

Past climate-driven range shifts and population genetic diversity in Arctic plants

L. Pellissier, P. Eidesen, D. Ehrich, P. Descombes, P. Schönswetter, A. Tribsch, K.

Westergaard, N. Alvarez, A. Guisan, N. E. Zimmermann, S. Normand, P. Vittoz, M. Luoto,

C. Damgaard, C. Brochmann, M. S. Wisz, I. G. Alsos

Journal of Biogeography

Appendix S1

Table S1. Sample sizes for the genetic analyses of the 30 species included in the study and the predictive power from four species distribution model techniques measured with the Boyce index.

Species	Genetic data			Boyce index			
	No of pop.	No of ind.	AFLP data reference	GLM	GAM	GBM	RF
<i>Angelica archangelica</i>	41	405	^{1,2}	0.859	0.538	0.915	0.883
<i>Arabis alpina</i>	36	305		³ 0.948	0.974	0.99	0.981
<i>Arctous alpinus</i>	38	336	^{1,2,4}	0.932	0.947	0.99	0.996
<i>Arenaria humifusa</i>	17	92		⁵ 0.926	0.924	0.966	0.941
<i>Avenella flexuosa</i>	37	343	^{1,2,4}	0.966	0.931	0.921	0.918
<i>Betula nana</i>	65	528	^{1,2}	0.98	0.792	0.846	0.951
<i>Carex atrofusca</i>	23	203		⁶ 0.62	0.684	0.969	0.975
<i>Carex bigelowii</i>	23	186		⁷ 0.61	0.469	0.991	0.945
<i>Cassiope tetragona</i>	58	579		⁸ 0.459	0.897	0.967	0.994
<i>Chamerion angustifolium</i>	64	462	^{1,2,4}	0.884	0.566	0.857	0.43
<i>Dryas octopetala</i>	51	459		⁹ 0.929	0.919	0.797	0.967
<i>Empetrum nigrum</i>	46	413	^{1,10}	0.504	0.605	0.91	0.749
<i>Juncus biglumis</i>	24	205		¹¹ 0.945	0.946	0.953	0.944
<i>Juniperus communis</i>	53	446	^{1,2,4}	0.876	0.716	0.942	0.915
<i>Loiseleuria procumbens</i>	41	404	^{1,2}	0.986	0.961	0.982	0.994
<i>Micranthes foliolosa</i>	14	73		¹ 0.972	0.96	0.986	0.989
<i>Micranthes stellaris</i>	25	182	^{1,2,4}	0.969	0.992	0.958	0.996
<i>Minuartia biflora</i>	22	194		¹² 0.997	0.952	0.991	0.997
<i>Pedicularis oederi</i>	31	196		¹ 0.509	0.59	0.969	0.964

<i>Ranunculus glacialis</i>	85	268	13	0.744	0.979	0.986	0.997
<i>Ranunculus pygmaeus</i>	35	241	12	0.844	0.821	0.901	0.896
<i>Rubus chamaemorus</i>	44	387	13	0.889	0.855	0.986	0.903
<i>Sagina caespitosa</i>	16	133	4	0.851	0.856	0.989	0.805
<i>Salix herbacea</i>	41	399	14	0.363	0.922	0.934	0.972
<i>Saxifraga rivularis</i>	22	207	15	0.841	0.955	0.963	0.874
<i>Sibbaldia procumbens</i>	18	151	Alsos et al., unpubl.	0.998	0.993	0.95	0.993
<i>Thalictrum alpinum</i>	49	295	1	0.966	0.704	0.975	0.968
<i>Trollius europaeus</i>	79	395	16	0.88	0.936	0.986	0.976
<i>Vaccinium uliginosum</i>	131	958	17	0.986	0.997	0.467	0.597
<i>Vaccinium vitis-idaea</i>	66	628	1,2	0.953	0.957	0.72	0.822

Table S2. Species traits collected for the 30 species based on several sources and databases¹⁹⁻²³. We selected traits that are expected to be the most influential ones in determining levels of genetic variation in populations as well as of genetic differentiation among populations within species. Growth form (H = Hemicryptophyte, CH = Chamaephyte, G = Geophyte, P = Phanerophyte), Reproduction (s = Sexual, v/vv = Vegetative to varying degree), Pollination (se = predominant self-pollination (autogamy, including kleistogamy, pseudokleistogamy and geitonogamy), in = insect pollination (entomogamy, with or without potential for autogamy), wi = wind pollination (anemogamy)). Category of dispersal distances represents scores based on the seed typology as described in Vittoz and Engler²³, with 1 representing shortest (50% dispersed within 0.1 m) and 7 longest dispersal distance (50% dispersed within 500 m).

Species	Growth	Reprod.	Polli n.	Dispers.
<i>Angelica archangelica</i>	H	s	in	3
<i>Arabis alpina</i>	H	s	in	1
<i>Arctous alpinus</i>	CH	sv	in	6
<i>Arenaria humifusa</i>	CH	s	in	1
<i>Avenella flexuosa</i>	H	sv	wi	3
<i>Betula nana</i>	P	svv	wi	4
<i>Carex atrofusca</i>	G	sv	wi	2

<i>Carex bigelowii</i>	G	sv	wi	2
<i>Cassiope tetragona</i>	CH	svv	in	1
<i>Chamerion angustifolium</i>	H	sv	in	5
<i>Dryas octopetala</i>	CH	sv	in	3
<i>Empetrum nigrum</i>	CH	sv	wi	6
<i>Juncus biglumis</i>	G	sv	wi	2
<i>Juniperus communis</i>	P	s	wi	6
<i>Loiseleuria procumbens</i>	CH	s	in	1
<i>Micranthes foliolosa</i>	H	svv	in	1
<i>Micranthes stellaris</i>	H	sv	in	1
<i>Minuartia biflora</i>	CH	s	in	1
<i>Pedicularis oederi</i>	H	s	in	3
<i>Ranunculus glacialis</i>	H	sv	in	4
<i>Ranunculus pygmaeus</i>	H	s	se	2
<i>Rubus chamaemorus</i>	CH	sv	in	3
<i>Sagina caespitosa</i>	CH	s	in	1
<i>Salix herbacea</i>	CH	svv	in	5
<i>Saxifraga rivularis</i>	H	sv	se	6
<i>Sibbaldia procumbens</i>	H	sv	in	6
<i>Thalictrum alpinum</i>	H	sv	in	2
<i>Trollius europaeus</i>	H	sv	in	7
<i>Vaccinium uliginosum</i>	CH	sv	in	6
<i>Vaccinium vitis-idaea</i>	CH	svv	in	7

References for supplementary material

1. Alsos, I. G., Ehrich, D., Thuiller, W., Eidesen, P. B., Tribsch, A., Schönswetter, P. et al. (2012) Genetic consequences of climate change for northern plants. *Proceedings of the Royal Society B: Biological Sciences*, **279**, 2042–2051.
2. Eidesen, P. B., Ehrich, D., Bakkestuen, V., Alsos, I. G., Gilg, O., Taberlet, P. & Brochmann, C. (2013) Genetic roadmap of the Arctic: plant dispersal highways, traffic barriers and capitals of diversity. *New Phytologist*, **200**, 898–910.
3. Ehrich, D., Gaudeul, M., Assefa, A., Koch, M. A., Mummenhoff, K., Nemomissa, S. & Brochmann, C. (2007). Genetic consequences of Pleistocene range shifts: contrast

- between the Arctic, the Alps and the East African mountains. *Molecular Ecology*, **16**, 2542–2559.
4. Westergaard, K. B., Alsos, I. G., Ehrich, D., Eidesen, P. B., Hollingsworth, P. M. & Brochmann, C. (2008) Genetic diversity and distinctiveness in Scottish alpine plants. *Plant Ecology and Diversity*, **1**, 329–338.
 5. Westergaard, K. B., Alsos, I. G., Popp, M., Engelskjøn, T., Flatberg, K. I. & Brochmann, C. (2011) Glacial survival may matter after all: nunatak signatures in the rare European populations of two west-arctic species. *Molecular Ecology*, **20**, 376–393.
 6. Schönswetter, P., Popp, M. & Brochmann, C. (2006). Central Asian origin of and strong genetic differentiation among populations of the rare and disjunct *Carex atrofusca* (Cyperaceae) in the Alps. *Journal of Biogeography*, **33**, 948–956.
 7. Schönswetter, P., Elven, R. & Brochmann, C. (2008) Trans-Atlantic dispersal and large-scale lack of genetic structure in the circumpolar, arctic-alpine sedge *Carex bigelowii* s. lat. (Cyperaceae). *American Journal of Botany*, **95**, 1006–1014.
 8. Eidesen, P. B., Carlsen, T., Molau, U. & Brochmann, C. (2007) Repeatedly out of Beringia: *Cassiope tetragona* embraces the Arctic. *Journal of Biogeography*, **34**, 1559–1574.
 9. Skrede I., Eidesen, P. B., Portela, R. P. & Brochmann, C. (2006) Refugia, differentiation and postglacial migration in arctic-alpine Eurasia, exemplified by the mountain avens (*Dryas octopetala* L.). *Molecular Ecology*, **15**, 1827–1840.

10. Alsos, I. G., Eidesen, P. B., Ehrich, D., Skrede, I., Westergaard, K., Jacobsen, G. H. et al. (2007) Frequent long-distance plant colonization in the changing Arctic. *Science*, **316**, 1606–1609.
11. Schönswetter, P., Suda, J., Popp, M., Weiss-Schneeweiss, H. & Brochmann, C. (2007) Circumpolar phylogeography of *Juncus biglumis* (Juncaceae) inferred from AFLP fingerprints, cpDNA sequences, nuclear DNA content and chromosome numbers. *Molecular Phylogenetic and Evolution*, **42**, 92–103.
12. Schönswetter, P., Popp, M. & Brochmann, C. (2006) Rare arctic-alpine plants of the European Alps have different immigration histories: the snowbed species *Minuartia biflora* and *Ranunculus pygmaeus*. *Molecular Ecology*, **15**, 709–720.
13. Schönswetter, P., Tribsch, A., Stehlik, I. & Nickfeld, H. (2004) Glacial history of high alpine *Ranunculus glacialis* (Ranunculaceae) in the European Alps in a comparative phylogeographical context. *Biological Journal of the Linnean Society*, **81**, 183–195.
14. Ehrich, D., Alsos, I. G. Brochmann, C. (2008) Where did the northern peatland species survive the dry glacials: cloudberry (*Rubus chamaemorus*) as an example. *Journal of Biogeography*, **35**, 800–814.
15. Alsos, I. G., Alm, T., Normand, S. & Brochmann, C. (2009) Past and future range shifts and loss of diversity in dwarf willow (*Salix herbacea* L.) inferred from genetics, fossils and modelling. *Global Ecology and Biogeography*, **18**, 223–239.
16. Westergaard, K. B., Jørgensen, M. H., Gabrielsen, T. M., Alsos, I. G. & Brochmann, C. (2010) The extreme Beringian/Atlantic disjunction in *Saxifraga rivularis* (Saxifragaceae) has formed at least twice. *Journal of Biogeography*, **37**, 1262–1276.

17. Espíndola, A., Pellissier, L., Maiorano, L., Hordijk, W., Guisan, A., & Alvarez, N. (2012) Predicting present and future intra-specific genetic structure through niche hindcasting across 24 millennia. *Ecology Letters*, **15**, 649–657.
18. Eidesen, P. B., Alsos, I. G., Popp, M., Stensrud, Ø., Suda, J. & Brochmann, C. (2007) Nuclear versus plastid data: complex Pleistocene history of a circumpolar key species. *Molecular Ecology*, **16**, 3902–3925.
19. Klotz, S., Ingolf, K. & Durka, W. (2002) *BIOLFOR – Eine Datenbank mit Biologisch-Ökologischen Merkmalen zur Flora von Deutschland*, 1 edn. Bundesamt für Naturschutz, Bonn.
20. Aeschimann, D., Lauber, K., Moser, D. & Theurillat, J. P. *Flora Alpina: ein Atlas Sämtlicher 4500 Gefäßpflanzen der Alpen*. (Haupt Verlag, 2004).
21. Landolt, E. & Bäumler, B. *Flora Indicativa. Ecological Indicator Values and Biological Attributes of the Flora of Switzerland and the Alps*. (Haupt Verlag, 2010).
22. Pignatti S. (2005) *Biondificazione attraverso le piante vascolari. Valori di indicazione secondo Ellenberg (Zeigerwerte) per le specie della Flora d'Italia*. *Braun-Blanquetia* 39. Camerino, Italy.
23. Vittoz, P., Engler R. (2007). Seed dispersal distances: a typology based on dispersal modes and plant traits. *Botanica Helvetica*, **117**, 109–124.

Appendix S2

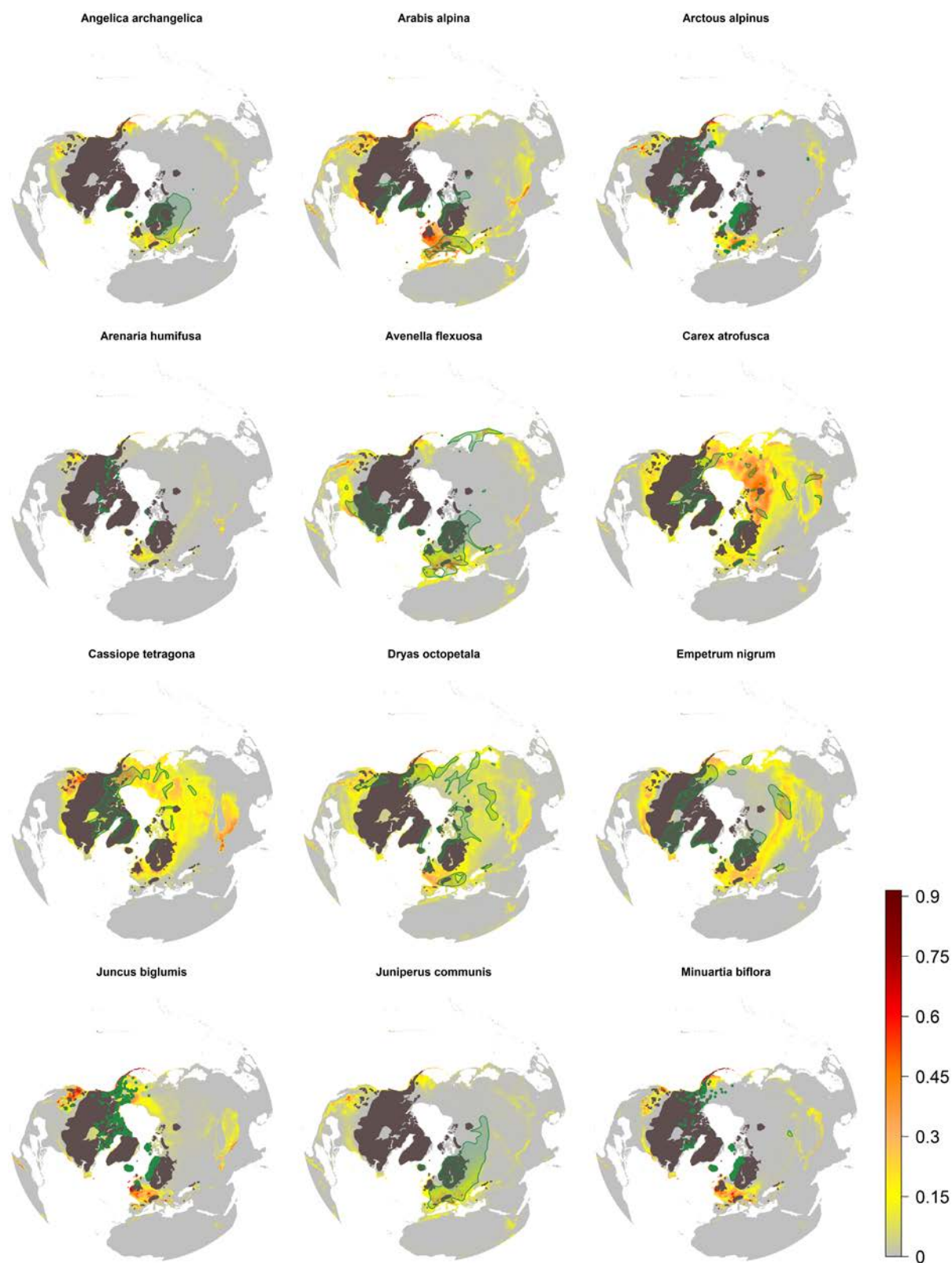


Figure S1. Potential distribution based on climatic suitability of the investigated species hindcasted to the Last Glacial Maximum (-21 Ky), from the species *A. angelica* to *M. biflora*.

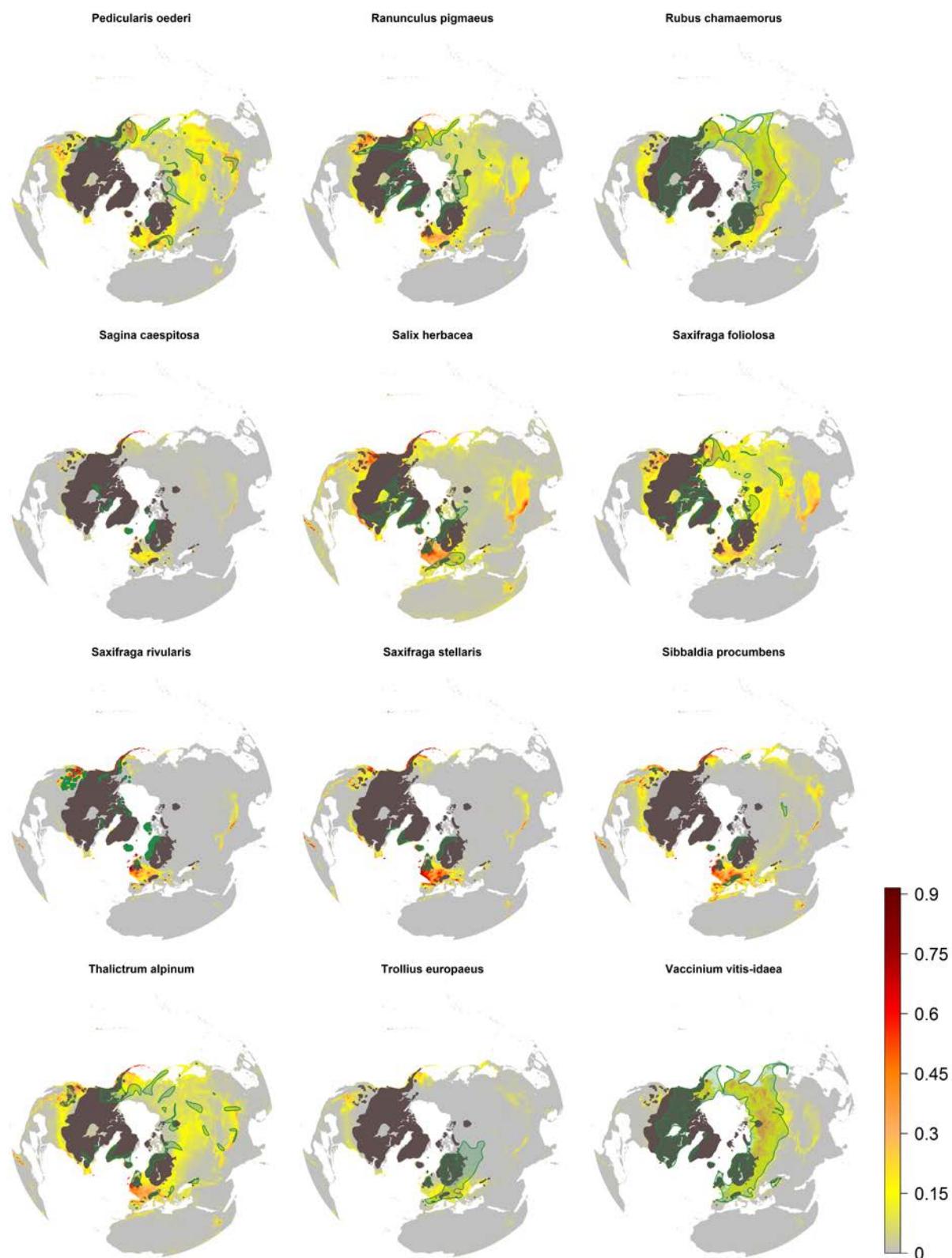


Figure S2. Potential distribution based on climatic suitability of the investigated species hindcasted to the Last Glacial Maximum (-21 Ky) from the species *P. oederi* to *V. vitis-idaea*.

Appendix S3

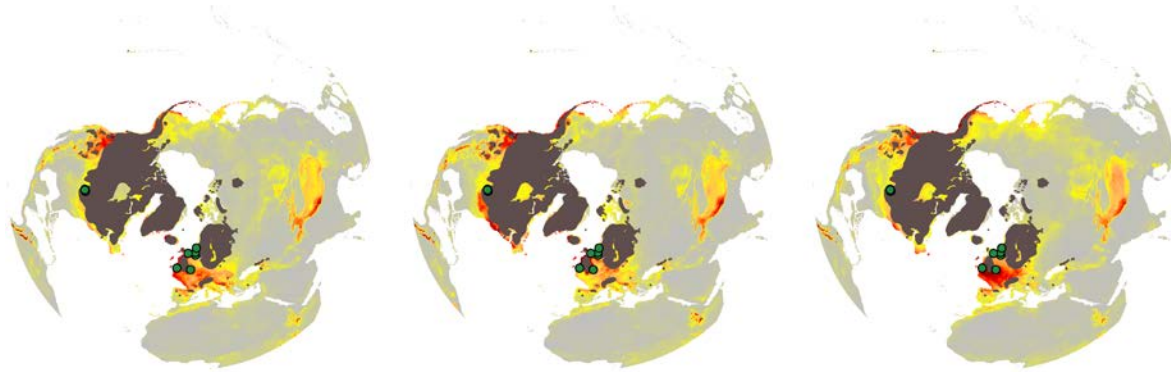
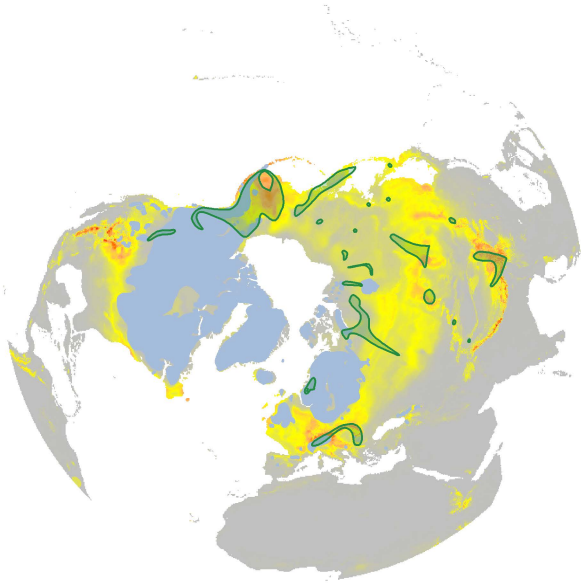
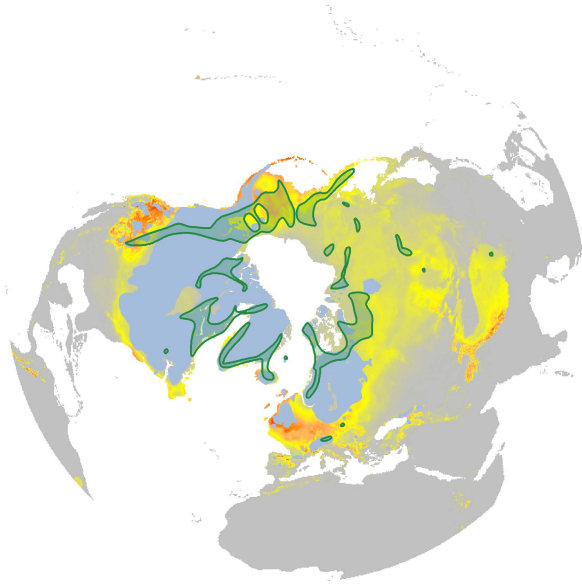


Figure S3. Potential distribution based on climatic suitability for *Salix herbacea* hindcasted to the last glacial maximum (-21 Ky) with the three GCMs a) CCSM4, b) MPI-ESM-P, c) MIROC-ESM. Known fossil records are indicated in green. Only MPI-ESM-P was able to confidently predict fossil occurrences in eastern North America at the LGM

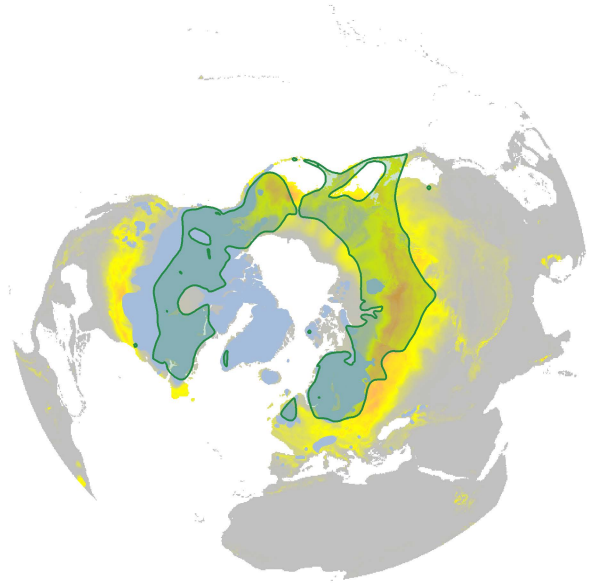
Pedicularis oederi



Ranunculus pigmaeus



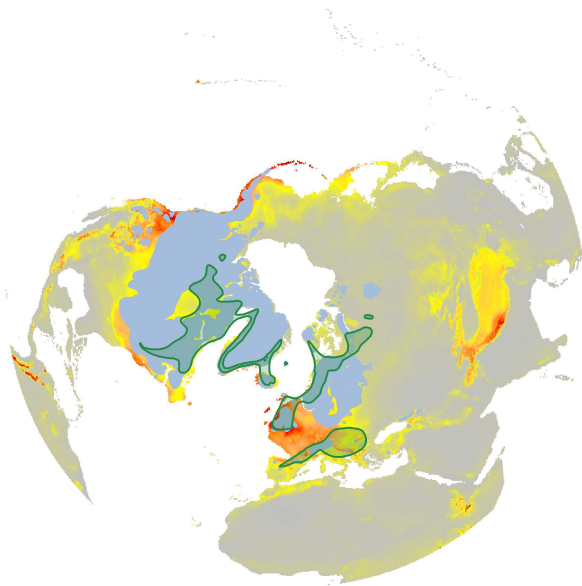
Rubus chamaemorus



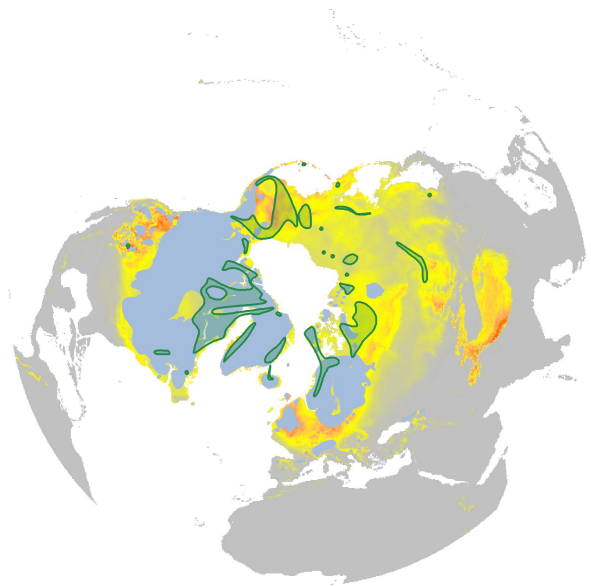
Sagina caespitosa



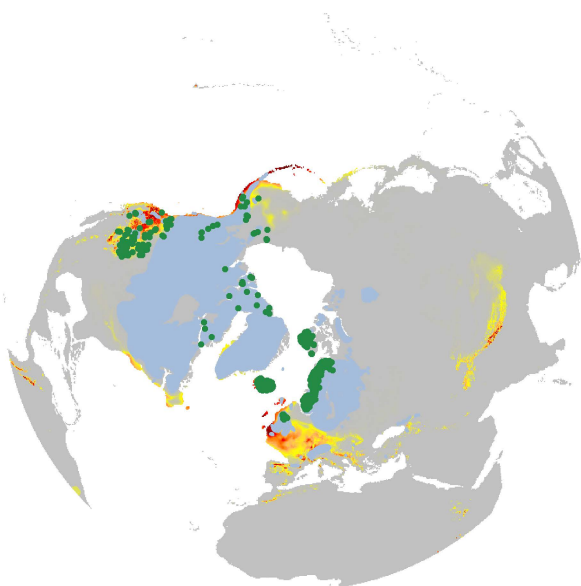
Salix herbacea



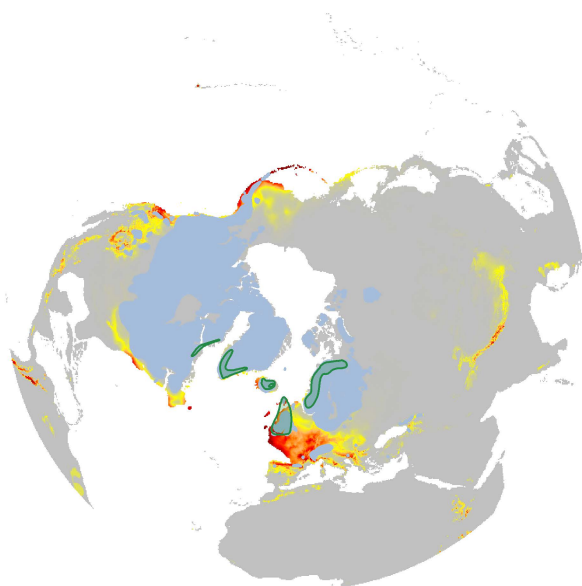
Saxifraga foliolosa



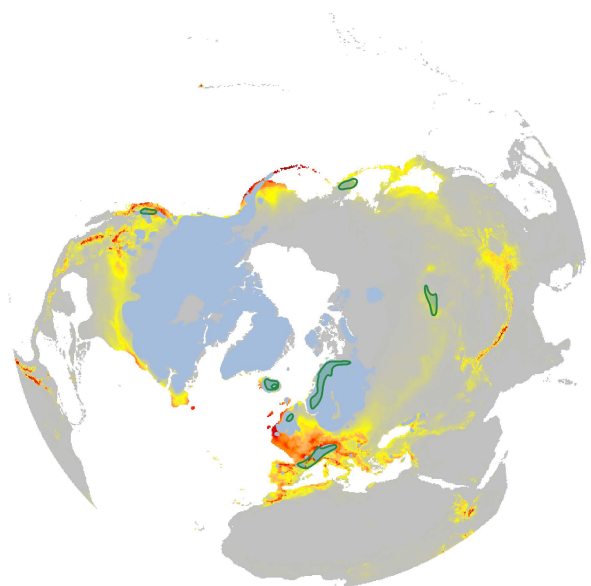
Saxifraga rivularis



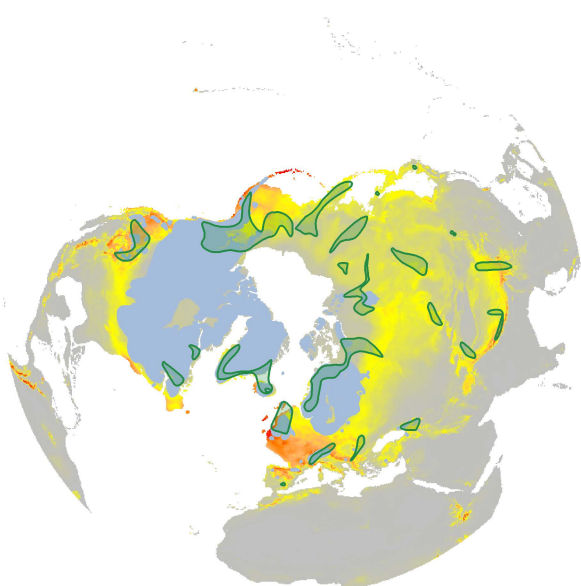
Saxifraga stellaris



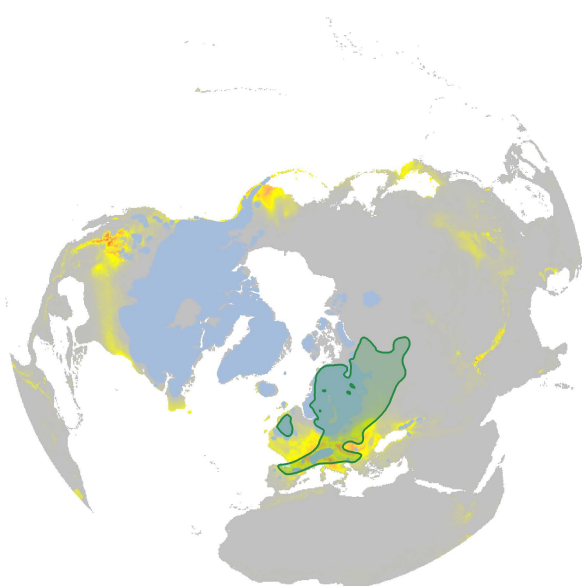
Sibbaldia procumbens



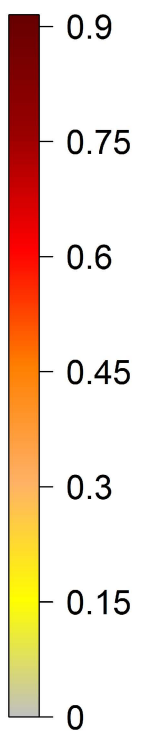
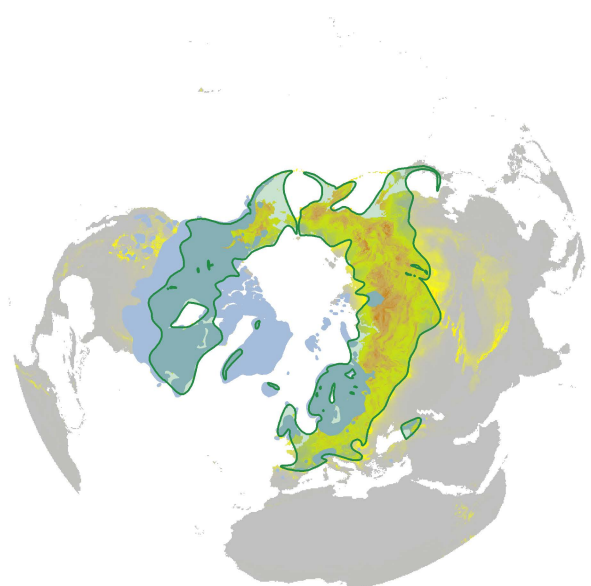
Thalictrum alpinum



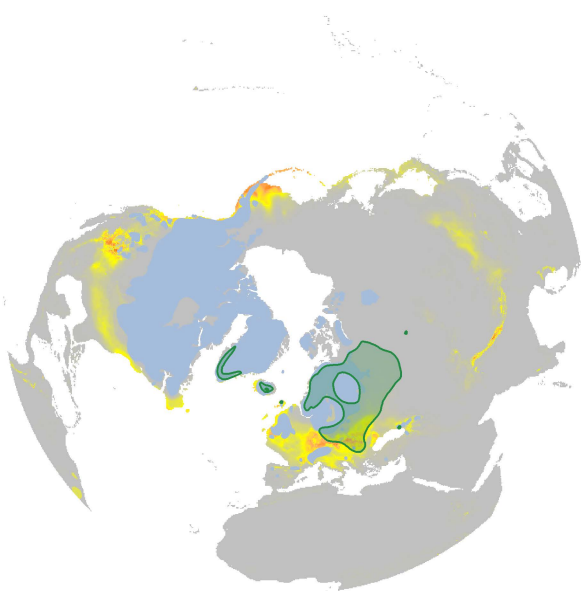
Trollius europaeus



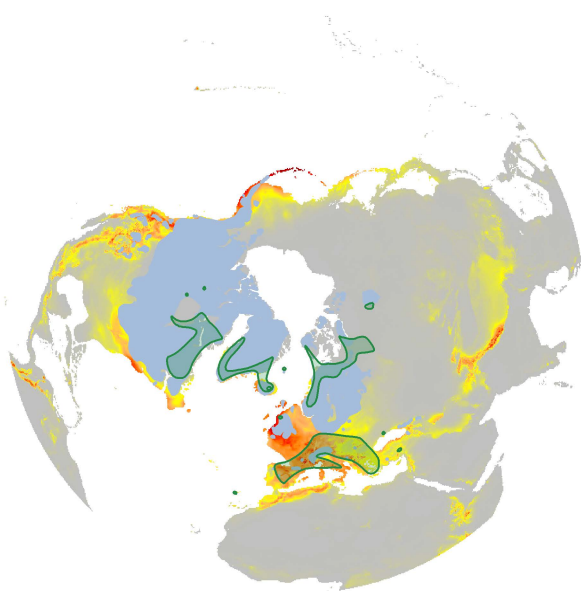
Vaccinium vitis-idaea



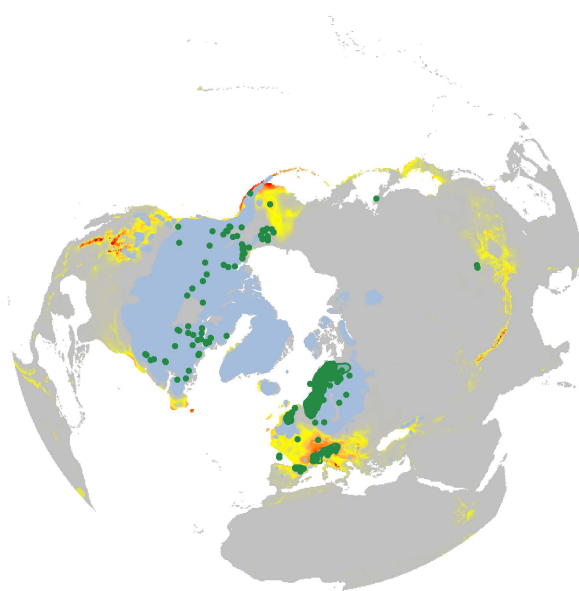
Angelica archangelica



Arabis alpina



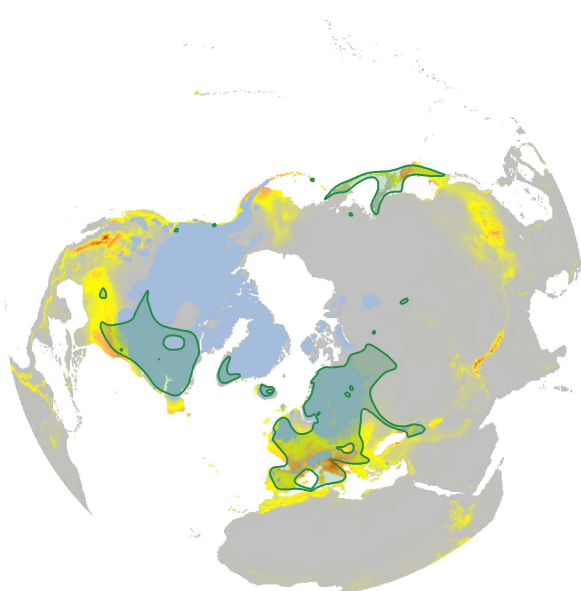
Arctous alpinus



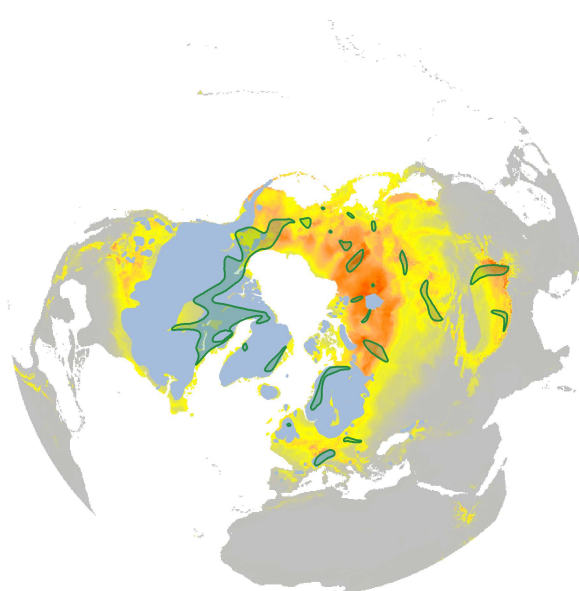
Arenaria humifusa



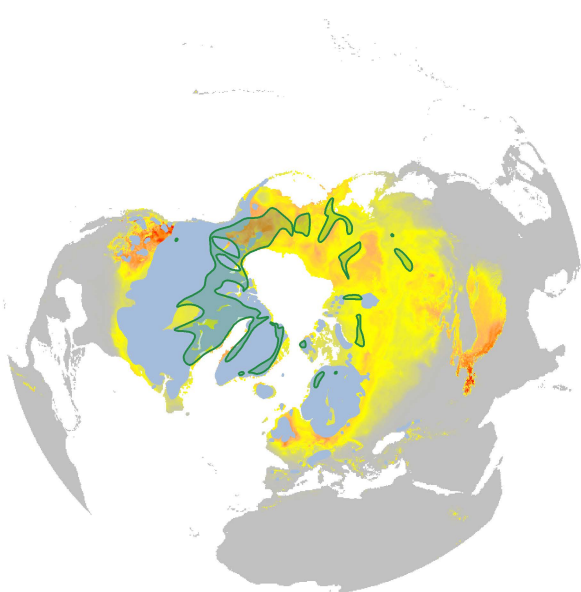
Avenella flexuosa



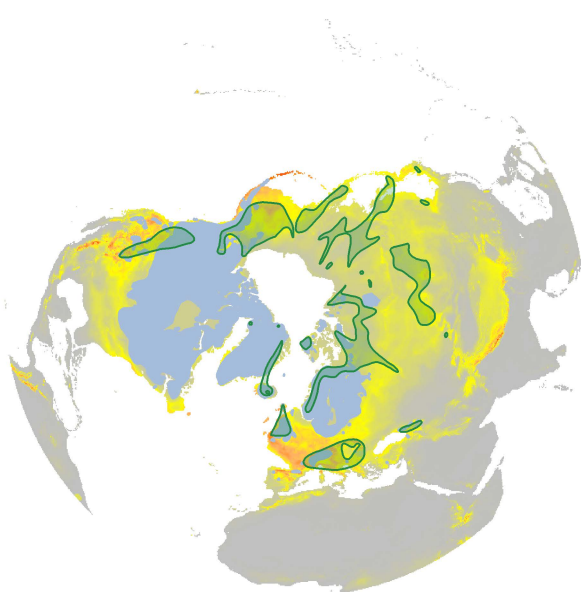
Carex atrofusca



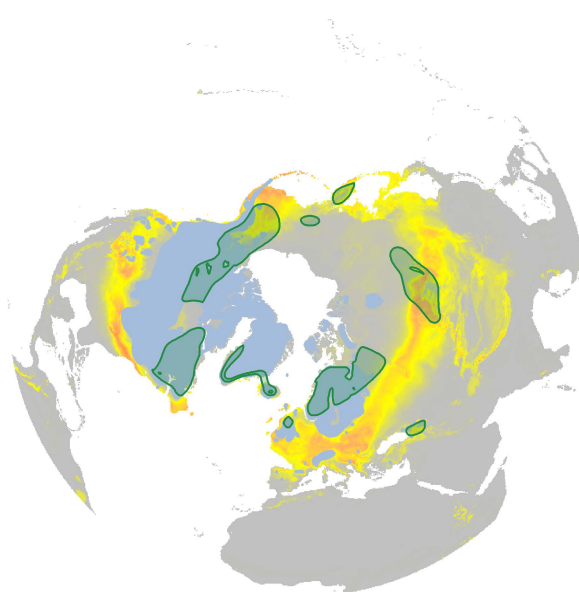
Cassiope tetragona



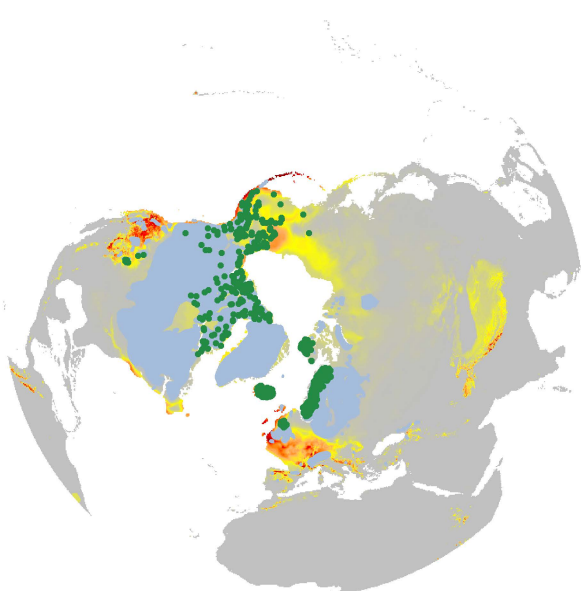
Dryas octopetala



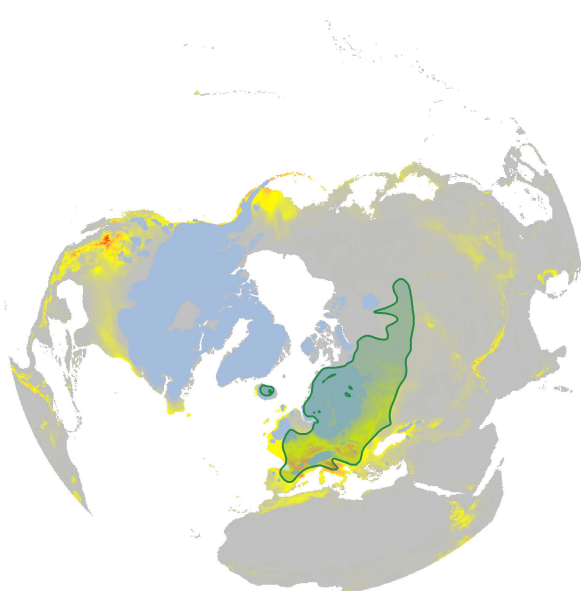
Empetrum nigrum



Juncus biglumis



Juniperus communis



Minuartia biflora

