot has an “origin” site and a “destination” site (Figure 2). Comparison of transplanted turfs to origin controls assesses community change with climate change, while comparison of transplanted turfs to destination controls assesses degree of convergence to new climate. Prior to transplanting, we marked each corner of the plots with metal tubes and the upslope left-hand corner of each turf extracted from those plots with a plastic toothpick, ensuring permanent marked plots and that the turfs could be placed in the same orientation relative to the slope and block at the destination site. We used a knife to cut the turfs, and cut two cm outside the plot margins, giving turfs of

29 x 29 cm and to a depth below the rooting depth or at least 10 cm, unless the soil was shallower, as was the case for some of the alpine plots. After excavation, the turfs were packed into 29 × 29 cm water-proof carton boxes and transported to their respective target sites within one or two days. To keep the transplant disturbance as similar as possible among treatments, the excavated control (‘home transplant’) turfs were also kept in boxes while digging out the climate transplant plots, and put into their designated target plots within the origin block before leaving the site. The transplantations were done at the end of the growing season, in September 2009, to minimize impact.

Vegetation in each of the turfs was surveyed before transplantation in 2009 and in 2011, 2012, and 2013. In 2010 we left the turfs to recover from any transient effects of the transplant process. Vegetation was sampled at the peak of the growing season each year, i.e. mid-June, late June/July, and August for Boreal, Sub-alpine and Alpine sites, respectively. We visually estimated percentage cover of all vascular species in each plot. Nomenclature follows Lid & Lid (3). We also collected data on a number of community attributes in each turf at each census, including percentage cover of all vascular species, bryophytes, litter, and bare soil. We used a ruler at four fixed points in each turf to measure the mean height of the vascular vegetation and of bryophytes. Graminoid cover and cover of new colonists were calculated by summing cover of all appropriate species. New colonists were defined as all species not present in the turf before transplantation. This sampling regime gave a total of 235 turfs and 940 turf surveys, and included information on 181 vascular plant taxa.

Four out of 940 turf surveys were discarded due to physical damage by animals or rock fall. Due to the extensive vegetation sampling over many years and involving many people, there is a risk of observer errors. In particular, closely related and difficult-to-distinguish species and life stages such as sterile graminoids might be confounded and/or some species might be overlooked in one or more of the consecutive censuses of a particular turf. Such errors will result in pseudo-turnover in the community data. To reduce the noise from such errors in our data, we thoroughly compared species records from each of the turfs over the four years. During vegetation sampling, each plot was divided into 25 sub-turfs and species and their reproductive status (with bud, flower, fruit or not) were recorded for each sub-turf. Data on sub-turf occurrence and reproductive status are not used elsewhere in this paper, but were extremely useful in the process of identifying observer errors. In many cases, we could assign unidentified sterile individuals (typically, graminoids identified only to genus level) to a particular species if the species’ was flowering and thereby could be accurately identified to species in the same sub-turf the year before or after. Similarly, we corrected obvious misidentifications of species that are difficult to identify if the species were correctly identified in the same sub-turf in other years (as confirmed by information on fertility and/or other data), and we corrected obviously overlooked perennial species in a particular sub-turf in a particular year by adding the species to the list with an averaged percentage cover from the year before and after the gap. As part of this pre-processing we also merged taxa that are often sterile and so difficult to distinguish with confidence, such as for example *Alchemilla* spp. (excluding *A. alpina*), *Euphrasia* spp. (*wettsteinii* and *stricta*), *Luzula* spp. (*multiflora* coll. and *sudetica*), *Pyrola* spp., *Sagina* spp. (*procumbens* and *saginoides*) and *Taraxacum* spp..

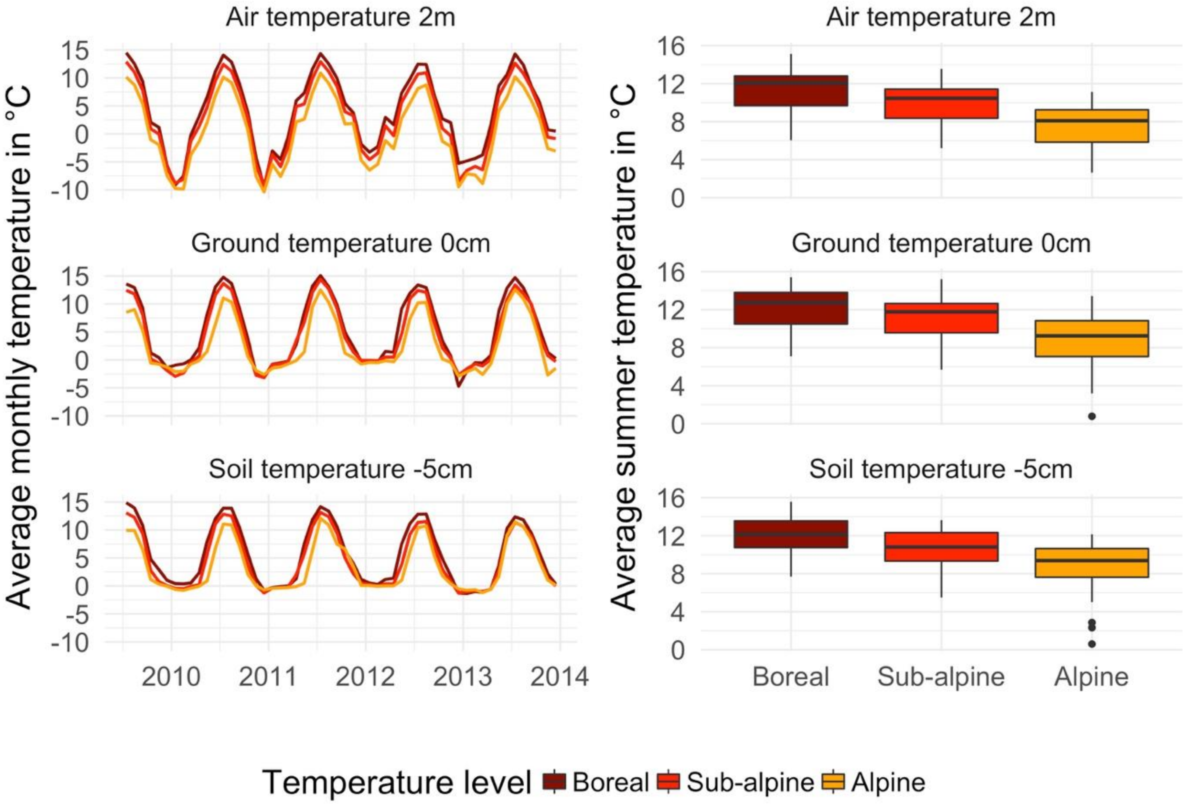
Extended methods 3. Climate grid confirmation

The climate grid (figure 2 in main text) was set up on the basis of downscaled climate data from the 1960 – 1990 normal period (0.1 km gridded data from The Norwegian Meteorological Institute; (Tveito *et al.* 2005)). In this supplement we explore weather data patterns measured locally at the SeedClim sites over the study period to confirm the climate grid with ground-measured data (see Extended methods 1. Site selection and climate).

1. Temperature

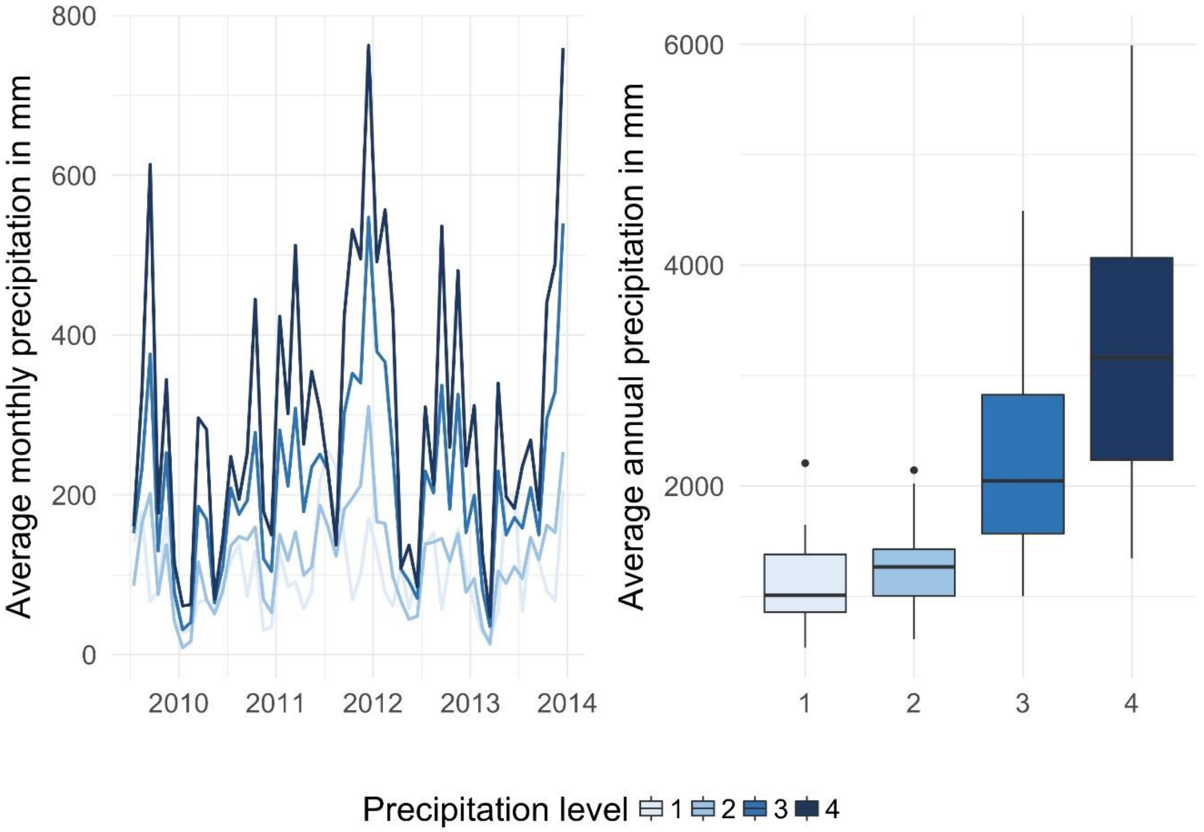
Time series of monthly average temperature for boreal (dark red), sub-alpine (red) and alpine (orange) sites measured at 2 m and 0 cm above ground and -5 cm below ground confirm that there are systematic differences between the sites in temperature overall (left side), and especially during the four warmest months (right side), over the six years for which we have logged climate data (see figure 2 and table S1 for information on the temperature levels):

Note that the differences are less clear during winter for the ground and soil measurements, which is partly due to snow cover. Snow insulates the ground and soil from sub-zero temperatures, and our logger data reflect this in that the temperature at the ground and soil level is close to zero for extended periods during the winter, and can fall below zero when snow cover is lacking, especially at low-elevation sites and early in the winter season.



2. Precipitation

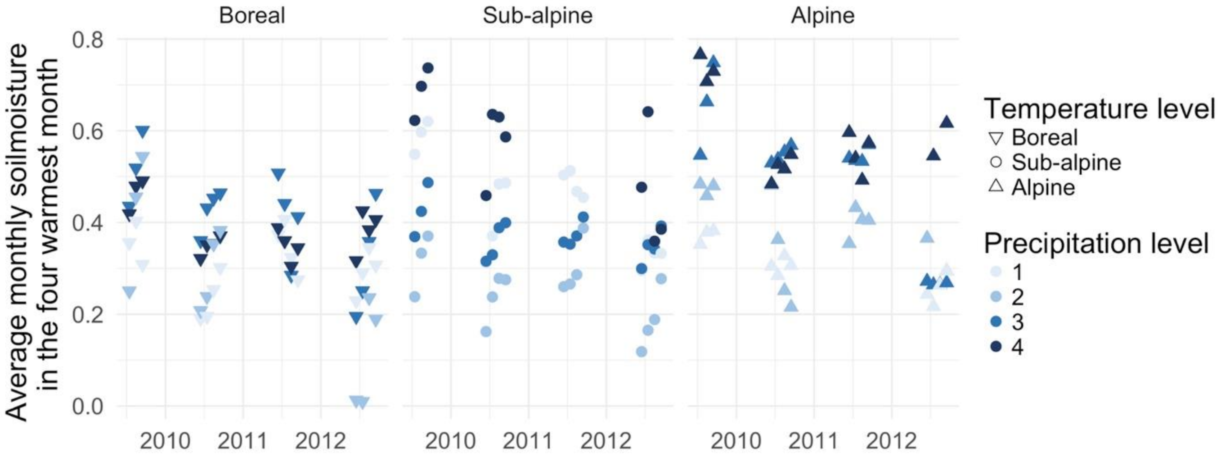
The logged precipitation data are much noisier than the temperature data (more missing values and outliers), due to logger failure (due to economic constraints we did not have replicate tipping buckets within sites, and so logger failure led to missing data) and also because precipitation falls as snow for a large part of the year. Time series of sum of monthly precipitation for the 5 years of the experiment from downscaled gridded data (0.1 km grid, www.met.no), averaged across sites for each precipitation level according to increasing precipitation levels, from light (1) to dark (4) blue, confirm systematic differences between the sites in precipitation over the study period (left side). The same trend across precipitation level can be seen for the sum of annual precipitation across the 5 years of the experiment (right side):



Note that the variation in annual precipitation increases towards the wetter end of the climate grid (for site placement in the climate grid, see Figure 2 and Table S1).

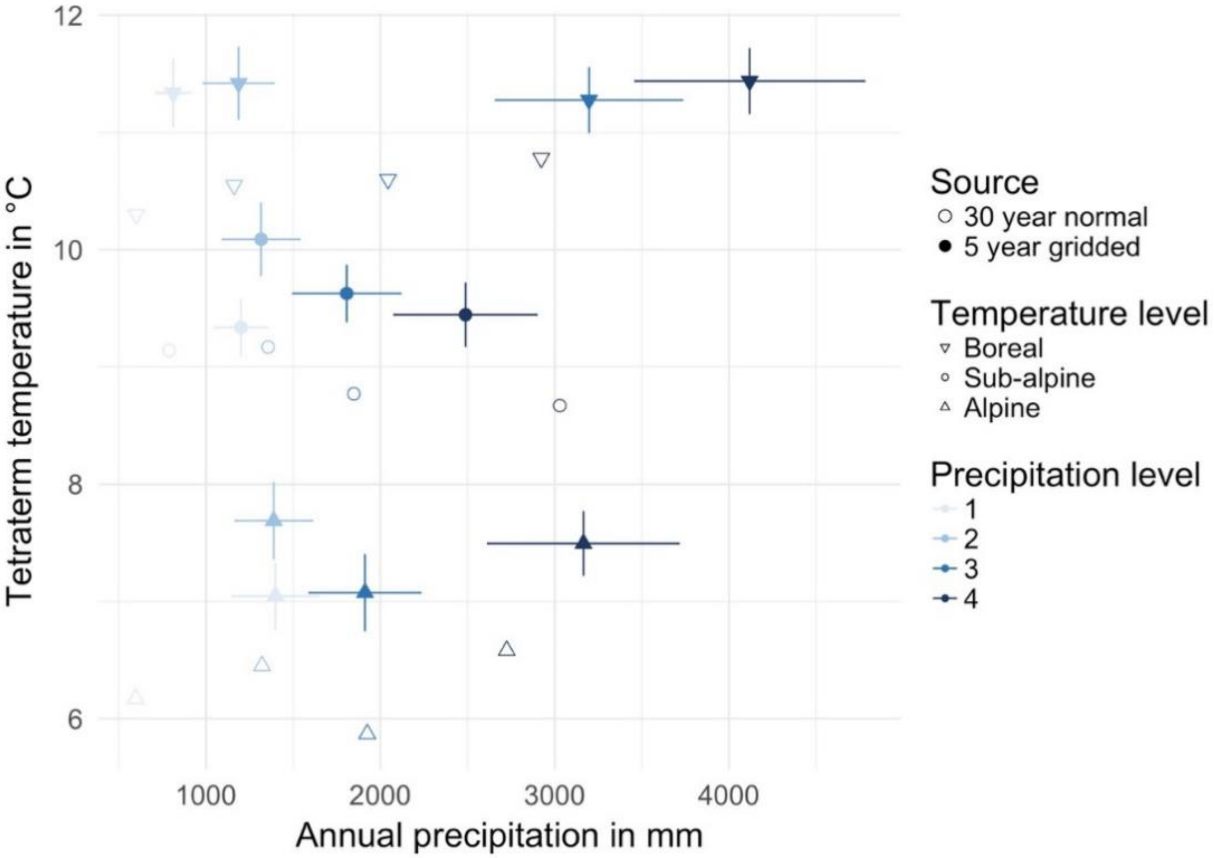
3. Soil moisture

Average monthly soil moisture for the four warmest months are shown below for precipitation levels from the driest (light blue) to the wettest (dark blue). The shape of the symbols represent the temperature levels. The soil moisture data broadly confirm the general trend in the grid but are also highly variable. This is partly because soil moisture is strongly affected by fine-scale heterogeneity in the soil, and was only measured by two replicate loggers at each site. Soil moisture data was only available from 2010-2012, dues to widespread logger failure in 2013:



4. Climate grid

We used downscaled gridded data provided by The Norwegian Meteorological Institute to compare the weather in the five years of the experiments (2009-2013; closed symbols) to the 30-year normal used to establish the experimental climate grid (1960-90 open symbols). Data below are mean annual precipitation and mean annual tetraterm temperatures (averages of the four-month period June-September) ± SE (vertical and horizontal error bars, respectively):



Tetraterm temperature increases from alpine to boreal sites and precipitation increases from dry to the wet sites, but with considerable year to year variation, especially in precipitation. Interestingly, the annual precipitation and tetraterm temperature show that the climate has been consistently both warmer and wetter during the experiment than in the 1960-1990 normal period, paralleling the longer-term climate change projections for this region. These changes are especially pronounced in the warmer and wetter parts of the grid (Boreal 3 and Boreal 4; see Figure 2 and Table S1).

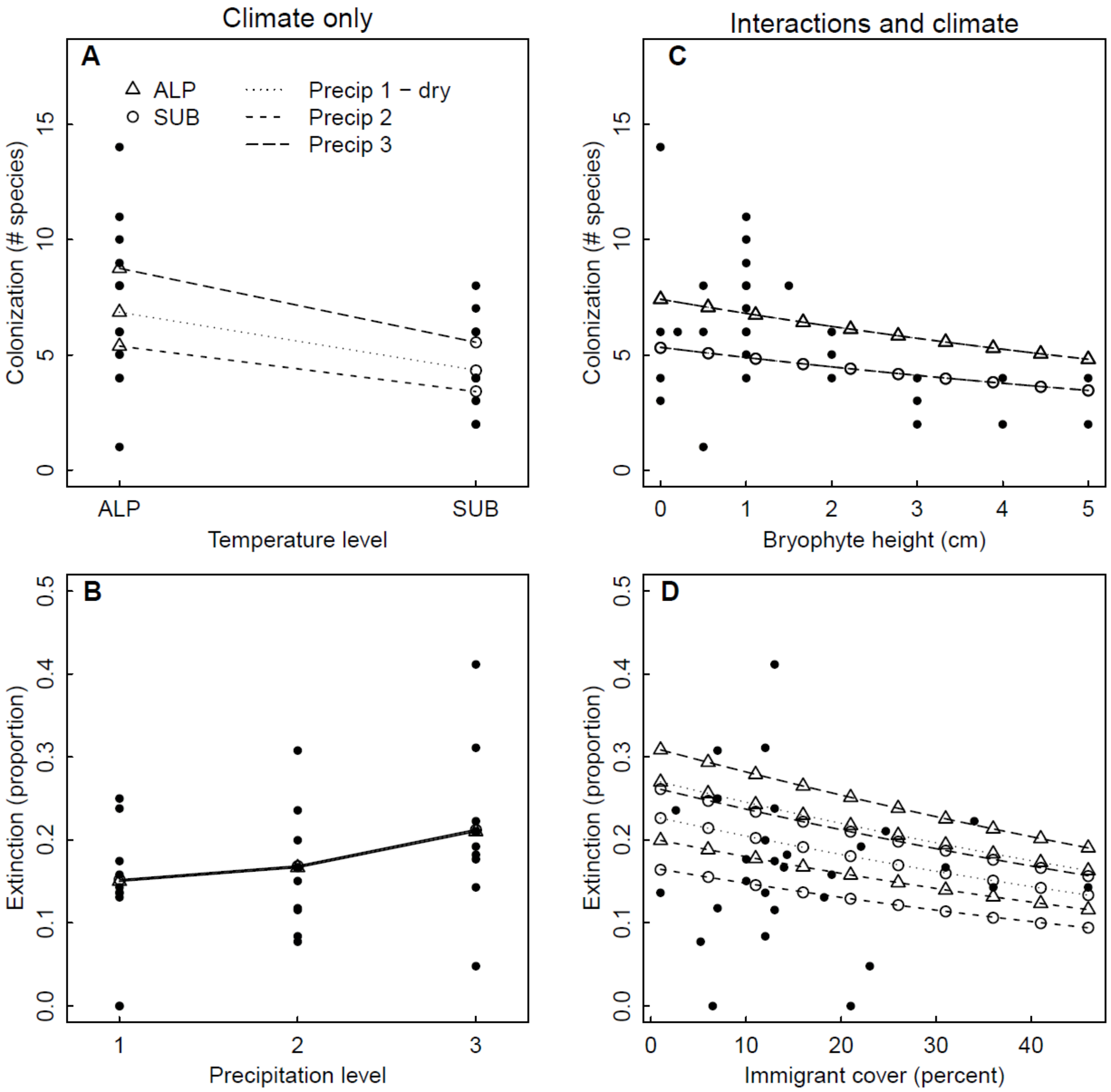


Figure S1. Background plot-level colonization and extinction rates in response to climate context (A, B) and biotic interactions (C, D) based on a series of GLMs of the full factorial data. Colonization rate is expressed as the number of new species colonizing the control plots between 2009 and 2013. Extinction rate is expressed as the proportion of the original species disappearing from the control plots between 2009 and 2013. For biotic interactions, these background colonization and extinction rates are plotted against two of the community metrics tested; coefficients for other significant community metrics see Figure S2 and results text. Black dots (n=60) represent the five replicate plots for each control and local transplant treatment in the six sites in which all climate change treatments are represented. Within each panel, symbols and line types indicate the climatic context (temperature and precipitation levels; see legend on panel A). In cases where the climatic contexts are not significant (Table S4), the associated symbols, or line types are not differentiated on the panel.

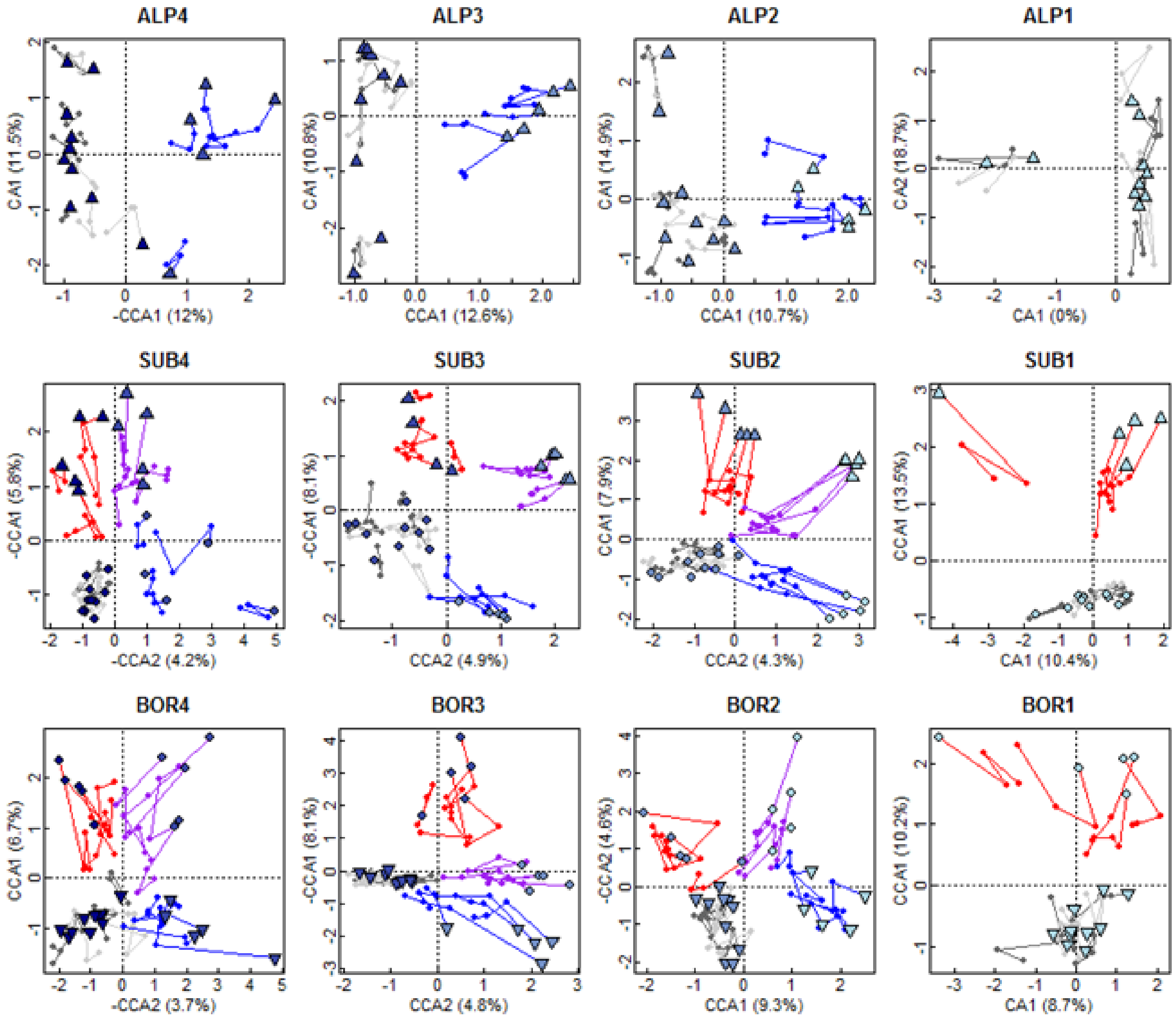


Figure S2. Community response to experimental transplantation to warmer (red) wetter (blue) and warmer and wetter (purple) across the 12 study sites. Controls and local transplants are shown in gray. Based on constrained canonical ordination analysis (CCA; warming and wetting treatments as axis constraints) of plot-level plant communities at each site, with axes fitted to data on initial community composition (2009) and turfs plotted as mean species scores for each treatment in 2009 (symbols according to source site as in Figure 2) and lines for the three subsequent years (2011, 2012 and 2013; colors according to treatment; see Figure 2). The plots are rotated to match the orientation of the grid (Figure 2; reversed axes are indicated by '-' in front of the axis label). For further site and treatment information, see Figure 2 and Table S1. Percentages indicate the % deviance accounted for by each axis. Eigenvalues for each axis are given in Table S3.

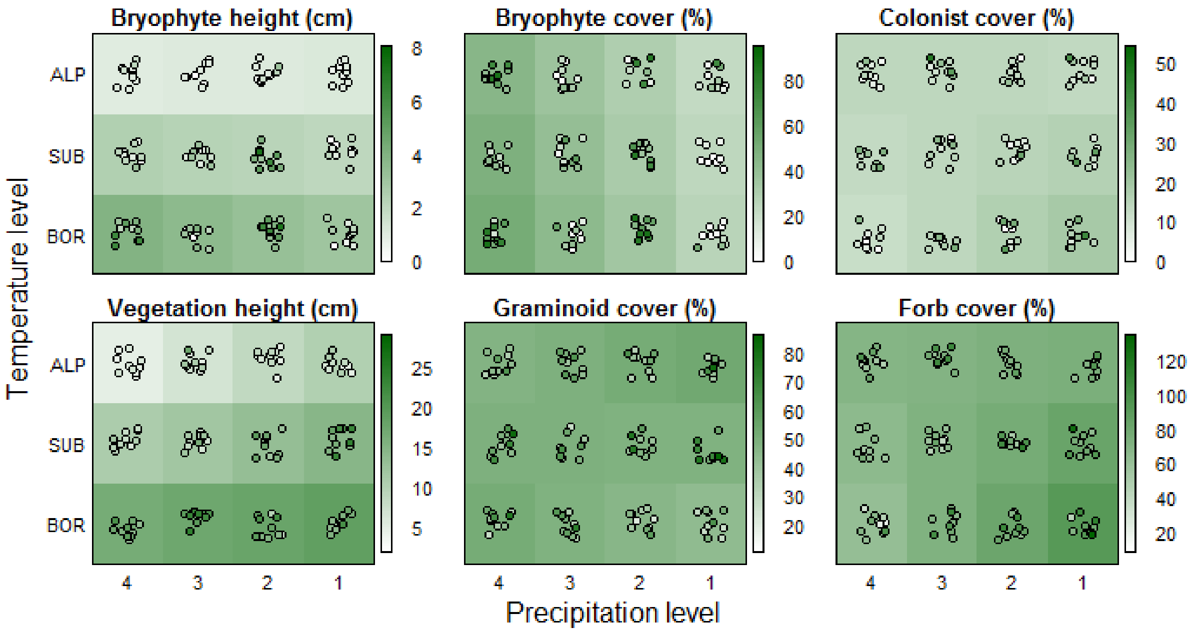


Figure S3. Variation in background levels of the biotic proxies used in models of biotic interactions across the climate grid. Dots indicate observed values for 5 control and 5 local transplant plots per site, the background colours indicates the regression model across the climate grid (see Figure 2). The biotic interactions were relatively uncorrelated with each other ($r < 0.3$) except that bryophyte height was positively correlated with bryophyte cover ($r=0.51$, $p < 0.001$) and vegetation height ($r = 0.36$, $p < 0.001$), and forb cover was positively correlated with colonist species ($r = 0.32$, $p < 0.001$).

Table S1. Geographic and climatic information for the 12 field sites. The table includes site codes, biogeographic classification into zones and sections(4) (Moen & Odland 1998), site names, longitudes and latitudes (in degrees), elevations (in meters above sea level), precipitation (in the three classes used in this paper and in millimeters per year) and growth season temperature (in the three classes used in this paper and in mean temperature of the four warmest months; June – September). Temperature and precipitation data are according to the 1960-1990 normal period data from the Norwegian Meteorological Institute.

Code	**Biogeographic classification**		**Site name**	**Longitude**	**Latitude**	**Elevation**	**Precipitation**		**Temperature**	
	Zones	*Sections*		*(°E)*	*(°N)*	*(m. a. s. l)*	*level*	*(mm)*	*level*	*(°C)*
ALP1	Low-Alpine	O2	Ulvhaugen	61.0243	8.12343	1208	1	596	ALP	6.17
ALP2	Low-Alpine	O1	Låvisdalen	60.8231	7.27596	1097	2	1321	ALP	6.45
ALP3	Low-Alpine	O1	Gudmesdalen	60.8328	7.17561	1213	3	1925	ALP	5.87
ALP4	Low-Alpine	OC	Skjellingahaugen	60.9335	6.41504	1088	4	2725	ALP	6.58
SUB1	Sub-Alpine	O2	Ålrust	60.8203	8.70466	815	1	789	SUB	9.14
SUB2	Sub-Alpine	O1	Høgsete	60.8760	7.17666	700	2	1356	SUB	9.17
SUB3	Sub-Alpine	O1	Rambæra	61.0866	6.63028	769	3	1848	SUB	8.77
SUB4	Sub-Alpine	OC	Veskre	60.5445	6.51468	797	4	3029	SUB	8.67
BOR1	North-Boreal	O2	Fauske	61.0355	9.07876	589	1	600	BOR	10.30
BOR2	North-Boreal	O1	Vikesland	60.8803	7.16982	474	2	1161	BOR	10.55
BOR3	North-Boreal	O1	Arhelleren	60.6652	6.33738	431	3	2044	BOR	10.60
BOR4	North-Boreal	OC	Øvstedal	60.6901	5.96487	346	4	2923	BOR	10.78

Table S2. Descriptive statistics of all candidate variables for proxies of biotic interactions. Means and standard deviations (SD) across all sites, plots, and years. N=940.

Variable	unit	Mean	SD
Graminoid cover	proportion	0.459	0.175
Forb cover	proportion	0.658	0.172
Colonist cover	proportion	0.274	0.172
Vegetation height	m	0.111	0.061
Bryphyte cover	proportion	0.319	0.260
Bryophyte height	m	0.024	0.019

Table S3. **Eigenvalues of the primary constrained axes (CCA) and unconstrained axes (CA)** in the site-wise ordinations (Figure S2). For site information, see Figure 2 and Table S1.

Site	CCA1	CCA2	CA1	CA2
ALP1	-	-	0.268	0.162
ALP2	0.230	-	0.320	0.182
ALP3	0.351	-	0.303	0.227
ALP4	0.275	-	0.264	0.204
SUB1	0.414	-	0.319	0.289
SUB2	0.319	0.174	0.386	0.280
SUB3	0.354	0.216	0.344	0.293
SUB4	0.238	0.171	0.329	0.272
BOR1	0.280	-	0.238	0.233
BOR2	0.380	0.188	0.333	0.229
BOR3	0.279	0.166	0.287	0.225
BOR4	0.279	0.156	0.375	0.316

Table S4. Coefficients from models of colonization (number of new species; Poisson regression) **and extinction** (proportion of possible extinctions; logistic regression) based on only climate variables (climate change, climate context, and climate context-dependency), or climate and biotic interactions (see Figure S3). Climate models are full models containing all climate variables. Biotic interaction models were constructed using forward selection, based on AIC, within two groups of variables which were combined as follows: First, we included variables representing biotic interactions, then main effects for climate change or context, and lastly climate interactions Any selected interaction terms involving biotic interactions were included with those main effects. See Figure 5 for overview and Table S5 for details of deviances explained per model and variable group, and Figure 4 for illustration of some model predictions. The temperature and precipitation levels (TL_SUB; PL_2 and PL_3) specify the contrast to the lowest level within each variable, see Figure 2 and Table S1. Full factorial dataset, n = 150. NA = not relevant in this model, - = no significant effect. + = $p<0.1$, * = $p<0.05$, **$p<0.01$, ***$p<0.001$.

Variable group	Parameters	Colonization		Extinction	
		Climate	Biotic interactions	Climate	Biotic interactions
	Intercept	1.92 ***	1.79 ***	-1.73 ***	-1.37 ***
Climate change	Warmer	0.75 ***	0.56 ***	0.95 ***	0.44 *
	Wetter	*0.11*	0.33 **	0.76 **	0.34 +
	Warmer&Wetter	0.45 *	0.70 ***	1.47 ***	0.67 ***
Climate context	TL_SUB	-0.46 **	-0.33 +	*0.01*	-0.23 +
	PL_2	*-0.24*	-	*0.12*	-0.39 **
	PL_3	*0.25*	-	*0.41*	*0.19*
Climate context-dependency	Warmer : TL_SUB	0.21	*0.20*	-0.61 *	-
	Wetter : TL_SUB	0.57 **	0.59 **	*0.26*	-
	Warmer&Wetter : TL_SUB	*-0.20*	*-0.13*	*0.17*	-
	Warmer : PL_2	*-0.24*	-	*0.25*	-
	Wetter : PL_2	0.55 *	-	-1.17 **	-
	Warmer&Wetter : PL_2	0.44 +	-	-1.14 ***	-
	Warmer : PL_3	-0.54 *	-	*-0.37*	-
	Wetter : PL_3	*0.01*	-	-0.71 *	-
	Warmer&Wetter : PL_3	*-0.12*	-	-0.92 **	-
Biotic interactions	Bryophyte height	NA	-0.16 ***	NA	0.35 ***
	Bryophyte cover	NA	-	NA	*-0.03*
	Vegetation height	NA	*0.00*	NA	-
	Gramoinoid cover	NA	*0.03*	NA	-
	Forb cover	NA	*0.05*	NA	-
	Colonist cover	NA	-	NA	*-0.25*
	Warmer : Colonist cover	NA	-	NA	0.69 **
	Wetter : Colonist cover	NA	-	NA	0.42 +
	Warmer&Wetter : Colonist cover	NA	-	NA	*0.30*

Table S5. Deviances and AIC from models of colonization (number of new species; Poisson regression) **and extinction** (proportion of possible extinctions; logistic regression) based on only climate variables (climate change, climate context, and climate context-dependency), or climate and biotic interactions (see Figure S2). See Table S4 for details on the model specification, Figure 5 for an overview of deviances explained per model and variable group, and Figure 4 for some model predictions. Full factorial dataset, n = 150. NA = not relevant in this model.

Variable group	**Parameters**	**Colonization**		**Extinction**	
		Climate	**Biotic interactions**	**Climate**	**Biotic interactions**
Climate change	TTtreat	46.0	60.8	48.5	9.2
Climate context	T_level	21.2	2.6	0.1	4.1
	P_level	1.7	-	11.8	11.2
Climate context-dependency	TTtreat:T_level	21.2	19.3	12.8	-
	TTtreat:P_level	23.7	-	37.1	-
Biotic interactions	BryophyteHeight	NA	17.6	NA	26.2
	BryophyteCover	NA	-	NA	2.6
	VegetationHeight	NA	2.6	NA	-
	GramoinoidCover	NA	2.7	NA	-
	ForbCover	NA	3.0	NA	-
	ColonistCover	NA	-	NA	49.6
	Tttreat:ColonistCover	NA	-	NA	14.6
Model assessment	Residual deviance	94.8	100.1	168.3	161.1
	Null deviance	208.8	208.8	278.6	278.6
	AIC	588.7	586.0	545.0	531.8

Table S6. Coefficients from models of the candidate proxies of biotic interactions across the climate grid. The best models were constructed using forward selection amongst the main and interactive effects of temperature and precipitation contexts, based on AIC. Only integrators retained in either the colonization or the extinction models (Table S4) are included here. Analyses are based on the 2013 vegetation survey data of the control and local transplant plots, n = 120. - = no significant effect. + = p<0.1, * = p<0.05, **p<0.01, ***p<0.001.

	Bryophyte height (cm)		**Bryophyte cover (%)**		**Colonist cover (%)**		**Vegetation height (cm)**		**Graminoid cover (%)**		**Forb cover (%)**	
Full model												
Intercept	-0.92	+	-0.79		-0.47		-0.67		0.87		-0.52	
Temperature	0.38		0.05		0.37		0.60	**	-0.46	+	0.62	*
Precipitation	-0.13		0.24		0.13		-0.40	**	-0.27		0.11	
Temperature:Precipitation	0.10		0.02		-0.12		0.10		0.15		-0.20	*
Best model												
Intercept	-1.24	***	-0.69	**	0.00	***	-1.14	***	0.87		-0.52	
Temperature	0.62	***	-		-		0.84	***	-0.46	+	0.62	*
Precipitation	-		0.27	***	-		-0.21	***	-0.27		0.11	
Temperature:Precipitation	-		-		-		-		0.15		-0.20	*

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