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To cite this article: Heli Fitzgerald *et al* 2025 *Environ. Res. Commun.* **7** 105022

Environmental Research Communications

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RECEIVED
30 January 2025

REVISED
25 September 2025

ACCEPTED FOR PUBLICATION
14 October 2025

PUBLISHED
29 October 2025

PAPER

Climate change modelling predicts dramatic changes in the species distribution of Nordic crop wild relatives

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Keywords: crop wild relatives, plant genetic resources, species distribution modelling

Supplementary material for this article is available online

Abstract

Introduction. Crop wild relatives (CWR) play an important role in combatting threats to global food security and the adverse effects of climate change on food production. At the same time, climate change is predicted to lead to significant challenges for species survival, including Nordic CWR taxa. *Aim*. The modelling of future climate scenario effects on Nordic priority CWR taxa was undertaken to set priorities for *in situ* and *ex situ* conservation for both species and areas. *Methods*. We modelled the effect of future climate change on suitable habitats for 84 taxa under two CMIP6 Shared Socio-economic Pathways scenarios (SSP 2-4.5, and SSP 5-8.5). The present potential distribution range was compared to the status by year 2100. *Results*. The results revealed that even modest climate change causes negative effects in many species. There was large variation among the species' responses to climate change, but over half of the taxa showed a reduction in suitable future habitats under both SSP scenarios. Threatened and mountainous species appear to be more negatively affected than the rest of the priority CWR taxa. *Conclusions*. We recommend *in situ* conservation with active management of Nordic CWR, prioritizing *ex situ* collection for species vulnerable to climate change. In addition, regular monitoring of CWR populations is essential to detect diversity loss and guide management, and a comprehensive Nordic CWR *in situ* network, integrated with *ex situ* conservation, is critical for long-term species survival.

Introduction

Crop wild relatives (CWR) are wild species related to cultivated crops. They can be used in breeding to improve crop resistance to pests and diseases as well as to extreme climatic conditions, such as cold temperatures and drought. Consequently, they are important genetic resources for combating threats to global food security and the adverse effects of climate change on food production (Dempewolf *et al* 2014, EEA 2019, Mbow *et al* 2019, Walsh *et al* 2020, FAO 2022). Therefore, in addition to being components of natural or semi-natural ecosystems, they are of particular relevance to humankind. Estimations of the monetary value of CWR suggest substantial sums, such as, $115 billion per year worldwide (Pimentel *et al* 1997) and $196 billion in the potential value of CWR of 32 selected crops (PwC Valuations 2013).

The Nordic region contains CWR related to crop groups, such as vegetables, cereals, fruits, berries, nuts, and forages (Fitzgerald *et al* 2019). The largest species diversity among the prioritized species, is found in berries, vegetables, and forage relatives, while the number of Nordic CWR related to cereal and nut crops is rather low (Palmé *et al* 2019). Many of the priority CWR have large distributions across the Nordic region and are therefore adapted to a wide range of local conditions, such as climate, vegetation, photoperiod, pests, and diseases, all of which can be of relevance for breeders developing crops for the future. Examples of Nordic CWR used in plant breeding, or having potential for future use, include white clover (Rapp 1996, Svenning et al 2001, Helgadóttir et al 2008), perennial ryegrass (Rognli et al 2018), prickly lettuce (Lebeda et al 2014), lingonberry (Gustavsson 1997), and arctic bramble (Hiirsalmi et al 1987).

Changes in the Nordic climate by 2100 are predicted to include rising winter temperatures, heat waves, longer and warmer growing seasons, increased precipitation, reduction of snow cover and soil frost, reduction of winter sunshine and faster warming in the northern parts of the region (Eklund et al 2015, Climaguide 2017, Björnsson et al 2018, Ruosteenoja and Jylhä 2021, Icelandic Met Office 2023). These changes will lead to significant challenges for the survival of species in the future. Some of the priority CWR taxa presented in this article have already been classified as threatened, and according to climate projections, it seems likely that more CWR taxa will become threatened in the future (Phillips et al 2017). In addition, the areas north of the Arctic circle will be more affected by climate change than the rest of the region. Because of Arctic amplification (Serreze and Francis 2006, Serreze et al 2009, England et al 2021) the warming of the Arctic has been four times faster than in the rest of the world in recent decades (Rantanen et al 2022) and Arctic ecosystems are one of the areas that have a disproportionately higher climate-related risk for natural systems than other regions of the world (IPCC 2023).

Climate change is predicted to have a negative effect on many plants, for example, by decreasing range size and increasing fragmentation, which would result in an increasing number of threatened species and a higher likelihood of extinction (Thuiller et al 2005, Jarvis et al 2008). The same pattern can be seen among CWR, but they have not often been recognized as an important group in conservation contexts and therefore lack effective long-term protection (Maxted 2003, IPBES 2019). However, there is an increasing body of work that improves the knowledge of CWR and facilitates their conservation. Guidelines for conservation planning have been developed (Maxted et al 2013, Kell et al 2017, Magos Brehm et al 2017), and progress has been made at the European, Nordic, and national levels. In the Nordic region, national and regional CWR checklists and priority lists have been created (Fitzgerald and Kiviharju 2018, Sæther et al 2020, Weibull et al 2020, Fitzgerald et al 2023) as well as an analysis to identify prioritized target populations for *in situ* and *ex situ* conservation efforts, both at the national (Phillips et al 2016, Weibull and Phillips 2020, Fitzgerald et al 2023) and Nordic level (Fitzgerald et al 2019).

However, to date, no Nordic analysis of the effect of climate change on CWR has been conducted. In this study, which is part of a larger Nordic project on Nordic CWR (Palmé et al 2025, Weibull et al 2025), we present the results of such an analysis of the taxa in the updated Nordic priority list (Fitzgerald et al 2023), and based on this, provide recommendations for Nordic CWR conservation in the future. In the scope of this study, the term Nordic region refers to Denmark, Finland, Iceland, Norway, Sweden, but excludes Greenland, the Faroe Islands, and Svalbard.

Methods

Updating the Nordic CWR priority list

The aim of updating the CWR priority list was to include current data on observations, taxonomy, gene pool affinity, and to add invasiveness and threat categories from Nordic countries. The priority list serves as a basis for Nordic-level conservation planning and implementation, and the updated list was used in selecting taxa for climate change analysis. The first version of the priority list was created by (1) selecting taxa in food or forage categories, (2) selecting taxa established in Nordic countries for more than 10 generations, (3) prioritizing the socio-economic value of the related crop(s) (4) prioritizing potential utilization potential by selecting taxa in the gene pool or taxon group 1–2 or gene pool 3 / taxon group 3–4 with proven use or potential in plant breeding (Fitzgerald and Kiviharju 2018).

All the taxa from the first version of the priority list remained in updated list, but additional data on the national IUCN red list categories (Wasowicz and Heiðmarsson 2019, Hyvärinen et al 2019, Den Danske Rødliste 2019, SLU Artdatabanken 2020, Artsdatabanken 2021) and invasiveness (Strand et al 2018, Artsdatabanken 2020, Skipper and Calabruig 2020, Invasive Plant Species 2022, Vieraslajit 2022) were added. Potential new priority taxa from the food and forage groups were investigated. Nordic scientists and plant breeders were asked to suggest valuable forage wild relatives missing from the dataset. New gene pool data from GRIN taxonomy (USDA 2021) were compared with food wild relatives on the first version of the Nordic checklist. Data on socio-economic value and utilization potential were collected from literature sources, and specialists in the Nordic CWR network verified that the taxa fulfilled the criteria.

Climate change analysis

The climate change modelling of the updated priority list taxa was done on the species level, except for the sea beet (*Beta vulgaris* subsp. *maritima* (L.) Arcang.) on a subspecies level. The taxa were evaluated for the possibility of conducting distribution modelling. Some taxa were then excluded from the modelling based on their limited distribution in the area, insufficient observation data, status as a hybrid, or existence in the region mainly as a cultivated taxon. In total, 84 priority taxa were included in the analysis.

The occurrence data set was obtained from GBIF (GBIF 2024) and additional Icelandic data from the Icelandic Natural History Museum and from Göransson and Thorbjörnsson (2022). The data set was filtered to ensure data quality by the following classes: basis of record observation/specimen; country or area Norway, Finland, Denmark, Sweden, Iceland, and Åland Islands; only occurrences with coordinates and with no geospatial issues; scientific names including all accepted names in Nordic countries for the 84 taxa; occurrences recorded between 1970 and 2022; and coordinate uncertainty up to 3000 meters. Duplicate records were removed and outliers cropped using ArcGIS 10.8 (ESRI 2021). The Nordic region benefits from strong data coverage particularly on vascular plants species targeted. However, spatial biases exist, with some concentration of observations near cities, and less observations recorded in northern mountainous regions as shown in the bias map of Nordic CWR species by Fitzgerald *et al* (2019). Some species excluded from the analysis because of the very low number of filtered observations were *Lactuca quercina* L., *Brassica elongata* Ehrh., *Rorippa islandica* (Oeder & Murray) Borbás, *Elymus alopex* Salomon and *Allium fistulosum* L. For these species, the actual distribution is probably not dependent on the model parameters, but on other factors, and the climate model would not give a relevant outcome. The species excluded because of temporary or cultivated status were *Armoracia rusticana* P. Gaertn., B. Mey. & Scherb., *Fragaria* × *ananassa* (Weston) Decne. & Naudin, *Fragaria moschata* Weston, *Daucus carota* L., *Malus domestica* Borkh., *Prunus domestica* L., *Prunus cerasus* L., *Prunus mahaleb* L. and *Pyrus communis* L. For these species it is difficult to make conclusions regarding their long-term habitat and climate preferences based on the occurrence data, because of problem to distinguish naturalized populations (defined as self-sustaining for at least ten generations) and temporary escapes from cultivation outside their climate envelope, and therefore it is not possible to make reliable climate modelling. In addition, *Avena fatua* L. was excluded as it is a regulated pest and its distribution pattern is not reliable due to its eradication, which is the reason for its actual distribution rather than climate.

Altogether, 19 bioclimatic and five geophysical layers from WorldClim2.1 (Fick and Hijmans 2017) and 18 edaphic layers from the Harmonized World Soil Database 1.21 (FAO/IIASA/ISRIC/ISSCAS/JRC 2012) were used in climate modelling (table 1). Including edaphic and geophysical variables were included to improve model robustness, particularly in the northern parts of the region with partial underrepresentation of observations. The layers were clipped to the extent of Denmark, Iceland, Finland, Norway, Sweden, and the Åland Islands. Greenland, Faroe Islands, Svalbard and Arctic Islands were excluded from the analysis as the Nordic CWR priority list does not yet include taxa from these areas.

The present climate data from WorldClim 2.1 for 1970–2000 (Fick and Hijmans 2017, Harris *et al* 2020) were used at a 2.5 arc-min spatial resolution (~4.5 km2 at the equator). For future modelling, the CMIP6 (IPCC 2021a) downscaled future climate projections were downloaded from WorldClim 2.1 for 2081–2100 for the GCM model 'CMIP6 MRI_ESM2_0.' The model was selected using GCMeval (Parding *et al* 2020), which rated 'MRI_ESM2_0' and 'EC_Earth3' as the best-performing models for Northern Europe and Iceland. 'MRI-ESM2-0' was selected over 'EC_Earth3' due to its higher spatial resolution (~1.125°) and well-documented capacity to capture regional climate extremes and moisture variability (Yukimoto *et al* 2019). 'MRI-ESM2-0' also provides more moderate warming projections, reducing the likelihood of overestimating climate impacts on habitat suitability (Zelinka *et al* 2020, IPCC 2021b).

Two CMIP6 Shared Socio-economic Pathways scenarios were selected for climate change analysis: SSP 2–4.5, and SSP 5–8.5. The SSP 2–4.5 represents the medium part of the range of plausible future pathways with additional radiative forcing of 4.5 W m^{-2} and an estimated warming of approximately 2.7 °C by the end of the century. The SSP 5–8.5 represents the high end of plausible future pathways with a radiative forcing of 8.5 W m^{-2} and an estimated warming of approximately 4.4 °C by the end of the century (Riahi *et al* 2017, IPCC 2021a). Radiative forcing is a measure of the energy balance in the atmosphere, and an imbalance has already been observed with an increase of 0.53+/−0.11 W m^{-2} between 2003 and 2018 (Kramer *et al* 2021) and is predicted to increase under the models above.For the modelling of the current and future distribution of the selected taxa, specific bioclimatic, geophysical and edaphic variables were selected to be included. For each species, the most important species-specific uncorrelated variables were selected using Capfitogen3 SelecVar (Parra Quijano 2022), and can be found in Supplementary information 1, table S1. The analysis was run in R (R Core Team 2021) by using Random Forest (RF), bivariate correlation analysis (BCA), and principal component analysis (PCA) for each bioclimatic, geophysical, and edaphic variable (Parra Quijano 2021). The parameters used in SelecVar were resolution of 2.5 arc-min (~4.5 km2 at the equator), distdup of 1 (determining the distance in kilometer under which two presence sites represent the same population), minimum number of variables of 5 per species. For the following parameters, the SelecVar default values were used: percentage RF of 0.66, percentage BCA of 0.33, correlation value of 0.5, p-value of 0.05, and ecogeopcaxe of 5. Detailed explanations of these parameters can be found in Parra Quijano *et al* (2021). The layers were converted to ascii format in ArcGIS 10.8.

Table 1. Variables used in the modelling. The full list of variables selected for each taxon can be found in the Supplementary information 1, table S1.

Code	Bioclimatic variables	Unit	Source
bio_1	Annual average temp.	°C	http://worldclim.org
bio_2	Average daytime temp.	°C	http://worldclim.org
bio_3	Isothermality	°C	http://worldclim.org
bio_4	Temp. seasonality	°C	http://worldclim.org
bio_5	Maximum temp. for the warmest month	°C	http://worldclim.org
bio_6	Minimum temp. for the coldest month	°C	http://worldclim.org
bio_7	Annual temp. range	°C	http://worldclim.org
bio_8	Average temp. for the wettest quarter	°C	http://worldclim.org
bio_9	Average temp. for the driest quarter	°C	http://worldclim.org
bio_10	Average temp. for the hottest quarter	°C	http://worldclim.org
bio_11	Average temp.e for the coldest quarter	°C	http://worldclim.org
bio_12	Annual rainfall	°C	http://worldclim.org
bio_13	Rainfall during the wettest month	mm	http://worldclim.org
bio_14	Rainfall during the driest month	mm	http://worldclim.org
bio_15	Seasonality of rainfall	mm	http://worldclim.org
bio_16	Rainfall during the wettest quarter	mm	http://worldclim.org
bio_17	Rainfall during the driest quarter	mm	http://worldclim.org
bio_18	Rainfall during the hottest quarter	mm	http://worldclim.org
bio_19	Rainfall during the coldest quarter	mm	http://worldclim.org
Code	**Geophysical variables**	**Unit**	**Source**
Elevation	Elevation	M above sealevel	http://worldclim.org
Aspect	Aspect (degree) of the land	0 and 359 degrees correspond to north	http://worldclim.org
Estness	Eastness	Eastness	http://worldclim.org
Northness	Northness	Northness	http://worldclim.org
Slope	Slope of the land surface	in degrees	http://worldclim.org
Code	**Edaphic variables**	**Unit**	**Source**
r_horizon	Probability of occurrence of R horizon		https://soilgrids.org
depth_rock	Depth to bedrock (up to 200 cm)	cm	https://soilgrids.org
t_awc1	Topsoil available soil water capacity for h1	volumetric fraction	https://soilgrids.org
t_awc2	Topsoil available soil water capacity for h2	volumetric fraction	https://soilgrids.org
t_awc3	Topsoil available soil water capacity for h3	volumetric fraction	https://soilgrids.org
t_awcts	Topsoil saturated water content for tS	volumetric fraction	https://soilgrids.org
t_bulk_dens	Topsoil bulk density (fine earth)	kg / m3	https://soilgrids.org
t_cecsol	Topsoil cation exchange capacity	cmol/kg	https://soilgrids.org
t_clay_cont	Topsoil clay content (0-2 micrometer) mass fraction	%	https://soilgrids.org
t_coarse_frag	Topsoil coarse fragments	volumetric in %	https://soilgrids.org
t_oc_cont	Topsoil organic carbon content (fine earth fraction)	g per kg	https://soilgrids.org
t_oc_dens	Topsoil organic carbon density	kg/m3	https://soilgrids.org
t_oc_stock	Topsoil organic carbon stock	t/ha	https://soilgrids.org
t_ph_hox	Topsoil pH x 10 in H2O	index*10	https://soilgrids.org
t_ph_kcl	Topsoil pH x 10 in KCl	index*10	https://soilgrids.org
t_sand_cont	Topsoil sand content (50–2000 micrometer) mass fraction	%	https://soilgrids.org
t_soilwater_cap	Topsoil available soil water capacity until wilting point	volumetric fraction	https://soilgrids.org
t_silt_cont	Topsoil silt content (2–50 micrometer) mass fraction	%	https://soilgrids.org

Maxent 3.4.3. (Phillips *et al* 2023) was used for species distribution modelling of the present and future potential distributions. Maxent was selected for its wide use in species distribution modelling and for its robustness and reliability in predicting suitable habitat areas by utilizing species presence data and environmental variables (Elith *et al* 2006, Hernandez *et al* 2006, Hijmans and Graham 2006). Maxent has been used by several authors in CWR species distribution modelling (Jarvis *et al* 2008, Phillips *et al* 2016, Phillips *et al* 2017, Magos Brehm *et al* 2022, Rahman *et al* 2023). The species-specific occurrence points and bioclimatic, geophysical, and edaphic variables were run in Maxent. Models were generated using Maxent with a replicated run type set to 'Crossvalidate', applying 5-fold cross-validation. Five-fold cross-validation was used across all species to balance model robustness with computational efficiency. The models were evaluated against the standard

deviation of the Test AUC (STAUC) and the average Area Under the ROC Curve (AUC) (Receiver Operating Characteristic). Models were considered stable with STAUC < 0.15 and AUC > 0.7 (Ramírez-Villegas *et al* 2010).

The present and future output files were visualized in ArcMap10.8. Threshold values for maximum training sensitivity plus specificity (MTSS) for each species were used to create binary layers of presence-absence maps (Scheldeman and van Zonneveld 2010) to represent suitable or unsuitable habitat areas. MTSS is considered a valid method for threshold selection with presence-only data when random points are used instead of true absences (Liu *et al* 2005, Liu *et al* 2013). The number of raster squares where taxa were present was calculated using ArcMap10.8. for the present scenario and the two future scenarios. The percentage change was then calculated from the raster values to indicate future changes. Additionally, output maps from Maxent showing the continuous probability of suitable habitats from high to low probability were created.

Each species was classified according to its landscape type (SLU Artdatabanken 2024). The seven landscape types were mountain, forest, wetland, freshwater, seashore, agricultural land and urban land. One species could be assigned to several landscape types (Supplementary Information 1, table S2). As the landscape type classifications were not available at the Nordic level, we used Swedish data as a proxy for landscape type classification since it covers most of the latitudinal range and landscape type diversity of the region. The taxa were grouped in order to identify differences in patterns in their projected ranges depending on the landscape type. For each landscape type, the average changes in distribution were calculated for SSP 2–4.5 and SSP 5–8.5, respectively.

In addition, the differences among the threat categories were explored. Since there are differences among countries regarding this (table 2) and rather few CWR are included in the national red lists, it was decided to assign species to two different categories: (1) the more severe category that includes species that are VU, EN, or CR in at least one of the Nordic countries, and (2) the less severe category with species assigned as NT in at least one Nordic country, but not to any more severe national threat category. The average range change percentage was calculated across species for both climate models and groups and compared to species that were not included in any national red list.

Based on the results of the climate change analysis, two priority levels for *ex situ* conservation were defined (1=high priority, 2= priority). All species that are expected lose 80% or more of their suitable habitat by 2100, are assigned to the 'high-priority' category, and the rest of the species are assigned to the 'priority' category. Since all the species included in the analysis are prioritised CWR (see above), all of them should be included in *ex situ* conservation efforts. In general, *in situ* conservation is regarded as the main approach for conservation, with *ex situ* acting as backup. However, in some cases *in situ* conservation is not suitable and *in situ* conservation is only recommended in countries where the species is regarded as native or naturalised, and is not classified as invasive (table 3).Overview of the analysis methods is summarized in figure 1.

Results

Updating the Nordic CWR priority list

The updated priority list included 123 taxa. Altogether, 27 taxa were added (Supplementary Information 1, table S3) compared with the earlier version (Fitzgerald *et al* 2019) including relatives of a wide range of crops such as celery, wheat, rye, radish, raspberry, potato, and forages. The full Nordic CWR priority list dataset can be found in Fitzgerald *et al* (2023). Altogether, 20 taxa on the priority list are red listed in the Nordic countries (table 2), out of which one is critically endangered (CR), three endangered (EN), six vulnerable (VU), and the rest near threatened (NT). Altogether, 16 taxa from the priority list were classified as invasive in at least one of the Nordic countries (table 2), of which five were considered a very high risk (SE), five a high risk (HI), and the rest were in the low-risk category (LO).

Climate change modelling

The results include a binary present potential distribution map and future suitable habitat map for each species for both SSP 2–4.5 and SSP 5–8.5 scenarios in 2100 (see Supplementary Information 2). In the SSP 2–4.5 model, 45 taxa showed an increase in suitable habitats, and 40 of the 84 taxa decrease. The average change in the predicted distribution was −5,8%. In SSP 5–8.5, altogether 44 taxa showed an increase and 41 taxa decrease (table 3), with an average of −4,5%.

Both future models predicted an excess of taxa with a large range reduction (16 taxa with -80% or less) compared to the number of species with a large increase in range (four taxa with +80% or more) (Supplementary information 1, figure S1). Several taxa are predicted to lose more than 90% of their suitable habitats in SSP 2–4.5, including *Angelica archangelica* L., *Corylus avellana* L., *Dactylis glomerata* L., *Diplotaxis muralis* (L.) DC., *Diplotaxis tenuifolia* (L.) DC., *Elymus caninus* (L.) L., *Elymus fibrosus* (Schrenk) Tzvelev, *Elymus kronokensis* (Kom.) Tzvelev, *Elymus mutabilis* (Drobow) Tzvelev, *Festuca arenaria* Osbeck, *Hordeum jubatum* L., *Lactuca*

Table 2. Nationally red listed taxa and those classified as invasive in the updated CWR priority list. Invasive categories: SE very high risk, HI high risk, LO low risk, and NK no known risk. Threat categories: NT Near threatened, VU Vulnerable, EN Endangered, CR Critically endangered, and RE Regionally extinct.

Taxon	National IUCN threat category					National invasive category				
	DEN	ISL	FIN	NOR	SWE	DEN	ISL	FIN	NOR	SWE
Allium fistulosum L.				EN						
Allium schoenoprasum subsp. *schoenoprasum*	NT									
Allium schoenoprasum subsp. *sibiricum* (L.) Hartm.			NT							
Armoracia rusticana P. Gaertn., B. Mey. & Scherb.									HI	
Barbarea vulgaris R. Br.									SE	
Beta vulgaris subsp. *maritima* (L.) Arcang.				VU						
Brassica rapa subsp. *campestris* (L.) Clapham					NT					
Diplotaxis muralis (L.) DC.									LO	LO
Diplotaxis tenuifolia (L.) DC.									LO	
Elymus kronokensis (Kom.) Tzvelev			NT							
Erucastrum gallicum (Willd.) O. E. Schulz									LO	LO
Festuca arenaria Osbeck					NT					
Festuca brevipila Tracey										SE
Festuca rubra subsp. *commutata* Gaudin									SE	
Festuca rubra subsp. *megastachys* Gaudin									HI	
Fragaria moschata Weston									HI	HI
Fragaria viridis Weston	NT		VU	NT						
Hordeum jubatum L.									LO	HI
Lactuca serriola L.									SE	
Lactuca tatarica (L.) C. A. Mey.										SE
Lolium multiflorum Lam.						HI			HI	HI
Malus sylvestris Mill.			VU	VU						
Mentha aquatica subsp. *litoralis* Hartm.			NT							
Phleum arenarium L.	NT			CR						
Phleum phleoides (L.) H. Karst.				VU						
Phleum pratense subsp. *nodosum* (L.) Dumort.			NT	NT						
Poa supina Schrad.	VU									
Prunus cerasifera Ehrh.									LO	LO
Prunus spinosa L.			NT							
Rubus allegheniensis Porter ex L. H. Bailey									LO	LO
Rubus chamaemorus L.				NT						
Rubus laciniatus Willd.									LO	LO
Trifolium alpestre L.					EN					
Trifolium montanum L.	RE			NT	NT					
Vaccinium vitis-idaea L.		VU								
Vicia lathyroides L.			VU	EN						
Vicia villosa Roth					VU					

sibirica (L.) Benth. ex Maxim. and *Lactuca tatarica* (L.) C. A. Mey. (figure 2). The taxa with largest expected range increase (+80% or more) were *Medicago lupulina* L., *Prunus avium* (L.) L., *Prunus cerasifera* Ehrh. and *Prunus spinosa* L. in both models (figure 3). There were also several taxa that displayed a limited expected change in distribution (+/− 20%), 16, and 18 taxa in SSP 2–4.5 and SSP 5–8.5, respectively (Supplementary information 1, table S4).

Additionally, the results include a continuous present potential distribution maps and future suitable habitat maps for both SSP 2–4.5 and SSP 5–8.5 (see figure 5, Supplementary Information 3) for each species. Continuous maps provide a more varied image than binary maps (Guillera-Arroita *et al* 2015). They are made available alongside the binary maps, as they may be useful for further conservation planning based on the potential future effects of climate change on CWR.

The landscape type classification suggests that mountainous species are at the highest risk of range reduction under future climates, with an average range reduction of −38,2% and −36,5% compared to the general average of −5,8% and −4,5%, for SSP2–4.5 and SSP285, respectively. Species growing in urban land had the largest range expansion of 3,9% and 5,4% for SSP2–4.5 and SSP285, respectively, followed by agricultural species (figure 4).

The species that are classified as vulnerable, endangered, or critically endangered on at least one national red list in the Nordic countries have a larger expected range reduction than the species that are not on the red list: average −19.67% and 21.40% compared to −4.57 and −4.27 for the SSP 2–4.5 and SSP 2–8.5, respectively.

Table 3. The percentage of change of the number of raster squares in present and future scenarios. Conservation recommendations are given per country for *in situ* and by priority class for *ex situ* (1=high priority, 2= priority).

CWR taxa	Change	Change % of raster squares		Conservation recommendation	
		Future scenario SSP2-4.5 - 2100	Future scenario SSP5-8.5 - 2100	*In situ*	*Ex situ* priority
Allium schoenoprasum	increase	+28,21	+35,51	DEN, FIN, NOR, SWE	2
Angelica archangelica	decrease	−99,49	−99,45	DEN, FIN, ISL, NOR, SWE	1
Apium graveolens	increase	+14,06	+17,98	DEN, SWE	2
Asparagus officinalis	increase	−16,84	−23,80	DEN, FIN, NOR, SWE	2
Barbarea stricta	decrease	−24,64	−20,18	DEN, FIN, ISL, NOR, SWE	2
Barbarea vulgaris	increase	+51,53	+53,96	DEN, FIN, SWE	2
Beta vulgaris subsp. *maritima*	decrease	−71,12	−72,84	DEN, NOR, SWE	2
Brassica nigra	decrease	−46,05	−50,59	DEN, NOR, SWE	2
Brassica rapa	increase	+10,05	+8,44	DEN, NOR, SWE	2
Carum carvi	decrease	−72,46	−71,26	DEN, FIN, ISL, NOR, SWE	2
Cichorium intybus	increase	+46,21	+41,32	DEN, FIN, NOR, SWE	2
Corylus avellana	decrease	−98,23	−98,15	DEN, FIN, NOR, SWE	1
Crambe maritima	decrease	−41,56	−28,40	DEN, FIN, NOR, SWE	2
Dactylis glomerata	decrease	−99,37	−99,19	DEN, FIN,ISL, NOR, SWE	1
Diplotaxis muralis	decrease	−92,95	−84,39	DEN, FIN, NOR, SWE	1
Diplotaxis tenuifolia	decrease	−90,98	−91,37	DEN, NOR, SWE	1
Elymus caninus	decrease	−99,93	−97,78	DEN, FIN, NOR, SWE	1
Elymus fibrosus	decrease	−92,14	−93,94	FIN, NOR	1
Elymus kronokensis	decrease	−99,91	−99,92	FIN, ISL, NOR, SWE	1
Elymus mutabilis	decrease	−99,81	−99,93	FIN, NOR, SWE	1
Festuca arenaria	decrease	−97,79	−94,53	DEN, FIN, NOR, SWE	1
Festuca brevipila	increase	−15,75	−16,84	DEN, FIN, NOR	2
Festuca ovina	decrease	−49,42	−48,95	DEN, FIN, NOR, SWE	2
Festuca rubra	decrease	−0,45	−1,26	DEN, FIN, ISL, SWE	2
Fragaria vesca	increase	+0,26	+5,38	DEN, FIN, ISL, NOR, SWE	2
Fragaria viridis	increase	+79,85	+72,34	DEN, FIN, NOR, SWE	2
Hordeum jubatum	decrease	−98,51	−99,12	DEN, FIN, NOR	1
Humulus lupulus	decrease	−52,59	−49,93	DEN,FIN, NOR, SWE	2
Lactuca serriola	increase	+34,61	+31,63	DEN, FIN, SWE	2
Lactuca sibirica	decrease	−99,93	−99,91	FIN, NOR, SWE	1
Lactuca tatarica	decrease	−98,01	−96,13	DEN, FIN, NOR	1
Leymus arenarius	decrease	−42,92	−33,19	DEN, FIN, ISL, NOR, SWE	2
Lolium multiflorum	decrease	−83,01	−89,95	FIN	1

Table 3. (Continued.)

CWR taxa	Change	Change % of raster squares: Future scenario SSP2-4.5 - 2100	Change % of raster squares: Future scenario SSP5-8.5 - 2100	Conservation recommendation: *In situ*	Conservation recommendation: *Ex situ* priority
Lolium perenne	increase	+60,72	+60,88	DEN, FIN, NOR, SWE	2
Medicago lupulina	increase	+82,30	+82,31	DEN, FIN, NOR, SWE	2
Medicago sativa	increase	+78,37	+78,36	DEN, SWE	2
Mentha aquatica	increase	+46,70	+46,56	DEN, FIN, ISL, NOR, SWE	2
Mentha arvensis	increase	+59,92	+59,93	DEN, FIN, NOR, SWE	2
Phleum alpinum	decrease	−46,25	−39,60	FIN, ISL, NOR, SWE	2
Phleum arenarium	decrease	−34,47	−41,98	DEN, NOR, SWE	2
Phleum phleoides	decrease	−61,16	−64,87	DEN, FIN, NOR, SWE	2
Phleum pratense	increase	+38,40	+38,67	DEN, FIN, ISL, NOR, SWE	2
Poa alpina	decrease	−50,52	−40,71	FIN, ISL, NOR, SWE	2
Poa palustris	increase	+49,41	+47,51	DEN, FIN, NOR, SWE	2
Poa pratensis	increase	+20,94	+20,94	DEN, FIN, ISL, NOR, SWE	2
Poa supina	decrease	−84,80	−85,98	DEN, FIN, NOR, SWE	1
Poa trivialis	increase	+32,27	+24,75	DEN, FIN, ISL, NOR, SWE	2
Prunus avium	increase	+84,56	+84,48	DEN, NOR, SWE	2
Prunus cerasifera	increase	+86,14	+82,74	DEN, NOR, SWE	2
Prunus spinosa	increase	+85,45	+85,20	DEN, FIN, NOR, SWE	2
Raphanus raphanistrum	increase	+25,58	+24,40	DEN, FIN, NOR, SWE	2
Ribes nigrum	increase	+19,08	+19,87	DEN, FIN, NOR, SWE	2
Ribes rubrum	decrease	−57,44	−57,26	DEN, NOR, SWE	2
Ribes spicatum	decrease	−88,37	−98,77	DEN,FIN, NOR, SWE	1
Ribes uva-crispa	increase	+45,13	+41,74	DEN,FIN, NOR, SWE	2
Rubus allegheniensis	decrease	−51,61	−51,68	DEN, NOR, SWE	2
Rubus arcticus	decrease	−8,86	−16,92	FIN, NOR, SWE	2
Rubus armeniacus	increase	+51,50	+66,02	DEN, NOR, SWE	2
Rubus caesius	increase	+76,80	+75,66	DEN, FIN, NOR, SWE	2
Rubus chamaemorus	decrease	−3,34	−2,87	DEN, FIN, NOR, SWE	2
Rubus idaeus	increase	+26,15	+29,21	DEN, FIN, NOR, SWE	2
Rubus laciniatus	increase	+61,22	+60,93	DEN, NOR, SWE	2
Rubus saxatilis	increase	+4,13	+7,18	DEN, FIN, ISL, NOR, SWE	2
Rubus spectabilis	increase	+76,26	+69,19	DEN, NOR, SWE	2
Schedonorus arundinaceus	decrease	−19,15	−21,73	DEN, NOR	2
Schedonorus pratensis	decrease	−36,64	−28,66	DEN,FIN,ISL, NOR, SWE	2

Table 3. (Continued.)

CWR taxa	Change	Change % of raster squares		Conservation recommendation	
		Future scenario SSP2-4.5 - 2100	Future scenario SSP5-8.5 - 2100	*In situ*	*Ex situ* priority
Setaria viridis	increase	+72,44	+73,53	DEN, NOR, SWE	2
Sinapis arvensis	increase	+77,71	+77,22	DEN, FIN, NOR, SWE	2
Solanum nigrum	increase	+63,20	+62,81	DEN, FIN, NOR, SWE	2
Trifolium alpestre	decrease	−65,02	−76,88	DEN, SWE	2
Trifolium arvense	increase	+52,38	+53,29	DEN, FIN, NOR, SWE	2
Trifolium hybridum	increase	+39,72	+39,04	DEN, FIN, ISL, NOR, SWE	2
Trifolium medium	increase	+37,97	+40,22	DEN, FIN, ISL, NOR, SWE	2
Trifolium montanum	decrease	−74,59	−56,88	DEN, FIN, NOR, SWE	2
Trifolium pratense	increase	+22,74	+24,40	DEN, FIN, ISL, NOR, SWE	2
Trifolium repens	increase	+15,58	+15,59	DEN, FIN, ISL, NOR, SWE	2
Trifolium striatum	increase/ decrease	+7,82	−8,61	DEN, SWE	2
Vaccinium microcarpum	increase	+4,51	+4,91	DEN, FIN, ISL, NOR, SWE	2
Vaccinium myrtillus	increase	+3,51	+3,91	DEN, FIN, ISL, NOR, SWE	2
Vaccinium oxycoccos	decrease	−10,10	−7,89	DEN, FIN, NOR, SWE	2
Vaccinium uliginosum	increase	+1,27	+2,05	DEN, FIN, ISL, NOR, SWE	2
Vaccinium vitis-idaea	decrease	−6,32	−6,03	DEN, FIN, ISL, NOR, SWE	2
Vicia lathyroides	increase	+65,58	+64,22	DEN, FIN, NOR, SWE	2
Vicia sativa	increase	+60,35	+62,65	DEN, NOR, SWE	2
Vicia villosa	increase	+55,32	+54,94	DEN, NOR, SWE	2

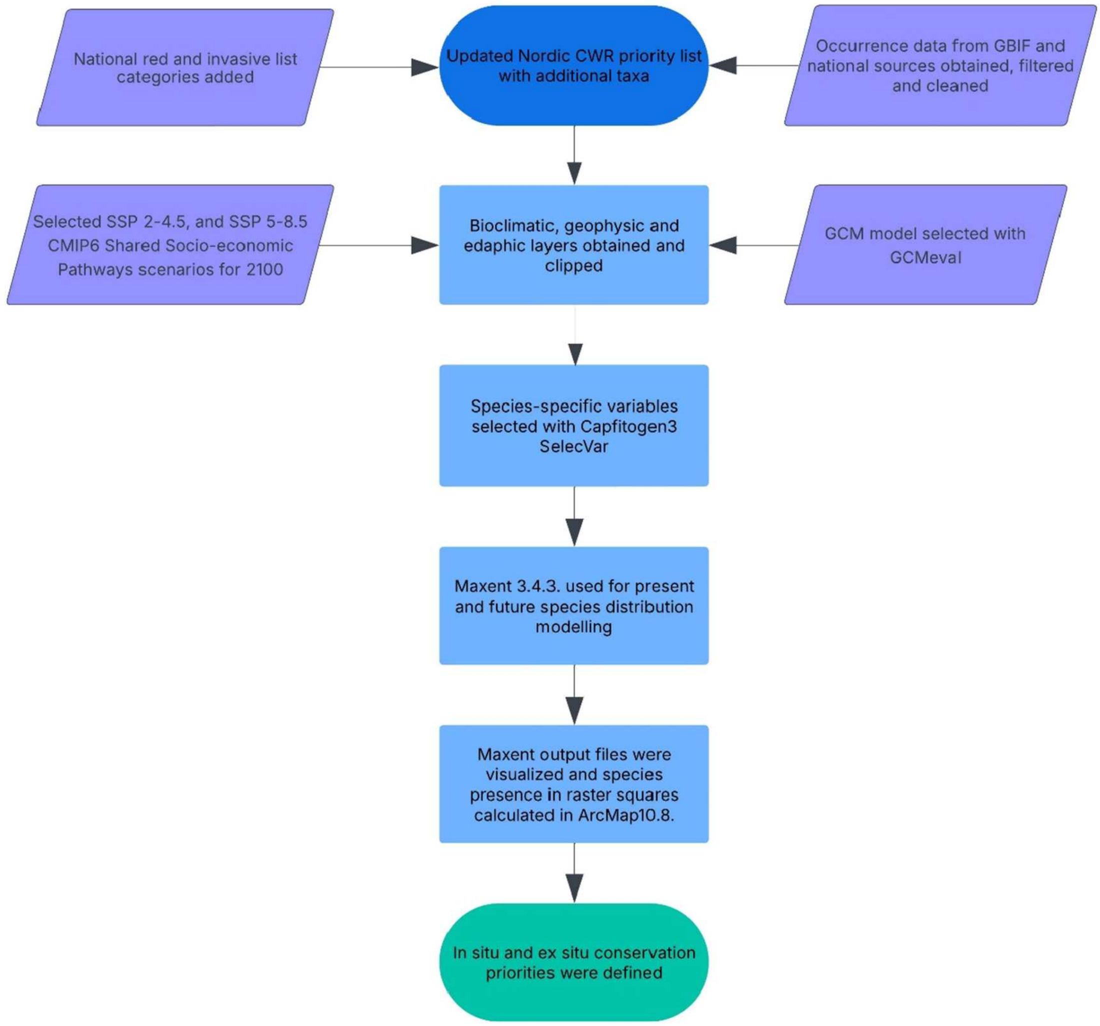

Figure 1. Overview of the methods used.

The species classified as Near Threatened showed a small, expected increase in range under both climate models (figure 4).

Discussion

Changes in species range under climate change

Two different future climate scenarios were investigated in this study: the modest scenario illustrates the effects if we globally manage to take action and cut greenhouse gas emissions (SSP 2–4.5), and a 'worst-case' scenario, where business continues as usual (SSP 5–8.5) (Riahi *et al* 2017, IPCC 2021a). The results varied greatly among the investigated species, with both large increases and decreases observed. However, the results of the two models are often similar for individual species (see table 3, figures 2 and 3), with overall average changes in distribution area of −5,8% and −4,5% respectively, suggesting that even modest climate change will have negative effects on many species. Other studies also show an overall reduction in range size for CWR under different climate change scenarios (Jarvis *et al* 2008, van Treuren *et al* 2020, Rahman *et al* 2023), although there is considerable variation among different models and species.

Overall, there was an excess of taxa with large range reductions compared to increases (Supplementary Information 1, figure S1). The future models suggest extreme reductions of suitable habitats for several species (figure 2), with only small areas of high likelihood of occurrence remaining in 2100 (Supplementary Information 1, table S4). Among the thirteen species that are predicted to have more than 90% range decrease under both future models, there are four *Elymus* species: *Elymus caninus* (L.) L., *Elymus fibrosus* (Schrenk) Tzvelev, *Elymus kronokensis* (Kom.) Tzvelev and *Elymus mutabilis* (Drobow) Tzvelev. The last three have northern/mountainous distribution and are therefore expected to be adversely affected by climate change. *Elymus*

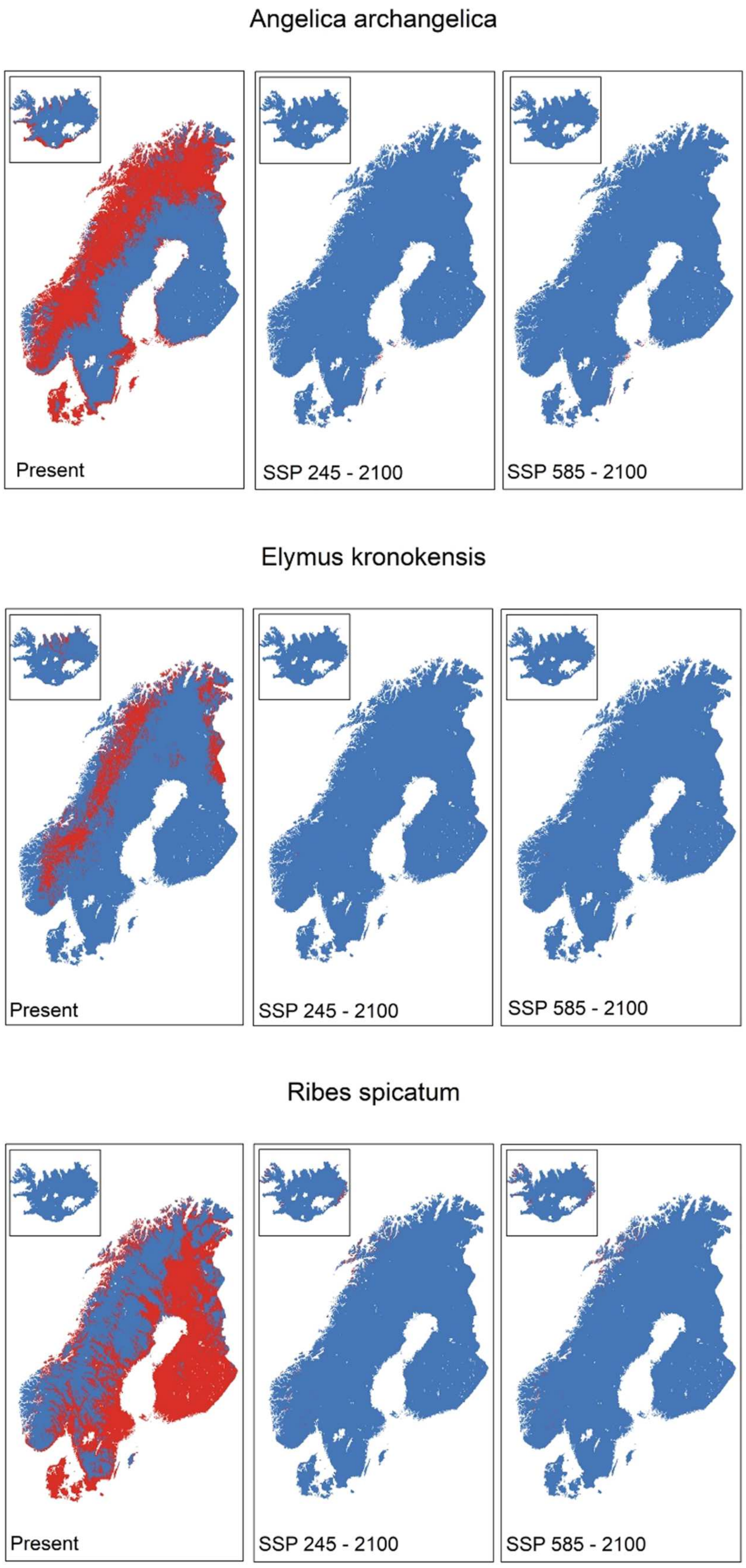

Figure 2. Examples of species showing the most adverse effects under investigated scenarios. Suitable habitats/high probability of species in the area are shown in red, and the areas not suitable in blue. The present potential distribution is shown on the left in each species, the future suitable habitats with scenario SSP 2–4.5 in the middle, and the future suitable habitats with scenario SSP 5–8.5 on the right.

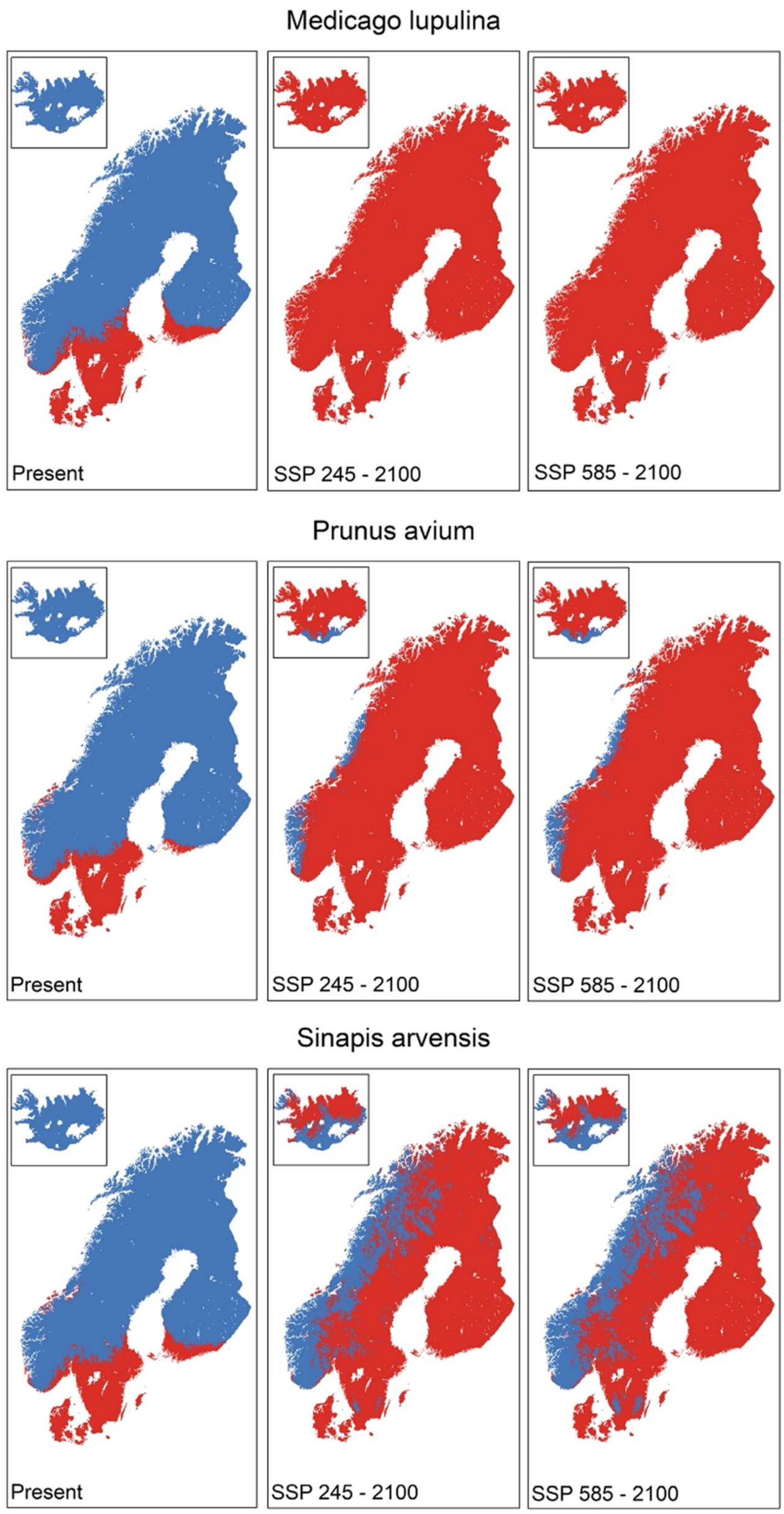

Figure 3. Examples of species with most increase in suitable habitats under the investigated climate scenarios. Suitable habitat/high probability of species in the area is shown in red, and areas not suitable in blue. The present potential distribution is shown on the left on each species, the future suitable habitats with scenario SSP 2–4.5 in the middle and the future suitable habitats with scenario SSP 5–8.5 on the right.

caninus, on the other hand, occurs across a large part of the region but is expected to lose most of its distribution area according to both future models. Overall, the group with over a 90% decrease in range includes a mix of species with northern and southern distributions.

Earlier studies suggest that threatened CWR, especially critically endangered ones, will be more severely affected by climate change than others (van Treuren *et al* 2020). In this study, there were rather few species

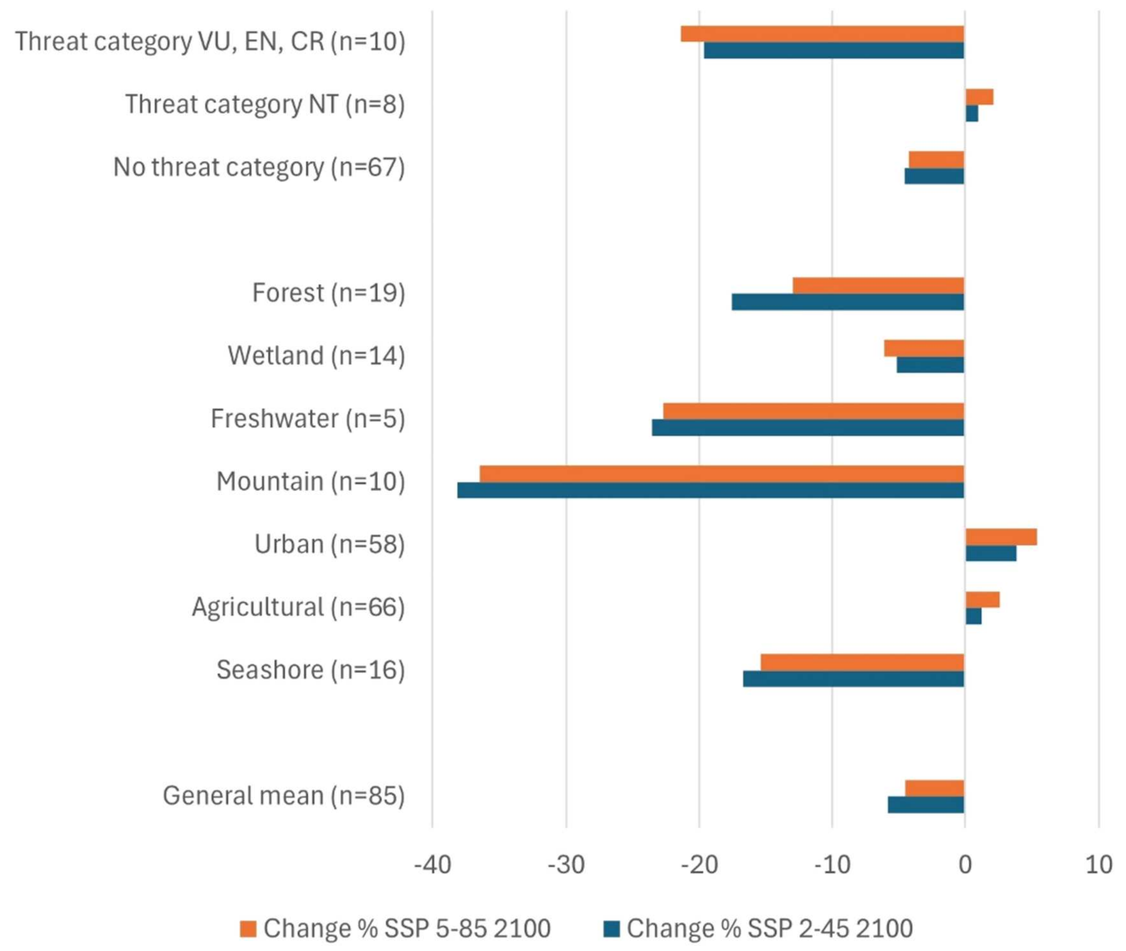

Figure 4. Average changes in the range distribution of CWR species grouped by threat category and landscape type for the two future climate scenarios SSP 2–4.5 (blue) and SSP 5–8.5 (orange) for the year 2100.

classified as threatened, and only one species, *Phleum arenarium* L., was regarded as critically endangered in one country (table 2). However, the observed pattern was similar, with the species classified as vulnerable, endangered, or critically endangered having on average, a larger expected range reduction than the non-threatened species (figure 4, Supplementary table S2). This pattern is not surprising. Climate change is expected to have a substantial impact on threatened plants (Wrobleski *et al* 2023) and species affected by climate change are likely to be disproportionally affected by non-climate threats (Fortini and Dye 2017). Thus, climate change adds to their already problematic situation.

Among the landscape types, species growing in mountainous areas were predicted to have the highest range reduction, whereas species growing in urban and agricultural land were predicted to have the largest range expansion (figure 3, Supplementary table S2). This was in accordance with previous studies on mountainous species vulnerability to climate change, which found a general trend of species range reduction across mountainous regions in Europe under future climate conditions (Engler *et al* 2011). In general, species adapted to high-altitude conditions face environmental changes, such as increased temperature, altered precipitation and snow cover, increased competition from species migrating upward, and altered access to pollinators (Inouye 2020). They may not be adapted to tolerating new stresses and have limited possibilities to migrate as suitable habitats disappear with a warmer climate, and thus their range will be reduced.

In general, movement to northern latitudes and fragmentation of distribution areas leading to the isolation of smaller populations are observed with many species in this study. Some taxa show a reduction in their entire range, others may lose only the southern parts of their ranges or populations from lower altitudes, such as *Phleum alpinum* L. and *Poa alpina* L., indicating a potential loss of genetic diversity from those populations. Other species, such as *Fragaria viridis* (Supplementary Information 2 and 3), show a substantial range shift, where most of the current distribution area is predicted to be lost by 2100, while a large area outside its current range is predicted to become suitable. Even in this case, where the suitable habitat is expected to increase under climate change (table 3), diversity could be lost when the populations in current distribution areas disappear or migrate, and new areas are colonised.

The modelling results show a general pattern of species predicted to expand their present distribution moving northwards or to higher altitudes (Supplementary Information 2 and 3). This change of southern species movement northwards has been already observed in the Arctic by the Circumpolar Biodiversity Monitoring Program (CAFF 2021). The movement of species to new areas can affect dynamics in plant communities, cause changes in species competitiveness, and potentially cause invasiveness (Rew *et al* 2020, Zhang *et al* 2023).

Ex situ and *in situ* conservation

The predictions presented in this paper can serve as guidelines for conservation, by directing the priorities to species at highest risk. The two complimentary approaches for long-term conservation, *in situ* and *ex situ,* need to be considered with CWR. *In situ* conservation takes place in natural habitats enabling the populations to evolve and adapt to new conditions and at the same time enabling the conservation of many species and populations at the same site. For these reasons, *in situ* conservation of CWR is considered the primary method for most populations, with *ex situ* serving as a backup (Maxted *et al* 1997, Heywood and Dulloo 2005). *Ex situ* conservation, where a seed sample from the population is stored in gene banks, provides a sample representing the population's diversity at the time of collection. The main aims of *ex situ* collections are to make CWR available for utilization in research, plant breeding, reintroductions or assisted migration to new areas. Species with a predicted range reduction (table 3) could thus be targeted for *ex situ* conservation to save genetic diversity before it is lost.

If conservation efforts fail, climate change in combination with other human induced pressures will result in loss of genetic diversity, populations and in some cases whole species. For CWR this will have ecological and evolutionary consequences, as well as an impact on agriculture and food security. CWR contain a wide range of diversity of relevance for plant improvement, for example traits that can contribute to adapting agriculture to climate change (e.g. Dempewolf *et al* 2014, Brozynska *et al* 2016). Lack of availability and access to this diversity can therefore impede progress towards assuring future food security. This problem has already been noted to restrict plant breeding (Maxted and Brehm 2023 and references therein) and loss of natural diversity will continue to have an impact. In natural populations, loss of genetic diversity will limit their ability to adapt to changes in the environment and have a negative impact on their evolutionary potential. As climate change is currently occurring at a fast rate, and many species are already affected by habitat reduction and fragmentation, many populations might not have the capacity to adapt to the changes and extinction risk is expected to increase (Jump and Peñuelas 2005 , Leimu *et al* 2010)

Model selection and limitations

The model MRI-ESM2–0 was selected for future projections based on its performance in Northern Europe, and due to its realistic representation of precipitation, temperature seasonality, and inclusion of interactive atmospheric chemistry, which isimportant for modeling vegetation responses. However, reliance on a single GCM introduces uncertainty, as different GCMs can vary substantially in regional climate projections, especially precipitation and extreme events. Species range shifts could be more or less pronounced, and areas of range expansion may vary depending on the climate model used. This model-dependent variability means that projections should be interpreted as one plausible scenario rather than a definitive forecast. While MRI-ESM2-0 performs well in the Nordic context, future studies could incorporate multiple GCMs or ensemble approaches, such as Aguirre-Gutiérrez *et al* (2017).

Plants differ widely in their strategies for colonizing new suitable habitats over large distances when conditions change. This affects their migration ability when the climate changes and conditions become unfavourable. An unlimited dispersal scenario, as used in this study, might lead to overestimation of the future range (Guisan and Thuiller 2005, Seaborn *et al* 2020). However, although dispersal estimates might in some ways provide more realistic projections of future species distributions, they were not included in this study because of the lack of species-specific dispersal data, including dispersal rate, for the target species. In addition to climate, non-climatic factors such as pollinator availability, pest and pathogen pressure, and land-use change can interact with shifting environmental conditions to influence CWR viability and distribution, posing further challenges for conservation. In Northern Europe, climate-driven phenological shifts—such as earlier flowering—can lead to mismatches with pollinators, reducing reproductive success in some species (Tiusanen *et al* 2020, Olsen *et al* 2022). Future modeling efforts could improve projections by integrating biotic interactions and habitat disturbance layers, where available, to capture the complexity of CWR responses to climate change.

The analysis does not consider natural migration barriers, such as water bodies or mountains, occurring within the Nordic region Therefore, even though the models presented in this paper indicate a suitable future habitat outside the current range, species might not be able to disperse to new suitable areas naturally. Therefore, the prognosis for some species, especially those with limited dispersal potential, might be worse than

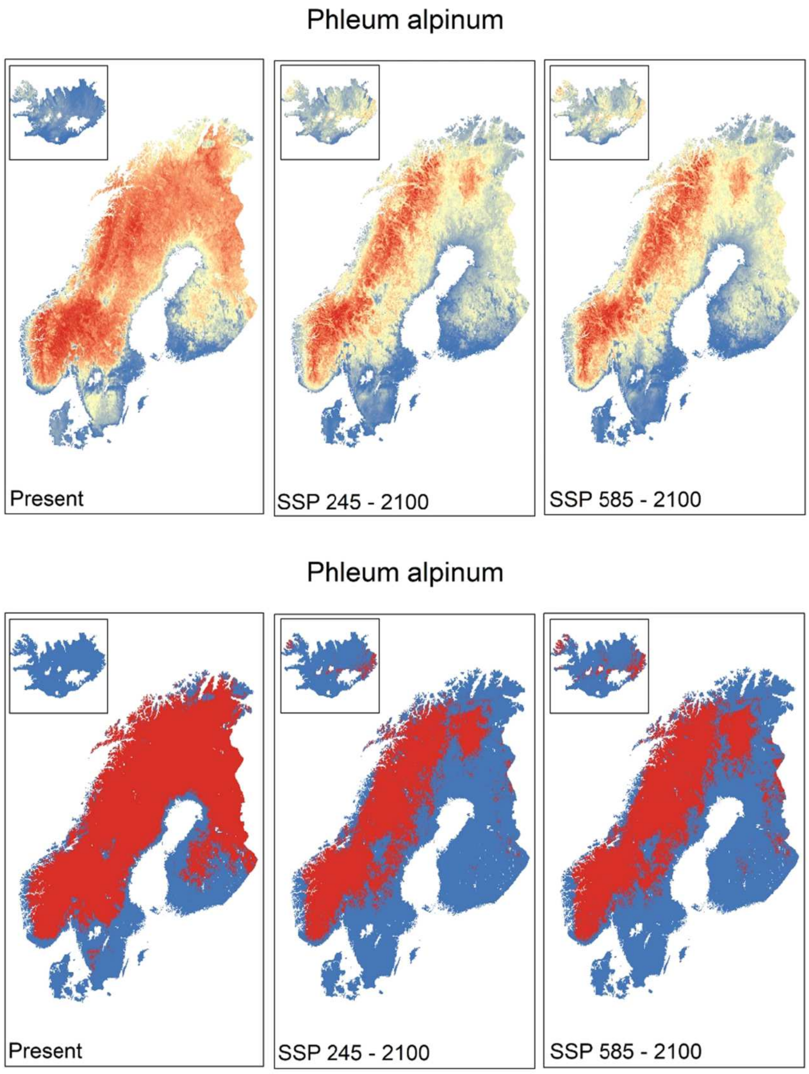

Figure 5. Continuous map (upper) and binary map (lower) showing the predicted present distribution (left), under SSP 2–4.5 (centre), and SSP 5–8.5 (right) for *Phleum alpinum* L. Suitable habitat/high probability of species in the area are shown with red and the areas not suitable/low probability as blue. For continuous maps of other species, see supplementary information 3.

indicated by the models presented here, and the results can in this way be regarded as a best-case-scenario. The results of the analysis can however indicate new suitable target areas for assisted migration.

In some cases, there are differences between the actual and modelled current distribution. Some species are predicted to occur in Iceland but are not present in the Icelandic flora (Wasowicz 2020), such as *Rubus armeniacus* Focke and *Rubus chamaemorus* L., or are classified as casual aliens and have a very limited distribution (Wasowicz 2020) such as *Ribes nigrum* L., *Rubus idaeus* L., and *Rubus spectabilis* Pursh. Other factors not included in the model might prevent them from thriving in Iceland such as lack of suitable pollinators, disease pressure, or dispersal potential. A few species appear to have a smaller distribution in present distribution maps than their actual range, such as *Phleum alpinum* (figure 5) and *Carum carvi* (Supplementary Information 2), which are widespread in Iceland but show a low probability of occurrence in the model. The present potential distribution maps are predictions based on the model parameters and input data. Compared with other Nordic countries, Iceland has a low number of recent observations with high coordinate accuracy ($<$3000 m). This affects the ability of the model to predict Icelandic distributions. The continuous maps (figure 5 and Supplementary Information 3) show the lower probability areas, which may better reflect the real distribution in Iceland. However, more high-quality observations are required to reliably model the distributions in Iceland.

A previous study (Fitzgerald *et al* 2019) shows some bias in the Nordic CWR observation data. Future analyses would therefore benefit from improvements of Nordic observation data, this could for example be achieved by targeted field surveys, herbarium digitization, and increased citizen science participation to improve data coverage and coordinate accuracy in underrepresented areas. To deal with other limitations of the model, future studies could consider ensemble forecasting approaches to reduce uncertainties, such as in Kheir *et al* (2024).

Conclusion

For all prioritized native or naturalised Nordic CWR (Fitzgerald *et al* 2023), we recommend *in situ* conservation with active management of key populations. Based on the analysis, the impact of climate change will vary among species, and some appear more vulnerable than others. We recommend urgent *ex situ* collecting to safeguard the diversity within wild populations of those species expected to be severely impacted by climate change. For others, *in situ* conservation with active management and monitoring may be sufficient, but would ideally include an *ex situ* component.

Based on the expected severe reduction in future distribution, *ex situ* collecting missions of some taxa with northern or mountainous distribution is recommended, including *Angelica archangelica* L., *Elymus fibrosus* (Schrenk) Tzvelev, *Elymus kronokensis* (Kom.) Tzvelev and *Elymus mutabilis* (Drobow) Tzvelev. Conservation efforts of the northern/mountainous/Arctic taxa should be prioritized as the changes occur faster in these areas. Other taxa with limited distribution or those which show drastic reduction or shifts of suitable habitats, should also be included in *ex situ* collecting programs, such as *Beta vulgaris* subsp. *maritima* (L.) Arcang., *Carum carvi* L., *Dactylis glomerata* L., *Elymus caninus* (L.) L., *Festuca brevipila* Tracey, *Fragaria viridis* Weston, *Phleum phleoides* (L.) H. Karst., *Poa supina* Schrad., *Ribes spicatum* E. Robson, *Trifolium alpestre* L. and *Trifolium montanum* L. *Ex situ* approaches can never replace habitat and *in situ* conservation as a long-term solutions for conservation, however it provides a backup if natural populations go extinct and offer the possibility for reintroduction or assisted migration of the population as long as suitable habitats are still available.

The taxa considered invasive in the Nordic countries are not recommended for *in situ* conservation, but could be included in *ex situ* collections as their wild populations may include traits of interest for plant breeding. Including CWR taxa in *in situ* monitoring programs is vital for catching early signs of diversity loss, population decline or signs of invasiveness, thereby enabling necessary management actions. As the impacts of climate change on ecosystems and vegetation are complex and have potentially unforeseen implications (Grimm *et al* 2013, Parmesan and Hanley 2015), monitoring CWR populations at regular intervals will provide necessary data to detect changes over time and guide conservation management decisions (Iriondo *et al* 2008, 2021).

Protected areas can serve as climate refugia and enable species to spread to new regions (Thomas *et al* 2012, Haight and Hammill 2020). Therefore, we recommend using the results of the current study to identify protected areas that can serve as climate refugia for species with substantial reduction or shift in distribution ranges. Overall, a comprehensive Nordic CWR *in situ* site network (Fitzgerald *et al* 2019), integrated with *ex situ* conservation, would aid priority species' survival in the future.

Recommendations:

- Establishing active *in situ* management and monitoring of key populations of the priority Nordic CWR taxa.
- Conducting analysis to identify protected areas that can serve as climate refugia for CWR expected to be severely affected by climate change.
- Where natural migration is limited by habitat fragmentation, increasing the connectivity between natural habitats (and protected areas) will facilitate natural migration of species.
- *Ex situ* conservation of species with predicted range reductions to conserve genetic diversity before it is lost and for utilization purposes (e.g. reintroductions, assisted migration, plant breeding, research).
- *Ex situ* conservation of species with predicted changes in distribution range to preserve genetic diversity from their whole current distribution as the dispersal process and new selection pressures may narrow their future genetic diversity
- Develop species-specific Nordic conservation recommendations for the CWR predicted to be severely affected by climate change
- Developing monitoring protocols for the species predicted to expand drastically (potential invasiveness).
- Collecting high-quality observations, particularly in underrepresented areas.

Include CWR and climate predictions as important elements of national biodiversity conservation plans, integrating the findings and recommendations of this paper as well as other scientific studies on this topic.In the recommendations above we suggest specific *in situ* and *ex situ* conservation actions for key populations. These populations should be prioritized based on available knowledge in each individual species, such as distribution, climate change modelling, and genetic diversity, as well as to optimise conservation efforts across species (e.g. via complementarity analysis approaches, Fitzgerald *et al* 2019)

Acknowledgments

The research presented here is part of the project 'Conservation and sustainable use of genetic resources in the Nordic countries', which is a collaboration among all Nordic countries and funded by the Nordic Council of Ministers as part of the Nature-based Solutions programme.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Data accessibility statement

The data supporting the findings of this study are available within the paper and its Supplementary Information.

References

Aguirre-Gutiérrez J, van Treuren R, Hoekstra R and van Hintum T J L 2017 Crop wild relatives range shifts and conservation in Europe under climate change *Diversity and Distributions* **23** 767–81
Artsdatabanken 2020 *Fremmede arter i Norge—med Økologisk Risiko* https://artsdatabanken.no/fremmedartslista2018 Artsdatabanken (In Norwegian)
Artsdatabanken 2021 *Norwegian Red List for Species 2021* https://artsdatabanken.no/lister/rodlisteforarter/2021 (In Norwegian) Norwegian Biodiversity Information Centre
Björnsson H, Sigurðsson B D, Davíðsdóttir B, Ólafsson J, Ástþórssson Ó S, Ólafsdóttir S, Baldursson T and Jónsson T 2018 *Loftslagsbreytingar og Áhrif Þeirra á Íslandi—Skýrsla Vísindanefndar um Loftslagsbreytingar 2018* (Veðurstofa Íslands - the Icelandic Meteorological Office)
Brozynska M, Furtado A and Henry R J 2016 Genomics of crop wild relatives: expanding the gene pool for crop improvement *Plant Biotechnol. J.* **14** 1070–85
Climaguide 2017 Projected Climate Change in Finland, Finnish Meteorological Institute https://climateguide.fi/articles/projected-climate-change-in-finland#ref_RUO13a
CAFF 2021 *State of the Arctic Terrestrial Biodiversity: Key Findings and Advice for Monitoring* Conservation of Arctic Flora and Fauna International Secretariat, Akureyri, Iceland Available at: www.arcticbiodiversity.is/terrestrial
Dempewolf H, Eastwood R J, Guarino L, Khoury C K, Müller J V and Toll J 2014 Adapting agriculture to climate change: a global initiative to collect, conserve, and use crop wild relatives *Agroecology and Sustainable Food Systems* **38** 369–77
Den Danske Rødliste 2019 Den Danske Rødliste https://ecos.au.dk/forskningraadgivning/temasider/redlistframe/ (In Danish)
EEA 2019 Climate change adaptation in the agriculture sector in Europe 1994-2019 *European Environment Agency* (Publications Office of the European Union) https://eea.europa.eu/en/analysis/publications
Eklund A, Mårtensson J A, Bergström S, Björck E, Dahné J, Lindström L, Nordborg D and Olsson J 2015 *Sveriges Framtida Klimat. Klimatologi* Sveriges Meteorologiska och Hydrologiska Institut, Norrköping (In Swedish) 14
Elith J *et al* 2006 Novel methods improve prediction of species' distributions from occurrence data *Ecography* **29** 129–51
England M R, Eisenman I, Lutsko N J and Wagner T J 2021 The recent emergence of Arctic amplification *Geophys. Res. Lett.* **48** e2021GL094086
Engler R *et al* 2011 21st century climate change threatens mountain flora unequally across Europe *Global Change Biol.* **17** 2330–41
ESRI 2021 *ArcGIS Desktop: Release 10.8* (Environmental Systems Research Institute)
FAO 2022 *FAO Strategy on Climate Change 2022–2031* (Food and Agriculture Organization of the United Nations) https://fao.org/3/cc2274en/cc2274en.pdf
FAO/IIASA/ISRIC/ISSCAS/JRC 2012 Harmonized World Soil Database (version 1.2). FAO Rome, Italy and IIASA, Laxenburg, Austria https://fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/
Fick S E and Hijmans R J 2017 WorldClim 2: new 1km spatial resolution climate surfaces for global land areas *Int. J. Climatol.* **37** 4302–15
Fitzgerald H, Palmé A, Asdal Å, Endresen D, Kiviharju E, Lund B, Rasmussen M, Thorbjörnsson H and Weibull J 2019 A regional approach to Nordic crop wild relative *in situ* conservation planning *Plant Genetic Resources: Characterization and Utilization* **17** 196–207
Fitzgerald H *et al* 2023 *Nordic Crop Wild Relative Priority List. Version 1.15* Checklist dataset Nordic Genetic Resource Center, NordGen
Fitzgerald H and Kiviharju E 2018 F*innish Crop Wild Relative priority list Figshare. Dataset*
Fortini L B and Dye K 2017 At a global scale, do climate change threatened species also face a greater number of non-climatic threats? *Global Ecology and Conservation* **11** 207–12
GBIF 2024 Filtered export of GBIF occurrence data *Derived Dataset GBIF* org (14 June 2024) (https://doi.org/10.15468/dd.z92cgw)

Göransson M and Thorbjörnsson H 2022 *Crop Wild Relatives - Inventories in Vatnajökull National Park 2021* (Figshare) (https://doi.org/10.6084/m9.figshare.21090133.v1)
Grimm N B *et al* 2013 The impacts of climate change on ecosystem structure and function *Frontiers in Ecology and the Environment* **11** 474–82
Guillera-Arroita G, Lahoz-Monfort J J, Elith J, Gordon A, Kujala H, Lentini P E, McCarthy M A, Tingley R and Wintle B A 2015 Is my species distribution model fit for purpose? Matching data and models to applications *Global Ecol. Biogeogr.* **24** 276–92
Guisan A and Thuiller W 2005 Predicting species distribution: offering more than simple habitat models *Ecology Letters* **8** 993–1009
Gustavsson B 1997 Breeding strategies in lingonberry culture (*Vaccinium vitis-idaea*) *Acta Hortic.* **446** 129–38
Haight J and Hammill E 2020 Protected areas as potential refugia for biodiversity under climatic change *Biological Conservation* **241** 108258
Harris I, Osborn T J, Jones P and Lister D 2020 Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset *Scientific Data* **7** 109
Helgadóttir A, Marum P, Dalmannsdóttir S, Daugstad K, Kristjánsdóttir T A and Lunnan T 2008 Combining winter hardiness and forage yield in white clover (Trifolium repens) cultivated in northern environments *Annals of Botany* **102** 825–34
Hernandez P A, Graham C H, Master L L and Albert D L 2006 The effect of sample size and species characteristics on performance of different species distribution modeling methods *Ecography* **29** 773–85
Heywood V H and Dulloo M E 2005 *In Situ* conservation of wild plant species—a critical global review of good practices *IPGRI Technical Bulletin No. 11* (IPGRI) https://hdl.handle.net/10568/104559
Hiirsalmi H, Saila J and Jaakko S 1987 'Aura' and 'Astra', Finnish arctic bramble hybrid varieties *Annales agriculturae Fenniae, Seria Horticultura (Journal of the Agricultural Research Centre)* **26** 261–9 https://jukuri.luke.fi/handle/10024/484754
Hijmans R J and Graham C 2006 The ability of climate envelope models to predict the effect of climate change on species distributions *Global Change Biol.* **12** 2272–81
Hyvärinen E, Juslén A, Kemppainen E, Uddström A and Liukko U-M 2019 The 2019 red list of finnish species *Ministry of the Environment* (Finland & Finnish Environment Institute) https://helda.helsinki.fi/items/2ec69a48-d943-488c-927f-19bbf9f92cb5
Icelandic Met Office 2023 *Climate report* The Icelandic Meteorological Office https://en.vedur.is/climatology/iceland/climate-report
Inouye D W 2020 Effects of climate change on alpine plants and their pollinators *Ann. N.Y. Acad. Sci.* **1469** 26–37
Invasive Plant Species 2022 Invasive plant species in Iceland *Icelandic Institute of Natural History* https://ni.is/en/flora-funga/invasive-plant-species
IPBES 2019 *Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* ed E S Brondizio *et al* (IPBES Secretariat) (https://doi.org/10.5281/zenodo.3831673)
IPCC 2021b *AR6 WGI Interactive Atlas. Intergovernmental Panel on Climate Change IPCC* https://interactive-atlas.ipcc.ch
IPCC 2023 *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change IPPC* ed H J Lee and R Romero pp 35–115
IPCC 2021a *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed V Masson-Delmotte *et al* (Cambridge University Press) pp 3–32 10.1017/9781009157896.001
Iriondo J M, Ford-Lloyd B V, de Hond L, Kell S P, Lefèvre F, Korpelainen H and Lane A 2008 Plant population monitoring methodologies for the *in situ* genetic conservation of CWR ed J M Iriondo *et al Conserving Plant Genetic Diversity in Protected Areas* (CABI International) pp 88–123
Iriondo J M, Magos Brehm J, Dulloo M E and Maxted N 2021 *Crop Wild Relative Population Management Guidelines* Farmer's Pride: Networking, partnerships and tools to enhance *in situ* conservation of European plant genetic resources http://farmerspride.eu/
Jarvis A, Lane A and Hijmans R J 2008 The effect of climate change on crop wild relatives *Agriculture, Ecosystems and Environment* **126** 13–23
Jump A S and Peñuelas J 2005 Running to stand still: adaptation and the response of plants to rapid climate change *Ecology Letters* **8** 1010–20
Kell S P, Ford-Lloyd B V, Brehm J M, Iriondo J M and Maxted N 2017 Broadening the base, narrowing the task: prioritizing crop wild relative taxa for conservation action *Crop Sci.* **57** 1042–58
Kheir A M S, Govind A, Nangia V, Devkota M, Elnashar A, El Din Omar M and Feike T 2024 Developing automated machine learning approach for fast and robust crop yield prediction using a fusion of remote sensing, soil, and weather dataset *Environ. Res. Commun.* **6** 041005
Kramer R J, He H, Soden B J, Oreopoulos L, Myhre G, Forster P M and Smith C J 2021 Observational evidence of increasing global radiative forcing *Geophys. Res. Lett.* **48** e2020GL091585
Lebeda A, Kristkova E, Kitner M, Mieslerova B, Jemelkova M and Pink D A C 2014 Wild *Lactuca* species, their genetic diversity, resistance to diseases and pests, and exploitation in lettuce breeding *European Journal of Plant Pathology* **138** 597–640
Leimu R, Vergeer P, Angeloni F and Ouborg N J 2010 Habitat fragmentation, climate change, and inbreeding in plants *Ann. N.Y. Acad. Sci.* **1195** 84–98
Liu C, Berry P M, Dawson T P and Pearson R G 2005 Selecting thresholds of occurrence in the prediction of species distributions *Ecography* **28** 385–93
Liu C, White M and Newell G 2013 Selecting thresholds for the prediction of species occurrence with presence-only data *J. Biogeography* **40** 778–89
Magos Brehm J, Gaisberger H, Kell S, Parra-Quijano M, Thormann I, Dulloo M E and Maxted N 2022 Planning complementary conservation of crop wild relative diversity in southern Africa *Diversity and Distributions* **28** 1358–72
Magos Brehm J, Kell S, Thormann I, Gaisberge H, Dulloo M E and Maxted N 2017 Interactive Toolkit for Crop Wild Relative Conservation Planning version 1.0. University of Birmingham, UK and Bioversity International https://cropwildrelatives.org/conservation-toolkit/
Maxted N 2003 Conserving the genetic resources of crop wild relatives in European protected areas *Biological Conservation* **113** 411–7
Maxted N and Brehm J M 2023 Maximizing the crop wild relative resources available to plant breeders for crop improvement *Frontiers in Sustainable Food Systems* **7**
Maxted N, Ford-Lloyd B V and Hawkes J G 1997 *Plant Genetic Conservation: The In Situ Approach* (Chapman & Hall)
Maxted N, Magos Brehm J and Kell S 2013 *Resource Book for Preparation of National Conservation Plans for Crop Wild Relatives and Landraces.* p 453 https://fao.org/fileadmin/templates/agphome/documents/PGR/PubPGR/ResourceBook/TEXT_ALL_2511.pdf
Mbow C C *et al* 2019 Food security *In: Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems* ed P R Shukla *et al* (The United Nations' Intergovernmental Panel on Climate Change's (IPCC)) https://ipcc.ch/site/assets/uploads/sites/4/2020/06/IPCCJ7230-Land_SM5_200226.pdf

Olsen S L, Evju M, Åström J, Løkken J O, Dahle S, Andresen J L and Eide N E 2022 Climate influence on plant–pollinator interactions in *Vaccinium myrtillus* in central Norway *Ecology and Evolution* **12** e8910

Palmé A, Fitzgerald H, Weibull J and Bjureke K 2019 *Nordic Crop Wild Relative Conservation: A REPORT from Two Collaborative Projects 2015–2019* (Nordisk Ministerråd (TemaNord)) p 75

Palmé A, Lund B, Madsen B, Kiviharju E and Fitzgerald H 2025 *Nordic Crop Wild Relative (CWR) conservation for a more resilient agriculture* A Report from a Nordic Project 2021—2024 Nordic Council of Ministers TemaNord 2025:515 (https://doi.org/10.6027/temanord2025-515)

Parding K M *et al* 2020 GCMeval - An interactive tool for evaluation and selection of climate model ensembles *Climate Services* **18** 100167

Parmesan C and Hanley M E 2015 Plants and climate change: complexities and surprises *Annals of Botany* **116** 849–64

Parra Quijano M 2022 *CAPFITOGEN3: a Toolbox for the Conservation and Promotion of the Use of Agricultural Biodiversity* (Universidad Nacional de Colombia. Facultad de Ciencias Agrarias) https://capfitogen.net/en/

Parra Quijano M, Iriondo J M, Torres M E, López F, Phillips J and Kell S 2021 *CAPFITOGEN3 Manual: a Toolbox for the Conservation and Promotion of the Use of Agricultural Biodiversity* (Universidad Nacional de Colombia. Facultad de Ciencias Agrarias) https://capfitogen.net/en/

Phillips J, Asdal Å, Magos Brehm J, Rasmussen M and Maxted N 2016 *In situ* and *ex situ* diversity analysis of priority crop wild relatives in Norway *Diversity and Distributions* **22** 1112–26

Phillips J, Magos Brehm J, van Oort B, Asdal Å, Rasmussen M and Maxted N 2017 Climate change and national crop wild relative conservation planning *Ambio* **46** 630–43

Phillips S J, Dudik M and Schapire R E 2023 version 3.4.3. Maximum Entropy Modeling of Species Geographic Distributions https://biodiversityinformatics.amnh.org/open_source/maxent

Pimentel D, Wilson C, McCullum C, Huang R, Dwen P, Flack J, Tran Q, Saltman T and Cliff B 1997 Economic and environmental benefits of biodiversity *BioScience* **47** 747–57

PwC Valuations 2013 *Crop Wild Relatives. A Valuable Resource for Crop Development.* Pricewaterhouse Coopers https://pwc.co.uk/services/sustainability-climate-change/

R Core Team 2021 R: A language and environment for statistical computing *R Foundation for Statistical Computing, Vienna, Austria* https://R-project.org/

Rahman W, Magos Brehm J and Maxted N 2023 The impact of climate change on the future distribution of priority crop wild relatives in Indonesia and implications for conservation planning *Journal for Nature Conservation* **73** 126368

Ramírez-Villegas J, Khoury K, Jarvis A, Debouck D G and Guarino L 2010 A gap analysis methodology for collecting crop gene pools: a case study with Phaseolus beans *PLoS One* **5** e13497

Rantanen M, Karpechko A Y, Lipponen A, Nordling K, Hyvärinen O, Ruosteenoja K, Vihma T and Laaksonen A 2022 The Arctic has warmed nearly four times faster than the globe since 1979 *Communications, Earth and Environment* **3** 168

Rapp K 1996 Selection response for dry matter yield in white clover (Trifolium repens L.) using different selection methods *Norwegian Journal of Agricultural Sciences* **10** 265–80

Rew L J *et al* 2020 Moving up and over: redistribution of plants in alpine, Arctic, and Antarctic ecosystems under global change *Arctic, Antarctic, and Alpine Research* **52** 651–65

Riahi K *et al* 2017 The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview *Global Environ. Change* **42** 153–68

Rognli O A *et al* 2018 Utilization of genebank accessions to improve northern adaptation of perennial ryegrass (Lolium perenne L.). *Breeding Grasses and Protein Crops in the Era of Genomics* ed G Brazauskas *et al* (Springer) (https://doi.org/10.1007/978-3-319-89578-9_1)

Ruosteenoja K and Jylhä K 2021 Projected climate change in Finland during the 21st century calculated from CMIP6 model simulations *Geophysica* **56** 39–69 https://geophysica.fi/article/id-56-3-ruosteenoja/

Scheldeman X and van Zonneveld M 2010 *Training Manual on Spatial Analysis of Plant Diversity and Distribution* (Bioversity International) https://bioversityinternational.org/fileadmin/user_upload/online_library/publications/pdfs/1431.pdf

Seaborn T J, Goldberg C S and Crespi E J 2020 Integration of dispersal data into distribution modeling: what have we done and what have we learned? *Frontiers of Biogeography* **12** e43130

Serreze M, Barrett A, Stroeve J, Kindig D and Holland M 2009 The emergence of surface-based Arctic amplification *Cryosphere* **3** 11–9

Serreze M C and Francis J A 2006 The Arctic amplification debate *Climate Change* **76** 241–64

Skipper L and Calabruig I 2020 National checklist of all species occurring in Denmark Version 9.3. *The Danish Environmental Protection Agency, Milj*ȷ*styrelsen* Checklist dataset (https://doi.org/10.15468/bpmaze) accessed via GBIF.org on 2024-11-11

SLU Artdatabanken 2020 Rödlistade arter i Sverige 2020 *SLU, Uppsala* https://slu.se/artdatabanken/rodlistade-arter/

SLU Artdatabanken 2024 Artfakta https://artfakta.se (In Swedish)

Strand M, Aronsson M and Svensson M 2018 Klassificering av främmande arters effekter på biologisk mångfald i Sverige—ArtDatabankens risklista *ArtDatabanken Report* **21** 1–42 ArtDatabanken SLU, Uppsala. (In Swedish)

Svenning M M, Røsnes K, Lund L and Junttila O 2001 Vegetative growth and freezing tolerance of white clover (Trifolium repens L.) Genotypes from Svalbard *Acta Agriculturae Scandinavica, section B — Soil & Plant Science* **51** 10–6

Sæther N, Holene A, Fjellstad K B, Rasmussen M and Wallin H G 2020 Nøkkeltall fra Norsk genressurssenter 2019. Status for bevaringsverdige husdyr, skogtrær og nytteplanter *NIBIO Rapprt* **6** 111–5 https://nibio.brage.unit.no/nibio-xmlui/bitstream/handle/11250/2660746/NIBIO_RAPPORT_2020_6_107.pdf (In Norwegian)

Thomas C D *et al* 2012 Protected areas facilitate species' range expansions *PNAS* **109** 14063–8

Thuiller T, Lavorel S, Araújo M B, Sykes M T and Prentice I C 2005 Climate change threats to plant diversity in Europe *PNAS* **102** 8245–50

Tiusanen M, Kankaanpää T, Schmidt N M and Roslin T 2020 Heated rivalries: Phenological variation modifies competition for pollinators among Arctic plants *Global Change Biol.* **26** 6313–25

USDA 2021 GRIN Taxonomy Crop Wild Relative Query, Agricultural Research Service, National Plant Germplasm SystemGermplasm Resources Information Network. National Germplasm Resources Laboratory https://tn-grin.nat.tn/gringlobal/taxon/taxonomysearchcwr

van Treuren R, Hoekstra R, Wehrens R and van Hintum T 2020 Effects of climate change on the distribution of crop wild relatives in the Netherlands in relation to conservation status and ecotope variation *Global Ecology and Conservation* **23**

Vieraslajit 2022 National List of Harmful Invasive Alien SpeciesFinnish Ministry of Agriculture and Forestry https://vieraslajit.fi/info/i-4182 (In Finnish)

Walsh M K, Backlund P, Buja L, DeGaetano A, Melnick R, Prokopy L, Takle E, Todey D and Ziska L 2020 *Climate Indicators for Agriculture* (USDA Technical Bulletin 1953) (https://doi.org/10.25675/10217/210930)

Wasowicz P 2020 Annotated checklist of vascular plants in Iceland *Fjölrit Náttúrufræðistofnunar nr.* **57** 5–192
Wasowicz P and Heiðmarsson S 2019 A vascular plant red list for Iceland *Acta Botanica Islandica* **16** 31–48
Weibull J *et al* 2025 *Nordic Wild Plant Genetic Resources: A Policy Brief* (https://doi.org/10.53780/OIKI7173)
Weibull J, Hagenblad J and Palmé A 2020 List of Swedish priority Crop Wild Relative taxa *Figshare* Version 28 September (https://doi.org/10.6084/m9.figshare.13135334.v1)
Weibull J and Phillips J 2020 Swedish Crop Wild Relatives: towards a national strategy for *in situ* conservation of CWR *Genetic Resources* **1** 17–23
Wrobleski A, Ernst S, Weber T and Delach A 2023 The impact of climate change on endangered plants and lichen *PLOS Climate* **2** e0000225
Yukimoto S *et al* 2019 The meteorological research institute Earth system model version 2.0, MRI-ESM2.0: description and basic evaluation of the physical component *Geoscientific Model Development* **12** 2287–328
Zelinka M D *et al* 2020 Causes of higher climate sensitivity in CMIP6 models *Geophys. Res. Lett.* **47** e2019GL085782
Zhang Z *et al* 2023 The poleward naturalization of intracontinental alien plants *Sci. Adv.* **9**