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Original Research Article

Effects of climate change on the distribution of crop wild relatives in the Netherlands in relation to conservation status and ecotope variation

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ABSTRACT

Crop wild relatives (CWR) are wild plant taxa that are genetically related to a cultivated species and are considered rich sources of useful traits for crop improvement. CWR are generally underrepresented in genebanks, while their survival in nature is not guaranteed. Inventories and risk analyses are needed to prioritize CWR for conservation in order to ensure that they remain available for utilization. Here the effects of climate change on the distribution of 214 CWR in the Netherlands are predicted by ecological niche modelling and related to data on IUCN conservation status and variation in key ecological habitat factors. It is shown that climate change is expected to affect red list species as well as species that currently are of least concern. Particularly worrisome is the finding that already critically endangered CWR show the largest expected loss of distribution area. In general, reduced distribution areas show a geographical shift to more northern locations in the Netherlands. No clear relationship is found between changes in distribution and the habitat characteristics vegetation structure, nutrient level, moisture condition, salinity and acidity. A moderate positive correlation is observed between ecological amplitude and tolerance level to climatic change. Study results are used in developing strategies to ensure that Dutch CWR remain available for utilization.

1. Introduction

The gene pools of many cultivated crops harbour wild species that to a greater or lesser extent can be crossed with the crop species (Harlan and de Wet, 1971). Such genetically related wild species are referred to as crop wild relatives (CWR). Because of the possibility to transfer desired traits through conventional crossing between species, CWR are recognized as important genetic resources for crop breeding. Especially for crops that are suffering from a lack of resistance against biotic and abiotic stresses, CWR have proved rich sources of useful traits, and hence they constitute major contributors to more sustainable agriculture and food security (Mammadov et al., 2018). It is expected that crop improvement will increasingly rely on the availability of CWR for genetic diversity (Hajjar and Hodgkin, 2007).

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Considering their crucial role in crop breeding, optimal accessibility of CWR for utilization is indispensable. Unfortunately, genebanks generally provide only limited service to this need as CWR are poorly represented in ex situ genetic resources collections (Castañeda-Álvarez et al., 2016; Khoury et al., 2010). Access to CWR occurring in situ is often even less straightforward. Moreover, many wild plant populations are threatened with extinction in their natural distribution area. The notion that access to CWR is limited, while their survival in nature is at risk, has resulted in initiatives to inventory the CWR for globally important crops (Vincent et al., 2013) and to develop concepts for their in situ conservation (Maxted et al., 2015). Initial steps in conservation efforts include the inventory of CWR within national boundaries and the prioritization of species for conservation (e.g. Fitzgerald et al., 2019; Rubio Teso et al., 2018).

Risk assessment regarding the survival of species in situ forms an essential element in prioritizing CWR for conservation (Maxted et al., 2015). Many national red lists have been developed for plant species according to the IUCN classification system. This classification system, which is based on abundance data of species within a region, is a useful information source to assess current threat levels for species (IUCN, 2012). In addition, climate change can be expected to have serious effects on future distribution areas of species (e.g. Bakkenes et al., 2002; Dempewolf et al., 2014), which should be evaluated when developing strategies for conservation. Scenarios for climate change are usually denoted by Representative Concentration Pathways (RCP) that vary in the assumed trajectories of greenhouse gas concentrations until the year 2100 (Stocker et al., 2013). The expected effects of these scenarios on species distribution can be evaluated through ecological niche modelling, using geographic occurrence data of specimens and data on current and predicted future climatic conditions at their origin locations (Aguirre-Gutiérrez et al., 2017; Jarvis et al., 2008).

The wild native flora in the Netherlands in 2012 comprised 1432 vascular plant species, of which 530 (37%) are included in the Dutch red list (Sparrius et al., 2014). Plant species in the Netherlands and Flanders (Belgium) have been classified according to the ecotope classification system, which is based on a combination of key ecological parameters, including vegetation structure, nutrient level, moisture condition, salinity and acidity of the habitat in which a species occurs (Runhaar et al., 2004). Large-scale data on the distribution of vascular plants in the Netherlands during the 20th century have been related to ecotope variation. Marked declines in nutrient-poor and in saline vegetation types were considered the most important changes revealed in that study (Tamis et al., 2005a). Climatic change is expected to cause more extreme meteorological conditions, such as increased variability in surface temperature and precipitation (IPCC, 2014). Species that are already threatened in their survival are expected to suffer most from such climatic effects as endangered species are often specialists and hence are considered less tolerant to strongly varying environmental conditions (Bartholomeus et al., 2011).

Previously, a CWR inventory in the Netherlands resulted in the identification of 214 wild relatives of economically important agricultural and horticultural crops, of which 53 are listed on the Dutch red list of plant species. So far, only for these 53 CWR the effects of climate change have been predicted through ecological niche modelling (Van Treuren et al., 2017). Here we describe the expected effects of climate change on the distribution in the Netherlands for the entire group of 214 CWR and we relate the niche modelling results to data on key ecological parameters. The aim of the study is to examine whether climate change effects can also be foreseen for species with current conservation status ‘least concern’ and whether species occurring in habitats with specific ecological conditions are more prone to the effects of climate change than others.

2. Material and methods

2.1. Study species

The species investigated in the present study resulted from an inventory of CWR occurring in the Netherlands, and comprised a total of 214 taxa of wild species related to economically important agricultural and horticultural crops (Van Treuren et al., 2017). The complete list of Dutch CWR is provided in Table A1, while it is also presented on the website CWRnl (www.cwrnl.nl). The studied species comprised 79 plant genera belonging to 20 plant families (Table 1). Poaceae (grasses, n = 53), Fabaceae (legumes, n = 49), Brassicaceae (crucifers, n = 27) and Amaranthaceae (amaranths, n = 20) formed the main part of the study materials.

Data on the conservation status of species in the Netherlands were as described in Van Treuren et al. (2017). These data (Table A1) originated from the ‘FLORON Verspreidingsatlas’ (www.verspreidingsatlas.nl/planten, accessed October 2014) and largely followed the classification system of the International Union for Conservation of Nature (IUCN, 2012).

2.2. Ecotope classification

Data on ecological species groups were collected from the website ‘Ecotopensysteem van Nederland en Vlaanderen’ (www.synbiosys.alterra.nl/ecotopen, accessed September 2018). The ecotope classification system classifies plant species on the basis of the characteristics of the habitat in which they occur (Table 2). The classification system comprises nearly 100 different ecotopes, which are defined by a combination of data on vegetation structure, nutrient level, moisture condition, salinity and acidity of the habitat (Runhaar et al., 2004). A single species may occur in up to ten different ecotopes, which are presented by the classification system in order of importance, corresponding with a fixed relative abundance. For example, the relative abundance of a species occurring in two ecotopes is presented consistently as 64:36, determined by the average ratio observed for species that occur in two ecotopes. Similarly, a ratio of 50:30:20 and 43:25:18:14 is used for species occurring in three and four ecotopes, respectively. In the ecotope classification system *Festuca lemanii* Bastard, *Salsola tragus* L.

Table 1
Taxonomic classification of the studied Dutch CWR. The number of species included within a genus is indicated between parentheses.

Family	Genus
Monocots	
Alliaceae	*Allium* (6)
Asparagaceae	*Asparagus* (2)
Poaceae	*Agrostis* (5), *Alopecurus* (5), *Arrhenatherum* (1), *Avena* (1), *Bromus* (4), *Cynodon* (1), *Dactylis* (1), *Digitaria* (2), *Echinochloa* (1), *Elymus* (1), *Elytrigia* (1), *Festuca* (7), *Hordeum* (3), *Leymus* (1), *Lolium* (2), *Phalaris* (1), *Phleum* (3), *Poa* (9), *Setaria* (3), *Trisetum* (1)
Dicots	
Amaranthaceae	*Atriplex* (6), *Beta* (1), *Chenopodium* (11), *Salsola* (2)
Apiaceae	*Anthriscus* (2), *Apium* (4), *Carum* (2), *Daucus* (1), *Pastinaca* (1), *Petroselinum* (1), *Pimpinella* (2)
Aquifoliaceae	*Ilex* (1)
Asteraceae	*Cichorium* (1), *Lactuca* (1), *Scorzonera* (1)
Betulaceae	*Corylus* (1)
Brassicaceae	*Arabidopsis* (1), *Armoracia* (1), *Barbarea* (3), *Brassica* (3), *Capsella* (1), *Coincya* (1), *Descurainia* (1), *Diplotaxis* (2), *Erucastrum* (1), *Isatis* (1), *Lepidium* (7), *Raphanus* (1), *Rorippa* (3), *Sinapis* (1)
Cannabaceae	*Humulus* (1)
Ericaceae	*Vaccinium* (5)
Fabaceae	*Astragalus* (1), *Cytisus* (1), *Lathyrus* (8), *Lotus* (3), *Lupinus* (1), *Medicago* (6), *Melilotus* (3), *Onobrychis* (1), *Ornithopus* (1), *Securigera* (1), *Trifolium* (13), *Vicia* (10)
Fagaceae	*Castanea* (1)
Grossulariaceae	*Ribes* (4)
Lamiaceae	*Mentha* (5)
Linaceae	*Linum* (1)
Papaveraceae	*Papaver* (3)
Rosaceae	*Comarum* (1), *Fragaria* (2), *Malus* (1), *Prunus* (3), *Pyrus* (1), *Rubus* (5)
Solanaceae	*Solanum* (2)
Valerianaceae	*Valerianella* (4)

and *Vicia sativa* subsp. *Segetalis* L. were unlisted, while *Chenopodium chenopodioides* (L.) Aellen was not classified because of its ephemeral nature.

2.3. Distribution modelling

Species distribution modelling (SDM), also known as ecological niche modelling (ENM), was used to predict the effects of climate change on the future distribution of CWR in the Netherlands. Modelling procedures essentially followed the methods described by Aguirre-Gutiérrez et al. (2017) and Van Treuren et al. (2017). Geographic occurrence data of the study species within the European region were downloaded from the Global Biodiversity Information Facility (GBIF) between February 2016 and January 2018 (Table A1). Records with missing or incorrect geographic information were removed, such as in the case of occurrence data pointing towards a botanical garden instead of a collecting site within the natural distribution area of a species. A spatial resolution, corresponding to a grid size of 2.5 min of a degree of longitude and latitude in the WorldClim dataset (Hijmans et al., 2005), was used to process the occurrence data. Multiple occurrence data per grid cell were reduced to a single observation, and only records were maintained that were separated by at least one grid cell in order to avoid potential effects of data clustering of species presence records (spatial autocorrelation). Following data cleaning and processing, on average 2492 records related to the European region were used in the modelling, ranging from 92 to 3096 per species. Data on a selection of seven bioclimatic variables related to temperature (mean temperature of the wettest quarter in °C, minimum temperature of the coldest month in °C, maximum temperature of the warmest month in °C and temperature seasonality expressed as $SD \times 100$) and precipitation (precipitation of the wettest quarter in mm, precipitation of the driest month in mm and precipitation seasonality expressed as coefficient of variation) from the WorldClim dataset (Hijmans et al., 2005) and data on soil pH and topsoil organic carbon from the harmonized world soil database (FAO et al., 2012) were used to represent current environmental conditions. The bioclimatic variables had been selected based on pairwise absolute Pearson's correlation coefficients smaller than 0.75 in order to avoid a high collinearity between available variables and potential model overfitting (Aguirre-Gutiérrez et al., 2017). Climatic conditions for the year 2070 according to an optimistic (RCP2.6) and pessimistic (RCP8.5) climate change scenario were obtained from the Coupled Model Intercomparison Project phase 5 (CMIP5) as published by the Intergovernmental Panel on Climate Change (Stocker et al., 2013). To account for variation in the prediction of climatic conditions, the average values from 14 different global climate models (BCC-CSM1-1, CCSM4, CNRM-CM5, GFDL-CM3, GISS-E2-R, HadGEM2-AO, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, MIROC-ESM, MIROC5, MPI-ESM-LR, MRI-CGCM3 and NorESM1-M) were used. Predictions for current and future distributions were based on the same set of bioclimatic variables, while the soil-related variables were assumed constant in time. Soil pH and topsoil organic carbon play a direct role in plant establishment and development (FAO et al., 2012) and were only included in the modeling to delimit potential species distribution under current as well as under future climatic conditions. To account for variation in model predictions, an ensemble approach consisting of three algorithms (Generalized Linear Models, MaxEnt and Random Forest) was used for the modelling. Twenty randomly distributed pseudo-absences data sets were used for each of the three algorithms, and an ensemble model was constructed using the median suitability (probability of species presence in a grid

Table 2
Occurrence of the studied CWR in the Netherlands according to the ecotope classification system.

Water vegetation										
Salinity	very sweet			sweet-light brackish					brackish	salty
Nutrient level	moderate			poor				rich	–	–
Acidity	(weakly) acid		alkaline	acid	weakly acid	alkaline		–	–	–
Submersed	1				1					
Emersed	1		3	1	2	–		4	2	–
Pioneer vegetation										
Salinity	sweet								brackish	salty
Nutrient level	poor			moderate				rich	–	–
Acidity	acid	weakly acid	alkaline	acid-alkaline		alkaline		–	–	–
Wet		1		4				9	1	2
Moist				24		8		35	7	–
Dry	1	3	6	25				15	7	–
Additional ecotope: dry walls (1x)										
Grassland										
Salinity	sweet								brackish	salty
Nutrient level	poor			moderate				rich	–	–
Acidity	acid	weakly acid	alkaline	acid-alkaline		alkaline		–	–	–
Wet	4	5	3	10				7	3	2
Moist	3	7	9	33		18		20	13	3
Dry	5	12	15	27				2	–	–
Brushwood										
Salinity	sweet								brackish	salty
Nutrient level	poor			moderate				rich	–	–
Acidity	–			acid-alkaline		alkaline		–	–	–
Wet				4				5	2	
Moist	2			10		2		7	2	–
Dry	2			4					1	–
Forest										
Salinity	sweet									
Nutrient level	poor			moderate				rich		
Acidity	acid	weakly acid	alkaline	acid-alkaline		alkaline		–		
Wet	1	1		6				5		
Moist	4	11	6	22		4		3		
Dry	7	7	5				7			

cell) score of the 3 × 20 predictions. It has been recommended to use either a large number of pseudo-absences (e.g. 10,000) or the results of several runs (e.g. 10) with fewer pseudo-absences (e.g. 100) for species distribution modelling (Barbet-Massin et al., 2012). We followed the latter approach by using 20 pseudo-absences data sets, each consisting of 1300 points. Model testing, based on the parameters 'area under the curve' (AUC) and 'model sensitivity', was performed in our earlier study with fewer species, which showed a high performance in all cases (Aguirre-Gutiérrez et al., 2017). In the present study, model performance was not examined, nor were SDMs selected for analysis. Instead we used all models in an ensemble approach as this method has been found to account for variation within and between algorithms and to result in consistent model predictions (Aguirre-Gutiérrez et al., 2013; Thuiller, 2014). The R programming language (R Core Team, 2019) was used for distribution modelling with the Biomod2 package (Thuiller et al., 2009). Further details of the modelling procedures are provided by Aguirre-Gutiérrez et al. (2017) and Van Treuren et al. (2017).

2.4. Data analysis

Changes in distributional range for groups of CWR, categorized by IUCN conservation status or plant family name, were based on the number of grid cells in which the species were predicted to occur in the present and future. Rather than calculating the arithmetic average of the percentage range change per species, we used the total sum of the number of grid cells in which the species of a group were predicted to occur in order to avoid bias due to small numbers of occupied grid cells. To investigate geographical shifts in distribution area, we used the centroid (average latitude and longitude) of the grid cells in which a species was predicted to occur under current conditions and under the climate change scenarios RCP2.6 and RCP8.5. For this analysis species were discarded that were predicted to cover (nearly) all grid cells in the Netherlands under current conditions and that showed less than 5% predicted range change under RCP2.6 and RCP8.5.

Changes in distributional range were also analysed in relation to the habitat characteristics vegetation structure, nutrient level, moisture condition, salinity and acidity. For this purpose, the ecotope classifications (Table 2) were used to calculate the relative abundance of CWR for each category of a habitat characteristic (Table A2). For example, a CWR occurring in three different ecotopes that are all characterized by a poor nutrient level has a relative abundance of 100% in nutrient-poor habitats. In some cases, where a habitat characteristic was not specified for the ecotope(s) involved, the sum of the relative abundances over categories was less than 100. Some categories were combined, or not used. The qualification 'very sweet' for salinity, only applying to water plants, was combined with the qualification 'sweet'. The qualifications 'emersed' and 'submersed' for moisture condition also apply only to water plants, and were not used in the analyses. Qualifications covering a range, i.e. 'sweet to light brackish' for salinity, 'moderate to rich' for nutrient level and 'acid to weakly acid' and 'acid to alkaline' for acidity were considered less informative and were therefore also excluded from the analyses. An overview of all categories is shown in Table 2.

Self-organising maps (SOMs) were used to relate the results of the distribution modelling to ecotope variation. SOMs, also referred to as Kohonen maps (Kohonen, 1995), project multivariate data sets to discrete locations in two dimensions, and can be seen as a clustering method where also relations between clusters are constrained: nearby clusters are more similar than clusters that are far apart in the Kohonen map. Here, the R implementation of the kohonen package (Wehrens and Kruisselbrink, 2018) was used, where distances between objects (i.e. species) can be calculated across several different data layers. The data layers employed correspond to the aforementioned habitat characteristics, derived from the ecotope classifications, plus the estimated climate effects for either of the two scenarios. Distances calculated for individual data layers are scaled in such a way that the climate effects are as important as the combined ecotope classifications, since the primary goal of the map is to group species according to climate effects. All ecotope layers are equally important in the overall distance. Simple Euclidean distances were used in all cases. Thus, species that are grouped together in one map unit are expected to be very similar in habitat characteristics as well as in estimated climate effects. A map size of six times eight units was chosen, corresponding to 4–5 species per unit on average. More units would lead to a more detailed clustering but also to more fragmentation, while fewer units would lead to more cases where compromises have to be made in terms of grouping dissimilar species.

The number of ecotopes in which a species occurs may be considered as the ecological amplitude of that species (Tamis et al., 2005a). To investigate whether species with a larger ecological amplitude are more resilient, range changes for CWR groups under climate change scenario RCP2.6 and RCP8.5, calculated similarly as for IUCN conservation status and plant family name, were plotted against the number of ecotopes in which species have been recorded in the Netherlands. Weighted trend lines were added to the plots.

3. Results

3.1. Effects of climate change

Considerable variation in the predicted effects of climate change on the occurrence of CWR in the Netherlands was observed among the study species, ranging from (near-)extinction to more than doubling of the distribution area. For example, *Vaccinium vitis-idaea* L. (cowberry) showed a predicted loss of 97% distribution area under the optimistic climate change scenario RCP2.6, while the species is not expected to persist anywhere in the Netherlands under the pessimistic scenario RCP8.5. Highly positive effects of climate change were most prominent for *Petroselinum segetum* (L.) Koch (corn parsley) and *Lepidium graminifolium* L. (tall pepperwort) that are expected to expand their Dutch distribution area more than twofold for both climate change scenarios considered. Predicted range changes in the Netherlands due to climate change are presented for each of the study species in Table A1 and on the website CWRnl.

Out of the 214 examined CWR, a reduction in the Dutch distribution area is expected for 51 species (24%) under RCP2.6 and for 119 (56%) under RCP8.5. For the entire study sample the average predicted percentage range decline in the Netherlands was 5% under RCP2.6 and 20% under RCP8.5 (Fig. 1: All CWR). Regarding the reduced CWR, 35 out of 51 (RCP2.6) and 85 out of 119 (RCP8.5) species currently are considered of least concern in the Netherlands according to the IUCN classification system, indicating that also common species are at risk of losing distribution area due to climate change (Table 3). Particularly concerning was the finding that climate change is expected to have a relatively large effect on CWR that are already critically endangered in the Netherlands as for this group of species 19% (RCP2.6) and 46% (RCP8.5) loss of the Dutch distribution area was predicted (Fig. 1).

Predicted effects of climate change on species occurrence in the Netherlands were not distributed evenly among plant families (Fig. 1). Some families, albeit represented by only a single or a few species, were found to be affected by neither of the considered climate change scenarios, such as observed for the Aquifoliaceae, Betulaceae, Cannabaceae, Fagaceae and Papaveraceae. For the other families, climate change was expected to have more severe effects under RCP8.5 as compared to RCP2.6, although the increase in severity could be rather small, such as observed for the Valerianaceae. The change in effect was found to be relatively large for several families, such as seen for the Grossulariaceae that showed a reduction in their Dutch distribution area of 3% under RCP2.6 but a 58% loss under RCP8.5. Relatively strong effects under both considered climate change scenarios were observed for the Amaranthaceae, Rosaceae and in particular the Ericaceae. The investigated Ericaceae included five species of the genus *Vaccinium*, showing a more than 90% reduction in distribution area under RCP8.5 (Fig. 1). In general, species with a predicted change in distributional range due to climate change showed a geographical shift to more northern locations in the Netherlands (Fig. 2).

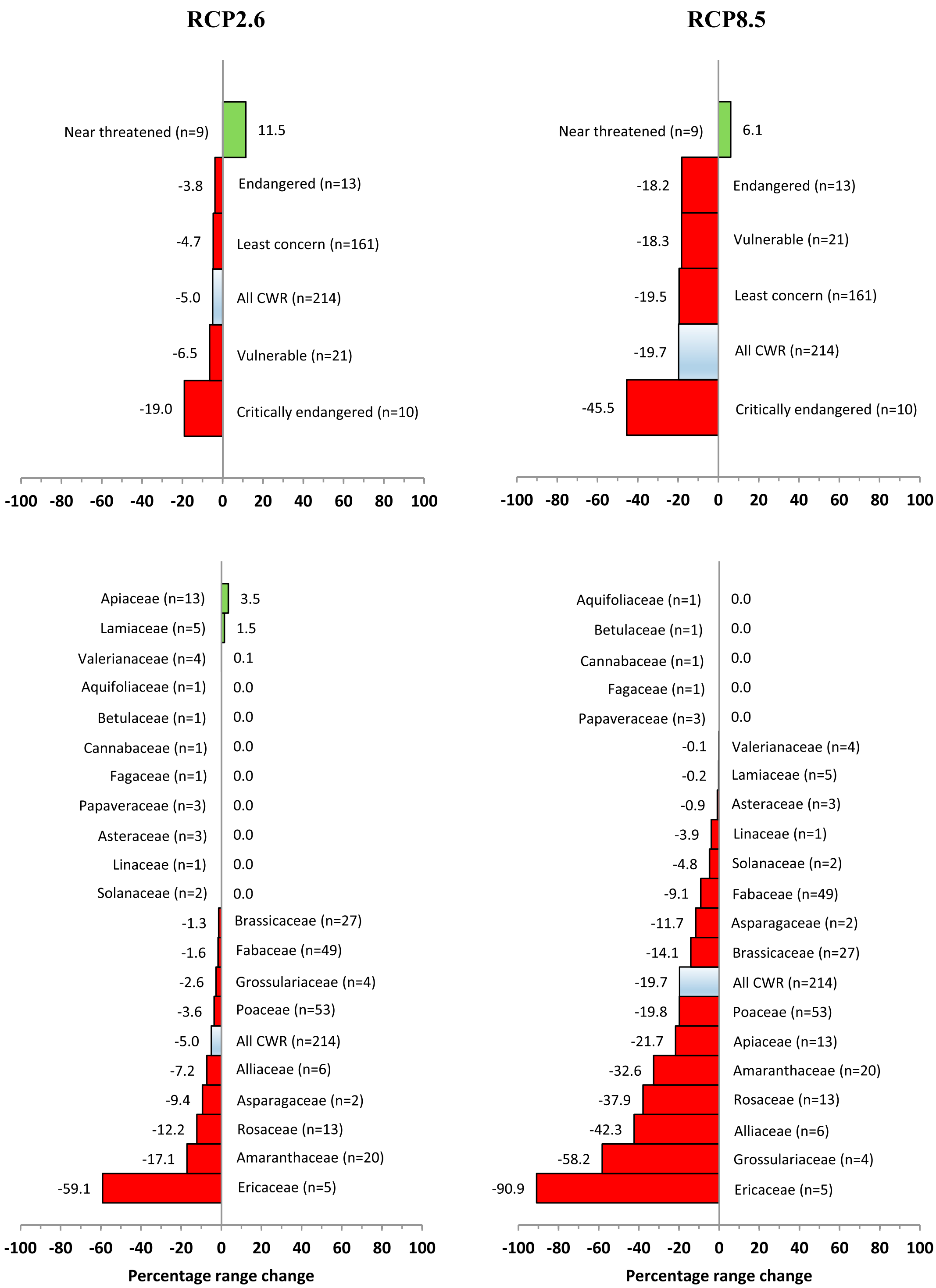

Fig. 1. Percentage range change in 2070 predicted for CWR in the Netherlands according to climate change scenario RCP2.6 and RCP8.5. Species are grouped by IUCN conservation status (upper panels) and plant family name (lower panels). The number of included species is presented between parentheses for each group.

3.2. *Relationship with ecology*

The number of different ecotopes in the Netherlands to which the investigated CWR were assigned, ranged from one to ten per species. The entire study sample comprised 69 different ecotopes with a total of 495 species/ecotope classifications (Table

Table 3
Percentage change in the Dutch distribution area according to climate change scenario RCP2.6 and RCP8.5 for taxa with current IUCN conservation status 'least concern' in the Netherlands. Only taxa with more than 10% reduction under the optimistic RCP2.6 are presented.

Taxon	RCP2.6	RCP8.5
Vaccinium vitis-idaea L.	−96.9	−100.0
Vaccinium oxycoccos L.	−90.8	−100.0
Barbarea stricta Andrz.	−86.5	−98.5
Atriplex glabriuscula Edmondston	−84.6	−94.3
Atriplex littoralis L.	−84.2	−97.0
Leymus arenarius (L.) Hochst.	−83.3	−95.2
Lupinus polyphyllus Lindl.	−82.5	−100.0
Elytrigia juncea subsp. *boreoatlantica* (Simonet & Guin.) Hyl.	−56.3	−63.2
Festuca arenaria Osbeck	−50.0	−56.5
Comarum palustre L.	−37.3	−98.1
Vaccinium macrocarpon Aiton	−33.3	−84.6
Allium scorodoprasum L.	−20.3	−85.8
Agrostis vinealis Schreb.	−12.4	−99.7

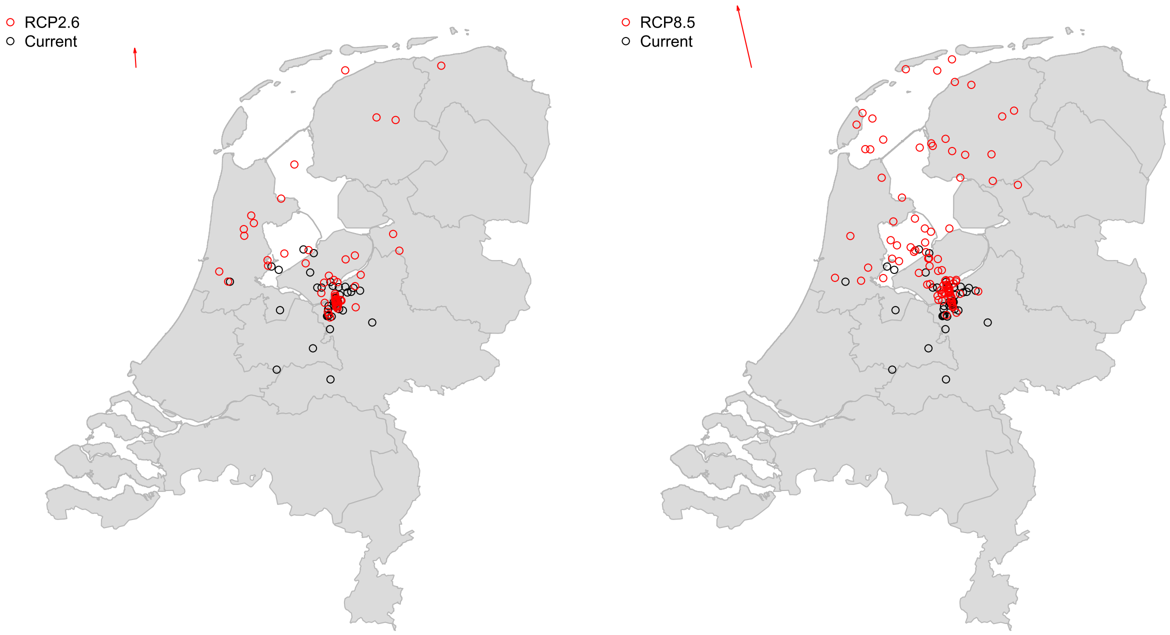

Fig. 2. Geographic position of the centroid of the predicted species distribution in the Netherlands under current conditions and under climate change scenario RCP2.6 (left map) and RCP8.5 (right map). Data are presented for 101 species showing at least 5% change in distribution area in the Netherlands according to either RCP2.6 or RCP8.5. The vectors at the top of the graphs denote the direction and magnitude of the shift in distribution based on the average latitude and longitude of the centroids.

2). The majority of the investigated CWR can be found in ecotopes of grassland and pioneer vegetations with 201 and 149 classifications, respectively.

Expected range changes in the Netherlands due to climate change were analysed in relation to each of the five habitat variables underlying the ecotope classification system (Fig. 3). Analyses by SOMs offer the advantage that the different features underlying the clustering can be compared directly. Each SOM unit shows the distribution of features for those species mapping to that unit in a so-called segment plot, the size of a pie slice corresponding to the relative abundance of the corresponding feature. Thus, plots can be presented for all six data layers, namely one climate effect layer and five layers relating to different habitat characteristics. The distribution of the investigated CWR over the SOM units is presented in Table A2. Zooming in on SOM units with more than 50% reduction in distribution area under RCP8.5 (Fig. 3, red units in the top left panel) revealed one single unit with six taxa and a group of eight units with a total of 33 taxa. The other panels in Fig. 3, corresponding to the habitat characteristics, show that the single unit with six taxa can be characterized as pioneer vegetation on dry to moist and brackish soils, whereas the group of seven units shows a wide variation, including nearly all classes of

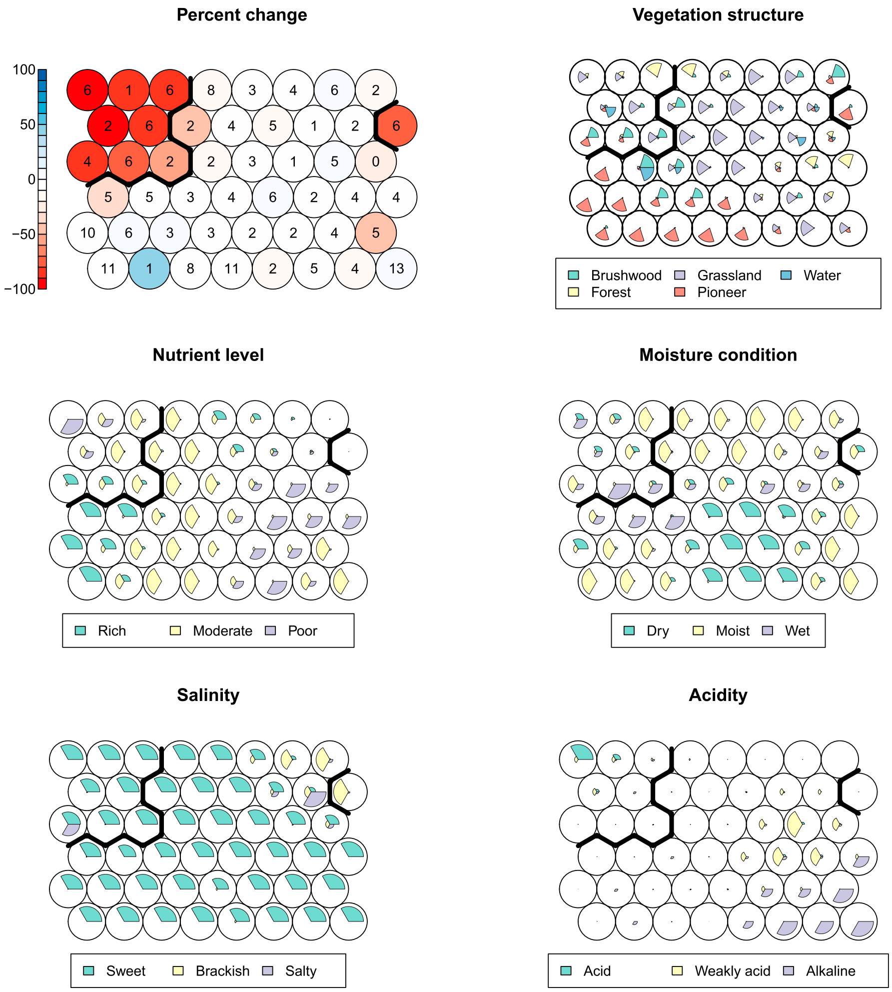

Fig. 3. SOM analysis of the effects of climate change scenario RCP8.5 and variation in ecological parameters. Changes in distributional range are presented in relation to the habitat variables vegetation structure, nutrient level, moisture condition, salinity and acidity. Numbers within units represent the number of included taxa, and bold lines mark (groups of) units with more than 50% reduction in distribution area.

characteristics with the exception of brackish, weakly acidic and alkaline soils. Similar findings were observed for the SOM figures under the optimistic scenario RCP2.6 (Figure A1).

Species occurring in relatively many different ecotopes were expected to be less reduced by climate change, which was found to be more pronounced for RCP2.6 than RCP8.5 (Fig. 4). Unfortunately, species occurring in five or more different ecotopes showed a low representation in the present study. The weighted trend lines showed a moderate correlation between ecological amplitude and tolerance level for each of the two examined climate change scenarios.

4. Discussion

Many national and international efforts have been initiated to conserve wild species in their natural habitats. For example, conserved areas in individual member states of the European Union have been organized into the Natura 2000 network of protected sites (Evans, 2012). Such areas may be protected against further deterioration as a result of habitat destruction, urbanisation, pollution and other present-day influences, but are defenseless against the effects of climate change. In a previous study similar patterns of change in distribution under climate change were predicted for 53 wild plant species regardless of their occurrence within or outside Natura 2000 areas (Van Treuren et al., 2017). Therefore, sound conservation strategies for CWR should take into account expectations of the risks that species experience in situ, including the effects of climate change (Maxted et al., 2015).

Here we investigated 214 wild species occurring in the Netherlands in order to develop national conservation policies for Dutch CWR. A subset of 53 red list species has been studied previously in more detail and at a wider geographic scale, and the results were used to prioritize those species for conservation (Van Treuren et al., 2017). To complement our conservation

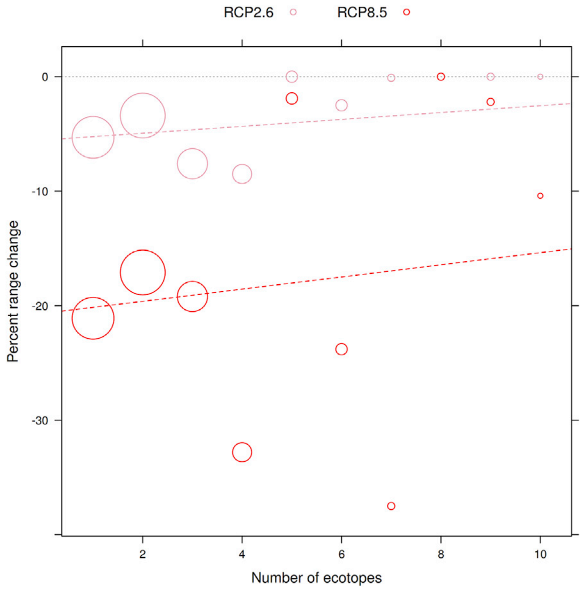

Fig. 4. Effects of climate change scenario RCP2.6 and RCP8.5 in relation to ecological amplitude. Range changes predicted for CWR in the Netherlands are plotted against the number of ecotopes in which a species has been observed in the Netherlands. The area of the data points is chosen according to the number of included taxa. Weighted trend lines are presented for each of the two scenarios.

strategy, the present study also includes the 161 CWR with current IUCN status 'least concern'. In order to explore identifiers for species vulnerable to climate change we analysed the effects thereof in relation to various species characteristics using the entire set of 214 species.

4.1. Assessing effects of climate change

To predict the effects of climate change on species distribution, ecological niche modelling or species distribution modelling is a commonly used approach (Jarvis et al., 2008). These models use meteorological and soil-related data at the collecting sites of plant specimens to predict species distributions under various scenarios of climate change (Aguirre-Gutiérrez et al., 2017; Jarvis et al., 2008). Rather than predicting whether or not a species will occur at a location, niche modelling actually predicts whether or not the conditions, in terms of the parameters included in the model, for a species are sufficiently favorable at that location. However, population biological parameters, such as level of phenotypic plasticity, competitive ability and dispersal capacity, can be expected also to contribute to the potential of establishment of a species at a location. Such variables are lacking from most niche modelling studies. In a previous modelling study it was shown that the prospects for maintenance of species such as *Carum verticillatum* (Whorled caraway) and *Valerianella rimosa* (Broad-fruited cornsalad) under climate change in the Netherlands depend on their ability to disperse (Van Treuren et al., 2017). Even if species are able to migrate the question is whether they can move to suitable habitats fast enough under the changing conditions (Cobben et al., 2013; Minteer and Collins, 2010; Williams et al., 2016), and whether they can establish at the new location in the presence of competition with other species. Niche modelling results will also depend on the question how well the various niches of the distribution range of a species are covered by the collected samples. Insufficient coverage of the niches of a species may underestimate its resilience under changed climate conditions. In the present study a relatively high number of 2492 GBIF records on average per species from the entire European region were used in order to maximize the probability that the different niches of a species were included in the modelling.

Our niche modelling study on 214 CWR predicted a reduction in the Dutch distribution area for 51 species under climate change scenario RCP2.6 and for 119 under RCP8.5 by the year 2070. Reduced distribution areas generally shifted in northward direction under both scenarios, the magnitude of the changes being larger under RCP8.5 (Fig. 2). Also at the European level shifts in distribution in northward direction were predicted in a previous study on eight CWR (Aguirre-Gutiérrez et al., 2017). As most of the studied CWR grow in temperate climates, these predicted geographical shifts in distribution most likely represent a response to an increased temperature and decreased precipitation that are expected under climate change in the Netherlands (Stocker et al., 2013). Analysis of botanical biodiversity using nation-wide databases has shown a marked increase in the number of thermophilic species in the Netherlands, coinciding with a marked increase in ambient temperature in the country (Tamis et al., 2005b). Thus, climate change can be expected to cause the introduction of non-native species in the Netherlands as well as the migration of Dutch native species from neighbouring countries in the South to niches in the Netherlands that are no longer suitable for locally adapted populations. The latter may apply to many of the examined CWR that showed stability or even an increase in their distribution area in the Netherlands. However, maintenance of distribution area through dispersal from neighbouring countries in the South will be problematic for species that are adapted to more temperate conditions, which possibly applies to the species shown in Fig. 2.

4.2. Relationship with species characteristics

Information on the type of species that can be expected to be most susceptible to the effects of climate change would be helpful to conservationists. Here we examined climate change effects in relation to IUCN conservation status, plant family name and several ecological parameters. For IUCN conservation status and plant family name we chose to use the total sum of the number of grid cells in which the species of a group were predicted to occur in the present and future, rather than the arithmetic average of the percentage range change per species. The drawback of using the arithmetic average is that a relatively small increase in distribution area of a species (e.g. predicted presence increased from two to ten grid cells, i.e. 400% increase) may obscure severe reductions in other species of the group (e.g. four species that each were reduced from 1000 to 500 grid cells). In this particular example the average effect would be zero, despite the clear and severe reductions of four out of five species. It can be argued that using the total number of grid cells may drive the analysis to widespread species. However, as in our study the predicted number of occupied grid cells under current conditions were not exceptionally low (Table A1: range 921–2935), a bias towards widespread species was considered unlikely.

Our results indicated that species with current IUCN status ‘least concern’ should not be ignored when developing conservation strategies for CWR as also for several of such unthreatened species severe negative effects of climate change on distribution were predicted. These effects were most pronounced for species of the genus *Vaccinium*, one of the many plant genera of the heather family (Ericaceae). *Vaccinium* species typically grow in wet, nutrient-poor, acidic environments, such as found in peatlands. Increased pressure on these habitats due to shortage of precipitation, such as experienced in 2018 and 2019 in the Netherlands, have been reported, causing typical peatland species such as *Vaccinium oxycoccos* (Small cranberry) to be outcompeted by species that thrive under dry conditions (Rick de Ruiter, State Forestry Service, unpublished results). Out of the five *Vaccinium* species occurring in the Netherlands, *V. oxycoccos*, *V. uliginosum* (Bog bilberry) and *V. vitis-idaea* (Cowberry) are predicted to have gone extinct in the country by the year 2070 under RCP8.5 (Table A1). Regarding IUCN conservation status, effects of climate change were found to be most severe for CWR that are already critically endangered. It has been suggested that such species are often specialists and hence are expected to be more susceptible to environmental variation (Bartholomeus et al., 2011). The critically endangered CWR included 7 species each confined to a single ecotope, while two species can be found in two and one species in three ecotopes. In general, a moderate positive correlation between ecological amplitude and susceptibility to climate change was observed in the present study. The SOM analyses did not reveal typical habitat characteristics for species groups that were predicted to be most prone to climate change. For example, the SOMs did show that all species occurring on acidic soils were reduced by more than 50% in distribution, but not all severely reduced CWR could be related to acidic environments (Fig. 3). In addition to acidity, neither for vegetation structure, nutrient level, moisture condition and salinity a clear relationship with changes in species distribution was found. Changes in distribution were not examined per habitat type, which may have obscured possible relationships between distributional change and habitat characteristics for species occurring in multiple ecotopes. For such species, incorporating ecological maps of the study area would be a valuable extension of the modelling in order to identify the habitat types in which species occurrence is expected to be most affected by climate change. As long as clear identifiers for vulnerable species groups are largely absent, effects of climate change need to be studied on a case by case basis. Introduction of a user-friendly web-based facility to estimate effects of climate change on species distribution would therefore be helpful in developing conservation plans.

4.3. Maintaining access to Dutch CWR

Our ultimate goal is to conserve the entire group of 214 Dutch CWR. Because this cannot be achieved within a few years, the question is where to begin. Our strategy is to start with the red lists species, as members of this group are already endangered to more or less extent. This group of 53 CWR has been studied in detail in previous research, in which we prioritized individual species based on degree of crop relatedness, observed occurrence data in the Netherlands, conservation status in neighbouring countries and expected effects of climate change on future distributions in the Netherlands as well as in the entire European region (Van Treuren et al., 2017). The 161 CWR with current IUCN status ‘least concern’ form the second group of conservation targets. For this group we will use the modelling results of the present study to prioritize individual species for conservation, starting with the species that were found most vulnerable to the effects of climate change (Table 3).

To complement in situ efforts, CWR can be conserved ex situ through inclusion of population samples in the regular collection of genebanks. However, due to the limited capacity of genebanks, this will mostly be restricted to the mandate crops of a genebank, while the range of crops covered by the CWR in a country may be much wider. For Dutch CWR only 19 taxa, comprising a total of 315 accessions, have so far been included in the regular collection of the Centre for Genetic Resources, the Netherlands (CGN). These materials are managed according to standard procedures that are largely based on consensus in the genebank community (FAO, 2013) as described in CGN’s quality management system, while the accessions are well-documented and available for distribution to users (www.cgn.wur.nl). However, including a wide variety of CWR in the regular collection may be a burden to genebanks because wild species often require substantial capacity and expertise for the their maintenance (Engels and Rao, 1998). For CWR that cannot be managed in a regular genebank collection, it can be decided to store population samples as safety duplicates. Such samples represent back-ups for populations persisting under natural conditions. The management of such CWR by genebanks could then be limited to proper ex situ storage under optimal conditions in order to ensure availability of the genetic diversity in case populations collapse in situ. Where and when appropriate, safety back-ups will allow population restoration and reintroduction. Using the priority setting for Dutch CWR from our previous research (Van Treuren et al., 2017) and the current study, CGN has planned to initiate this approach in 2020 by population sampling and storage of the samples as safety duplicates.

To provide access to the genetic resources of CWR that are not included in regular collections, genebanks could play a role as intermediate between interested users and the owners of the fields in which the CWR occur. This role includes the presentation of information on CWR (e.g. www.CWRnl.nl) and arranging the collecting of seed samples from natural populations according to terms and conditions of the field owners. Approaches for support of genebanks to CWR conservation and access are currently developed in the Netherlands, such as within the context of the EU project Farmer's Pride (www.farmerspride.eu).

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Declaration of competing interest

The authors declare that their research described in this manuscript is original, and all agree with the contents of this manuscript and its submission to Global Ecology and Conservation. The research results have not been published elsewhere, nor is it under consideration for publication elsewhere, nor do we have the intention to offer the manuscript for publication elsewhere as long as the manuscript is under consideration by Global Ecology and Conservation. All funding sources of the study have been acknowledged in the manuscript, and the authors declare that no financial benefits will result from publication of the research. Furthermore, the authors are unaware of any actual or potential conflict of interest that could inappropriately influence, or be perceived to influence, our work. To the best of our knowledge, the research was carried out according to appropriate ethical principles.

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Appendix A. Supplementary data

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References

Aguirre-Gutiérrez, J., Carvalheiro, L.G., Polce, C., van Loon, E.E., Raes, N., Reemer, M., Biesmeijer, J.C., 2013. Fit-for-purpose: species distribution model performance depends on evaluation criteria—Dutch hoverflies as a case study. PloS One 8, e63708.
Aguirre-Gutiérrez, J., van Treuren, R., Hoekstra, R., van Hintum, T.J.L., 2017. Crop wild relatives range shifts and conservation in Europe under climate change. Divers. Distrib. 23, 739–750.
Bakkenes, M., Alkemade, J.R.M., Ihle, F., Leemans, R., Latour, J.B., 2002. Assessing effects of forecasted climate change on the diversity and distribution of European higher plants for 2050. Global Change Biol. 8, 390–407.
Barbet-Massin, M., Jiguet, F., Albert, C.H., Thuiller, W., 2012. Selecting pseudo-absences for species distribution models: how, where and how many? Methods Ecol Evol 3, 327–338.
Bartholomeus, R.P., Witte, J.P.M., van Bodegom, P.M., van Dam, J.C., Aerts, R., 2011. Climate change threatens endangered plant species by stronger and interacting water-related stresses. J. Geophys. Res. 116, G04023. https://doi.org/10.1029/2011JG001693.
Castañeda-Álvarez, N.P., Khoury, C.K., Achicanoy, H.A., Bernau, V., Dempewolf, H., Eastwood, R.J., Guarino, L., Harker, R.H., Jarvis, A., Maxted, N., Müller, J.V., Ramirez-Villegas, J., Sosa, C.C., Struik, P.C., Vincent, H., Toll, J., 2016. Global conservation priorities for crop wild relatives. Native Plants 16022. https://doi.org/10.1038/nplants.2016.22.
Cobben, M.P., van Treuren, R., van Hintum, T.J.L., 2013. Climate change and crop wild relatives: can species track their suitable environment, and what do they lose in the process? Plant Genet. Resour. Charact. Util. 11, 234–237.
Dempewolf, H., Eastwood, R.J., Guarino, L., Khoury, C.K., Müller, J.V., Toll, J., 2014. Adapting agriculture to climate change: a global initiative to collect, conserve, and use crop wild relatives. Agroecol Sust Food Syst 38, 369–377.
Engels, J.M.M., Rao, Ramanatha, 1998. Regeneration of seed crops and their wild relatives. In: Proceedings of a Consultation Meeting, vols. 4–7. International Plant Genetic Resources Institute, Rome, Italy. December 1995, ICRISAT, Hyderabad, India.
Evans, D., 2012. Building the European union's Natura 2000 network. J. Nat. Conserv. 1, 11–26.
FAO, 2013. Genebank Standards for Plant Genetic Resources for Food and Agriculture. Food and Agriculture Organization of the United Nations, Rome, Italy.
FAO, IIASA, ISRIC, ISSCAS, JRC, 2012. Harmonized World Soil Database (Version 1.2). IIASA, Rome, Italy: FAO, Laxenburg, Austria.

Fitzgerald, H., Palmé, A., Asdal, Å., Endresen, D., Kiviharju, E., Lund, B., Rasmussen, M., Thorbjörnsson, H., Weibull, J., 2019. A regional approach to Nordic crop wild relative in situ conservation planning. Plant Genet. Resour. Charact. Util. 1–12. https://doi.org/10.1017/S147926211800059X.
Hajjar, R., Hodgkin, T., 2007. The use of wild relatives in crop improvement: a survey of developments over the last 20 years. Euphytica 156, 1–13.
Harlan, J., de Wet, J., 1971. Towards a rational classification of cultivated plants. Taxon 20, 509–517.
Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. Int. J. Climatol. 25, 1965–1978.
IPCC, 2014. In: Pachauri, R.K., Meyer, L.A. (Eds.), Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team. IPCC, Geneva, Switzerland.
IUCN, 2012. IUCN Red List Categories and Criteria, second ed. IUCN, Gland, Switzerland and Cambridge, UK, Version 3.1.
Jarvis, A., Lane, A., Hijmans, R.J., 2008. The effect of climate change on crop wild relatives. Agric. Ecosyst. Environ. 126, 13–23.
Khoury, C., Laliberté, B., Guarino, L., 2010. Trends in ex situ conservation of plant genetic resources: a review of global crop and regional conservation strategies. Genet. Resour. Crop Evol. 57, 625–639.
Kohonen, T., 1995. Self-Organizing Maps. Springer-Verlag, Berlin Heidelberg. https://doi.org/10.1007/978-3-642-97610-0.
Mammadov, J., Buyyarapu, R., Guttikonda, S.K., Parliament, K., Abdurakhmonov, I.Y., Kumpatla, S.P., 2018. Wild relatives of maize, rice, cotton, and soybean: treasure troves for tolerance to biotic and abiotic stresses. Front. Plant Sci. 9 https://doi.org/10.3389/fpls.2018.00886.
Maxted, N., Avagyan, A., Frese, L., Iriondo, J.M., Magos, B.J., Singer, A., Kell, S.P., 2015. ECPGR Concept for in Situ Conservation of Crop Wild Relatives in Europe. Wild Species Conservation in Genetic Reserves Working Group. European Cooperative Programme for Plant Genetic Resources, Rome, Italy.
Minteer, B.A., Collins, J.P., 2010. Move it or lose it? The ecological ethics of relocating species under climate change. Ecol. Appl. 20, 1801–1804.
R Core Team, 2019. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. www.R-project.org.
Rubio Teso, M.L., Torres Lamas, E., Parra-Quijano, M., de la Rosa, L., Fajardo, J., IriondoJM, 2018. National inventory and prioritization of crop wild relatives in Spain. Genet. Resour. Crop Evol. 65, 1237–1253.
Runhaar, J., van Landuyt, W., Groen, C.L.G., Weeda, E.J., Verloove, F., 2004. Herziening van de indeling in ecologische soortengroepen voor Nederland en Vlaanderen. Gorteria 30, 12–26.
Sparrius, L.B., Odé, B., Beringen, R., 2014. Basisrapport Rode Lijst Vaatplanten 2012 volgens Nederlandse en IUCN-criteria. FLORON Rapport 57. FLORON, Nijmegen.
Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Böschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., 2013. IPCC, 2013: Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Tamis, W.L.M., van't Zelfde, M., van der Meijden, R., Groen, C.L.G., Udo de Haes, H.A., 2005a. Ecological interpretation of changes in the Dutch flora in the 20th century. Biol. Conserv. 125, 211–224.
Tamis, W.L.M., van't Zelfde, M., van der Meijden, R., Udo de Haes, H.A., 2005b. Changes in vascular plant biodiversity in The Netherlands in the 20th century explained by their climatic and other environmental characteristics. Climate Change 72, 37–56.
Thuiller, W., 2014. Editorial commentary on 'Patterns and uncertainties of species' range shifts under climate change'. Global Change Biol. 20, 3593–3594.
Thuiller, W., Lafourcade, B., Engler, R., Araújo, M.B., 2009. Biomod – a platform for ensemble forecasting of species distributions. Ecography 32, 369–373.
Van Treuren, R., Hoekstra, R., van Hintum, T.J.L., 2017. Inventory and prioritization for the conservation of crop wild relatives in The Netherlands under climate change. Biol. Conserv. 216, 123–139.
Vincent, H., Wiersema, J., Kell, S., Fielder, H., Dobbie, S., Castañeda-Álvarez, N.P., Guarino, L., Eastwood, R., León, B., Maxted, N., 2013. A prioritized crop wild relative inventory to help underpin global food security. Biol. Conserv. 167, 265–275.
Wehrens, R., Kruisselbrink, J., 2018. Flexible self-organising maps in kohonen v3.0. J. Stat. Software. https://doi.org/10.18637/jss.v000.i00.
Williams, J.L., Kendall, B.E., Levine, J.M., 2016. Rapid evolution accelerates plant population spread in fragmented experimental landscapes. Science 353, 482–485.