

# A regional approach to Nordic crop wild relative *in situ* conservation planning

Heli Fitzgerald<sup>1\*</sup>, Anna Palmé<sup>2</sup>, Åsmund Asdal<sup>2</sup>, Dag Endresen<sup>3</sup>, Elina Kiviharju<sup>4</sup>, Birgitte Lund<sup>5</sup>, Morten Rasmussen<sup>6</sup>, Hjörtur Thorbjörnsson<sup>7</sup> and Jens Weibull<sup>8</sup>

<sup>1</sup>Finnish Museum of Natural History, University of Helsinki, Helsinki, Finland, <sup>2</sup>Nordic Genetic Resource Centre (NordGen), Alnarp, Sweden, <sup>3</sup>UiO Natural History Museum in Oslo, University of Oslo, Oslo, Norway, <sup>4</sup>Natural Resources Institute Finland, Jokioinen, Finland, <sup>5</sup>Agricultural Agency, Copenhagen, Denmark, <sup>6</sup>Norwegian Genetic Resource Center, Norwegian Institute of Bio-economy Research, Ås, Norway, <sup>7</sup>Reykjavík Botanic Garden, Reykjavík, Iceland and <sup>8</sup>Board of Agriculture, Alnarp, Sweden

Received 19 November 2018; Accepted 30 November 2018

## Abstract

Crop wild relatives (CWR) can provide one solution to future challenges on food security, sustainable agriculture and adaptation to climate change. Diversity found in CWR can be essential for adapting crops to these new demands. Since the need to improve *in situ* conservation of CWR has been recognized by the Convention on Biological Diversity (CBD) (2010) and the Global Strategy for Plant Conservation (2011–2020), it is important to develop ways to safeguard these important genetic resources. The Nordic flora includes many species related to food, forage and other crop groups, but little has been done to systematically secure these important wild resources. A Nordic regional approach to CWR conservation planning provided opportunities to network, find synergies, share knowledge, plan the conservation and give policy inputs on a regional level. A comprehensive CWR checklist for the Nordic region was generated and then prioritized by socio-economic value and utilization potential. Nordic CWR checklist was formed of 2553 taxa related to crop plants. Out of these, 114 taxa including 83 species were prioritized representing vegetable, cereal, fruit, berry, nut and forage crop groups. The *in situ* conservation planning of the priority CWR included ecogeographic and complementarity analyses to identify a potential network of genetic reserve sites in the region. Altogether 971,633 occurrence records of the priority species were analysed. A minimum number of sites within and outside existing conservation areas were identified that had the potential to support a maximum number of target species of maximum intraspecific diversity.

**Keywords:** crop wild relatives, food security, sustainable agriculture

## Introduction

Climate change does not only threaten species, but also world food security (Rosenzweig and Parry, 1994). Major crops are already becoming severely affected by climate change-induced events such as droughts, floods, new pests and diseases (Kang *et al.*, 2009; FAO, 2016) and having considerable impacts on agricultural production (IPCC, 2014). The arctic, boreal and alpine regions, which cover most of

the Nordic land area, are particularly vulnerable to effects of climate change on biodiversity and agriculture and the spread of pests and pathogens northwards (IPCC, 2007; Lindner *et al.*, 2010; Bebbler *et al.*, 2013; Juhola *et al.*, 2017).

Part of the solution to these challenges is provided by wild species related to crops, which harbour useful traits for food and forage crop improvement (Maxted and Kell, 2009; Helgadóttir *et al.*, 2016; Dempewolf *et al.*, 2017). However, many crop wild relatives (CWR) themselves are threatened and under-represented in species conservation programmes as their potential importance is not known or recognized (Ford-Lloyd *et al.*, 2011), and are themselves susceptible to

\*Corresponding author. E-mail: [heli.fitzgerald@helsinki.fi](mailto:heli.fitzgerald@helsinki.fi)

climate change (Jarvis *et al.*, 2008a). The importance to conserve Plant Genetic Resources for Food and Agriculture (PGRFA) and their CWR has been recognized in many international treaties such as the CBD Strategic Plan for Biodiversity 2011–2020 (CBD, 2010), the International Treaty on Plant Genetic Resources for Food and Agriculture (FAO, 2001) and the Global Plan of Action for Plant Genetic Resources for Food and Agriculture (FAO, 2011).

The Nordic region consists of five countries in Northern Europe: Denmark, Finland, Iceland, Norway and Sweden<sup>1</sup>. The region has relatively low species diversity with approximately 3580 vascular plant taxa (Dyntaxa, 2016). However, wild species of the region are likely to harbour unique traits due to the extreme climate conditions and remote location. Several species growing in the Nordic region are at the edge of their distribution range, with distinct subspecies occurring in the area. Peripheral populations such as these can be genetically distinct from central populations and may have traits allowing adaptation to environmental change, as Lesica and Allendorf (1995) suggest. The numerous isolated islands of the region may contain unique intraspecific diversity, as described by Whittaker and Fernandez-Palacios (2007) and Hargreaves *et al.* (2010).

The Nordic region has a long history of collaboration strengthened by the formation of the Nordic Council in 1952. One example of Nordic cooperation is the Nordic Genetic Resource Center (NordGen), which houses regional plant genetic resource collections. Although NordGen secures regional genetic resources *ex situ*, further efforts to secure regional CWR *in situ* are warranted. The aim of this study was to build on Nordic synergies to conserve wild species related to agricultural crops *in situ*. Regional conservation planning provides complementary and cost-efficient solutions for Nordic CWR conservation along with networking opportunities that benefit both regional and national activities. The rationale for taking a regional approach for CWR conservation has previously been discussed by Maxted (2003) and Kell *et al.* (2017). We present here the methods and results of regional CWR conservation planning which included preparation of a CWR checklist and priority lists, an *in situ* conservation analysis and suggestions for regional *in situ* conservation of CWR taxa.

## Methods

### Regional CWR species checklist

When planning the conservation of Nordic CWR diversity, we prepared a consolidated checklist of Nordic CWR taxa (Fitzgerald *et al.*, 2017a) by matching crop genera with

Nordic vascular plant genera. We applied a broad definition of CWR (Maxted *et al.*, 2006), where all the species in the same genus as a crop are given CWR status. We matched the Nordic vascular plant genera with a global crop genera list because all countries are interdependent on the use and conservation of plant genetic resources and most countries are dependent on crops whose primary regions of diversity are elsewhere (Maxted and Kell, 2009; Khoury *et al.*, 2013). The Nordic flora includes genetic resources of wild species related to crops used in other parts of the world and likewise many crops cultivated in Nordic countries have not originated from the area.

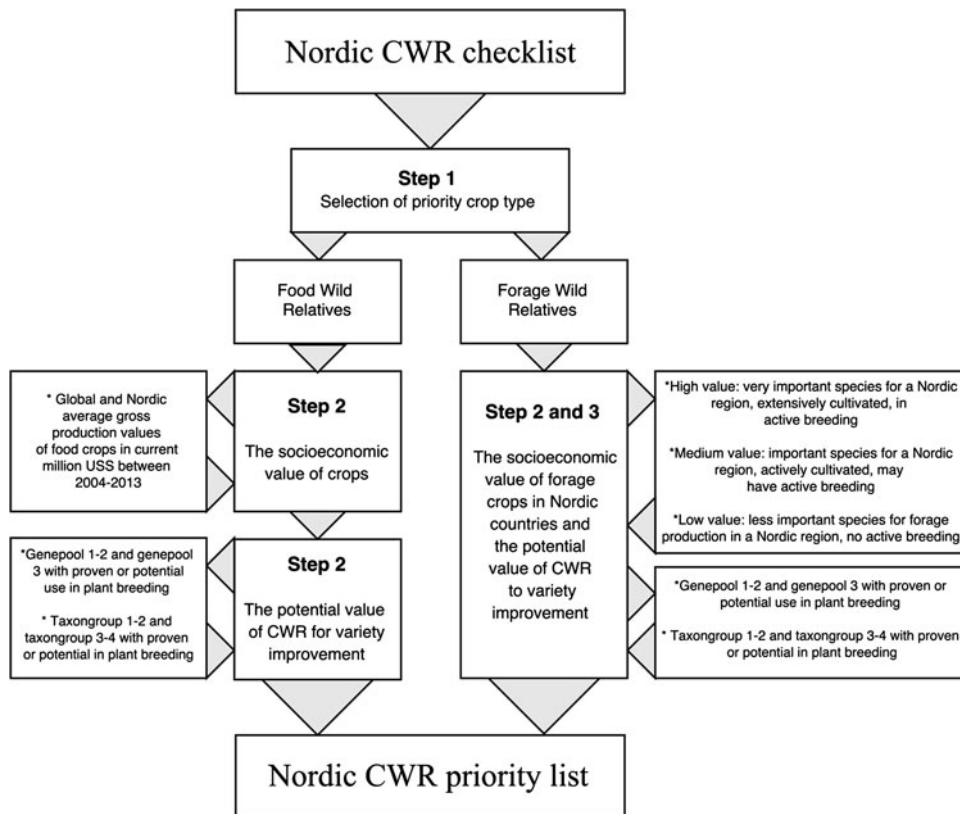
The Nordic vascular plant list was compiled from national sources, but follows common taxonomy from Dyntaxa (2016). The national sources were Dyntaxa (2016) for Sweden, Lid and Lid (2005) for Norway, Lampinen and Lahti (2016) for Finland, Atlas Florae Danica (Hartvig, 2015) for Denmark and the 'List of flowering plants and ferns on Island' (Kristinsson, 1998) for Iceland. The crop genera list came from several sources: lists of medicinal, ornamental and forestry crops (IPK, 2003), food crops (FAO, 2001, 2005; Groombridge and Jenkins, 2002; EU, 2016) and forage crops Feedipedia, 2016; NordGen, 2016). The lists were taxonomically harmonized. The Nordic CWR checklist was reduced by removing hybrid and temporary species as well as those recently introduced species present in the Nordic region for <10 generations. Taxonomic experts were consulted to determine whether the species were established <10 generations. The indigenous, naturalized and temporary species status was found from the national and regional floras. Taxa considered indigenous or naturalized in at least one of the five countries were included.

### Prioritization among CWR

The Nordic regional CWR checklist was subsequently prioritized by selecting wild relatives of food and forage crops with the greatest use potential. Fig. 1 illustrates the prioritization steps. Widely used prioritization criteria such as 'socio-economic value of crops' and 'potential value of wild relatives for variety improvement' (Kell *et al.*, 2017) formed the basis for prioritization. First, wild species related to ornamental, forestry and medicinal crops were removed from the analysis, and species related to food and forage crops were selected for the prioritization process. The wild species related to food and forage crops were selected due to their role in food security as a source of traits when developing new varieties and adapting crop species to changing conditions such as climate change or new pests and diseases (Maxted and Kell, 2009; Dempewolf *et al.*, 2017).

The second prioritization step was carried out separately for food and forage wild relative groups. The food wild

<sup>1</sup> Greenland, the Faroe Islands and Åland maintain certain autonomy in the region, but are not treated specifically in this article.



**Fig. 1.** Nordic region crop wild relative prioritization process.

relatives were prioritized based on global monetary values derived from FAO production values (FAO, 2015) for an average 10-year period. Both global and Nordic regional average gross production values in million US\$ for the years 2004–2013 were calculated and applied to all wild species related to the food crop genera. Those crop genera having an average global gross production value more than US\$200 million, were selected.

Data for the prioritization of the forage crops were collected in consultation with experts. A questionnaire was sent to breeders and other experts from each country, setting a priority for each forage genus in relation to importance and value in breeding and the scale of cultivation at a national level. National priority was estimated by breeders/experts for each Nordic country according to the following procedure. Top priority (Group 1) was given to genera with forage species that are commercially very important, are subject to active breeding in that country and are extensively cultivated. High priority (Group 2) was given to genera with forage species that are important, may be subject to active breeding in that country and are actively cultivated, but not included in Group 1. Low priority (Group 3) was given to genera with forage species which are considered less important for forage production and where there is no active breeding. A regional priority

level was calculated from the countries' responses and those species having the highest average across Nordic countries were selected.

The third part of the prioritization included applying the gene pool (GP) (Harlan and de Wet, 1971) and taxon group (TG) (Maxted *et al.*, 2006) concepts. GP and TG group data were obtained from the Harlan and de Wet Crop Wild Relative inventory (Vincent *et al.*, 2013; Crop Trust, 2016) and GRIN Global Taxonomy, World Economic Plants Database (USDA, 2016). Those wild species belonging to the primary (GP1b) and secondary (GP2) GPs of the crop and those in primary (TG1b) and secondary (TG2) TGs were prioritized. The taxa of the tertiary GP (GP3) or tertiary TG (TG 3 and 4) with proven use or potential use in plant breeding were also prioritized.

### **Complementarity conservation analysis**

The aim of the *in situ* conservation analysis was to find potential genetic reserve sites (Maxted *et al.*, 1997) for *in situ* conservation of priority CWR species in the Nordic countries. We used a method that combined a complementarity analysis, described by Rebelo (1994), with an ecogeographic land characterization (ELC) map of the region

**Table 1.** Environmental variables used for creating ELC map for the Nordic priority CWR

Code	Description	Unit	Source	Type
Bio_1	Annual average temperature	°C	Worldclim	Bioclimatic
Bio_12	Annual rainfall	mm	Worldclim	Bioclimatic
Ref_depth	Depth of the soil unit	M	HWS database	Edaphic
T_oc	Organic carbon content in surface soil	% weight	HWS database	Edaphic
T_ph_h2o	pH in soil water solution in surface soil	log(H+)	HWS database	Edaphic
Altitude	Elevation above sea level	m	Worldclim	Geophysical
Slope	Slope of the land surface	°	SRTM DEM	Geophysical
Northness	Values close to 1 if facing northwards, -1 if facing southwards		SRTM DEM	Geophysical
Eastness	Values close to 1 if facing eastwards, -1 if facing westwards		SRTM DEM	Geophysical

(Parra-Quijano *et al.*, 2012). The complementarity analysis is used to identify the minimum number of sites where a maximum number of target species occur (Maxted *et al.*, 2008).

An ELC map is produced by multivariate analysis and delineates areas with similar environmental characteristics. ELC maps can therefore be used for various purposes in agrobiodiversity conservation to provide information on ecogeographic scenarios to assess plant adaptation in relation to the prevailing environmental conditions (Parra-Quijano, 2012). The idea behind combining the complementarity conservation analysis and the ELC map is that by conserving sites that reflect the ecogeographic variation of a species geographic distribution, we are conserving a broad range of genetic diversity that has adaptive importance. This potentially conserves the variation of genes of most interest for crop improvement (Maxted *et al.*, 2013). As a part of the ecogeographic analysis, multi-species taxon richness and sampling bias maps were also created to provide additional information on the distribution data used. The maps were created using distribution data of priority species on DIVA-GIS (Hijmans *et al.*, 2012), with a cell size of 0.1 degrees.

Relevant climatic, ecological and geographical data influencing target species adaptation were selected. Altogether nine variables from edaphic (HWS Database, 2012), geophysical (Reuter *et al.*, 2007; Jarvis *et al.*, 2008b) and bioclimatic (Hijmans *et al.*, 2005; Worldclim, 2016; Fick and Hijmans, 2017) categories were selected to represent the target species adaptation (Table 1). The selection was based on variable selection used in the Norwegian diversity analysis (Phillips *et al.*, 2016) and modified by national experts' advice to suit the entire Nordic region. The selected variables included average annual rainfall, average annual temperature, soil depth, organic carbon content in surface soil, pH in soil water solution of surface soil, elevation (asl.), slope and aspects (North and East). The ELC map was created using the Capfitogen ELC map tool (Parra-Quijano, 2016). The parameters selected included latitude,

elbow method, 5 arc-minute and four clusters allowed by each bioclimatic, edaphic and geophysical component, following the description in Parra-Quijano *et al.* (2014). For those cells where an ELC category was not assigned due to lack of variable data, the ELC category was assigned by extracting values from the nearest cell. This was done with a maximum distance of 15 km to the border of the nearest cell.

Several tools were used in the complementary conservation analysis for analysing data and displaying results: Capfitogen tools (Parra-Quijano, 2016), DIVA (Hijmans *et al.*, 2012) and ArcGIS (ESRI, 2015). Target species distribution data were obtained from the Global Biodiversity Information Facility (GBIF), and national sources. These included GBIF (2016a) for Norway, GBIF (2016b) for Sweden, Lampinen and Lahti (2016) for Finland, GBIF (2016c) for Denmark and GBIF (2016d) and the database of the Icelandic Institute of Natural History (2016) for Iceland. The occurrence data were filtered by removing duplicate records, setting the georeferenced quality to a maximum of 1 km and checking for outlier locations. For each species occurrence point, only the most recent observation record was selected. Observations dated before year 1990 were discarded if the species had not been observed in that location since. The occurrence data types included observation, herbarium and gene bank data. Analysis was made on a species level. Altogether 971,633 occurrence records of priority species from the five Nordic countries were standardized into the Capfitogen format (Parra-Quijano, 2016), based on FAO/Bioiversity Multi-Crop Passport Descriptors (Alercia *et al.*, 2012).

The Finnish plant distribution records were available on a 1 km<sup>2</sup> grid system instead of a coordinate format. Therefore, centroids of the grid squares had to be calculated and transferred into coordinate points. If the grid square was only partly inside the country boundary and the species distribution point was near the edge of the boundary, the observation points were inadvertently not included in the analysis. This was a particular problem on

the Southern coastline and archipelago species-rich areas. The solution was to assign new coordinates to the closest land point.

For the ecogeographic complementary analysis, the Capfitogen Complementary tool (Parra-Quijano, 2016) was used with the ELC map to find potential genetic reserve locations. Two separate analyses were performed. First, a grid cell complementarity analysis for the whole land area of the Nordic countries was performed on a resolution of 5 arc-minutes (approximately 10 km grids). Second, a protected area (PA) complementarity analysis was carried out by selecting sites within PAs, using the data from World Database of Protected Areas (UNEP-WCMC and IUCN, 2016) on resolution of 30 arc-seconds (1 km<sup>2</sup>). All types of PAs were included in the analysis (i.e. National Parks, National Reserves and protected landscapes).

## Results

### CWR inventory and prioritization

A regional CWR checklist for the Nordic countries was created including 2553 CWR taxa (Fitzgerald *et al.*, 2017a), which is about 70% of the total Nordic vascular plant flora. The final checklist consists of native, archaeophyte and established neophyte vascular plant species occurring in the Nordic region. According to Kalliola (1973), the species introduced to the Nordic region before 17th century are considered archaeophytes and afterwards neophytes. Approximately one-third of the regional checklist taxa are related to food and forage crops only. However, the majority of CWR taxa are related to multiple crop types, for example, apple (*Malus*) and cherry (*Prunus*) species which are related to medicinal, food, forestry and ornamental crop categories.

Altogether the Nordic CWR priority list includes 114 taxa (online Supporting information 1). These include 83 species from 35 genera representing wild relatives of eight crop groups: vegetables, cereals, fruits, berries, nuts, and grass and legume forages. The vegetable group includes species related to Brassica, onion, lettuce, carrot and field/broad bean. The cereals include wild relatives of oat and millet. The fruit group includes wild relatives of fruit trees such as apple, pear, cherry, apricot, almond and plum. Wild relatives of cultivated berries are one of the largest groups, and include strawberry, raspberry, blackberry, blueberry, lingonberry, cloudberry, black currant and red currant. Nut relatives include wild hazelnut and walnut. The forage wild relatives can be divided into forage legumes and forage grasses and include species from many genera such as *Trifolium*, *Poa*, *Festuca*, *Phleum*, *Lolium* and *Medicago*. The priority taxa crop GP and TG concepts and the distribution classes in Nordic countries are listed in Fitzgerald *et al.* (2017b).

### Species richness and sample bias maps

Multi-species taxon richness and sampling bias maps were created for the 83 priority species. The species richness map (online Supporting information 3) shows a pattern of higher richness in the southern parts of the region and lower richness in the northern parts. Naturally species-poor areas include Vatnajökull glacier in Iceland and Jostedalsglacier in Norway along with many larger lakes and mountainous areas of the region. The sampling bias map (online Supporting information 4) shows fewer sampled areas in the Northern parts of Norway, Finland and Sweden, particularly in Finnmark County and highly sampled areas around larger cities such as Copenhagen, Helsinki, Oslo, Oulu and Stockholm.

### ELC maps

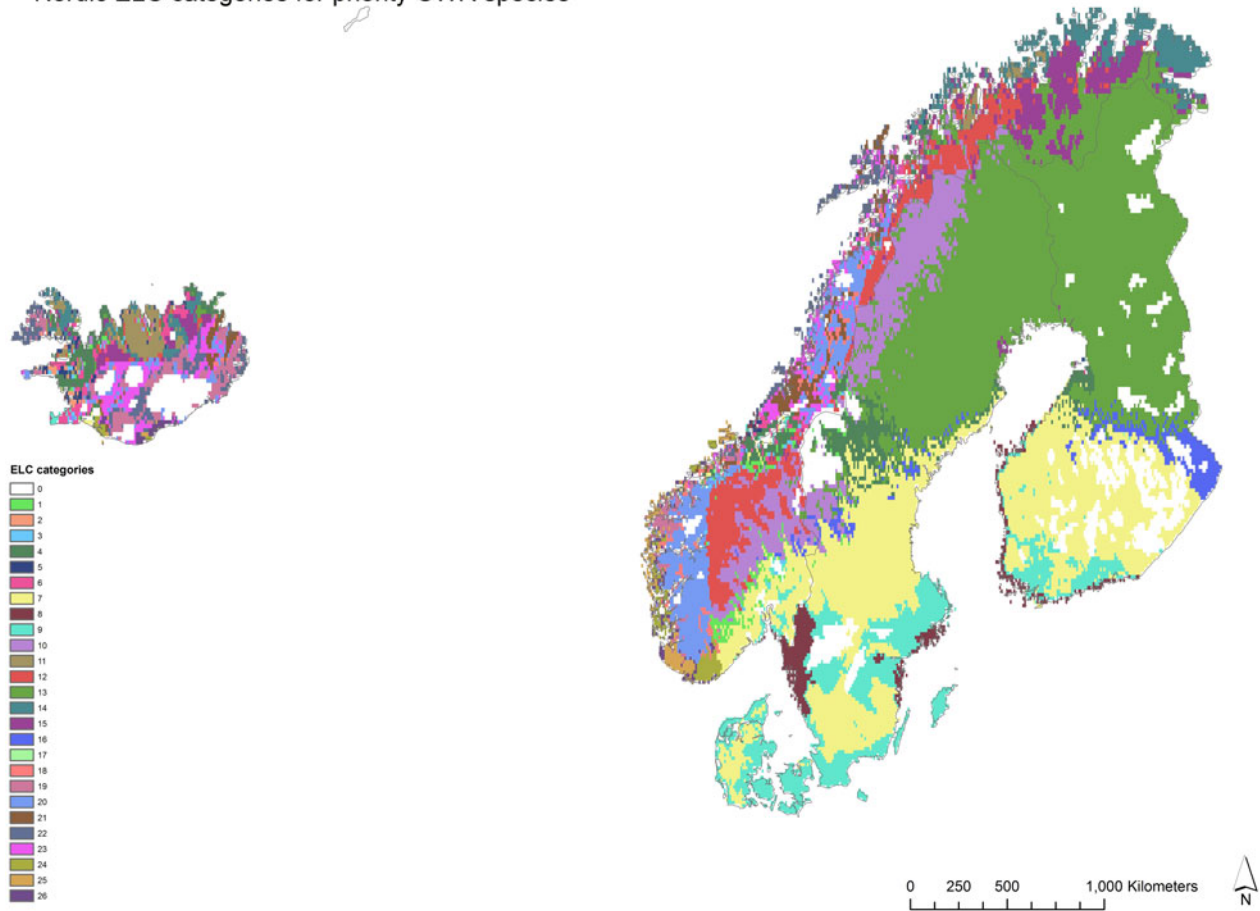
The Nordic ELC map contains 26 ecogeographic categories (Fig. 2 and online Supporting information 2). These zones reflect potential adaptation of the priority species in the Nordic region based on bioclimatic, geophysical and edaphic characteristics. The ELC map was used in Capfitogen's Complementary tool to find complementary *in situ* conservation areas that potentially reflect the intraspecific variation of the priority CWR based on the genetic adaptation to different environments.

### Complementarity conservation analysis

Altogether 971,633 occurrence records of the 83 priority species were analysed in Capfitogen's Complementary tool to find potential genetic reserve locations complementing each other. The results of the grid cell analysis show a network of 299 grid cells (Fig. 3 and online Supporting information 5) needed to conserve all the taxon-ELC zone combinations in at least one location. By using the ELC zones, the within-species diversity is taken into account in the conservation planning. The first complementary cell is closely located to Oslo in Drammen, Norway, and contained 116 priority taxa-ELC combinations. The second cell, in Oulu, Finland, had 64 complementary taxa-ELC combinations which were not found in the first site. The third cell near Kristiansand, Norway, had 61 and the fourth cell is on the border of Helsinki and Espoo cities, while Finland had 55 priority taxa-ELC combinations.

The results of the PA complementary analysis showed a network of 162 complementary genetic reserves within existing conservation areas (Fig. 4 and online Supporting information 6 and 7) with altogether 8164 observations of the target species. The first complementary PA site, covering the highest number of target species per ELC zone, was in Aalborg Kommune, Denmark. It contained 88 target species in two ELC zones. Each species is counted separately in

## Nordic ELC categories for priority CWR species



**Fig. 2.** The Nordic region ecogeographic land characterization (ELC) map with 26 ELC categories. The ELC categories represent different environments based on bioclimatic, geophysical and edaphic characteristics. Ecogeographic diversity is used as a proxy for genetic diversity of the priority CWR species in the complementarity conservation analysis. The ELC data analysis was undertaken with Capfitogen ELC map tool, DIVA (Hijmans *et al.*, 2012) and ArcGIS 10.3.1. (ESRI, 2015).

different ELC zones, representing the unique ecogeographic diversity of the species in that zone. The second site was the area of the Tornio and Muonio rivers in Northern Finland, a large natural-state river system bordering Sweden. The PA had three ELC zones with 59 complementary target taxa not present in the first site. The third was the Lista Wetlands system, Norway with 46 complementary taxa in two ELC zones. The fourth site was in the Tammisaari and Hanko Archipelago and Pojo Bay marine protection area, Finland, and included three ELC zones containing 42 complementary taxa not present in previous sites. The total number of target taxa in the site was 86.

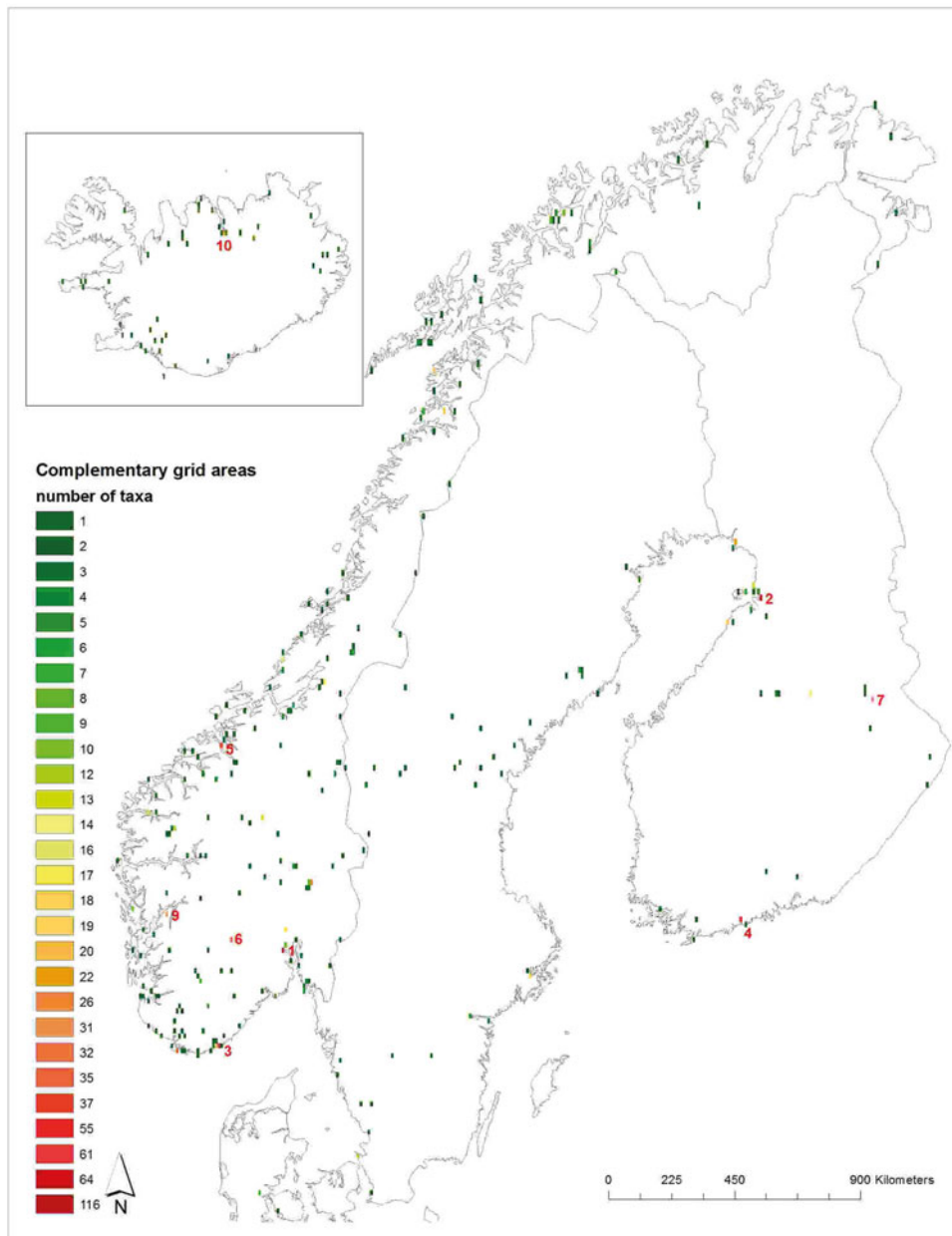
The 83 target species have altogether 822 taxon–ELC zone combinations (online Supporting information 7). The number of target species observations varied from 1 to 25,779, depending on the distribution of the species in the PAs and the ELC zones. The importance of ensuring that viable populations are conserved and maintained in genetic reserves is described by Iriondo *et al.* (2012). With a sufficient number

of populations, a taxon is less likely to be destroyed when facing possible adverse effects *in situ*. If observations are counted as populations and a minimum number of target species populations in *in situ* conservation is set for five populations (Brown and Briggs, 1991; Dulloo *et al.*, 2008), 554 out of 822 taxon–ELC zone populations in this study fulfil these criteria. When looking at numbers of species populations in all of the 26 ELC zones, there are only six species (*Brassica nigra* (L.) W. D. J. Koch, *Lactuca quercina* L., *Lactuca tatarica* (L.) C. A. Mey., *Prunus mahaleb* L., *Rubus allegheniensis* Porter ex L. H. Bailey, *Rubus spectabilis* Pursh) having fewer than five populations present in the complementary PAs.

## Discussion

### *Advantage of Nordic regional planning*

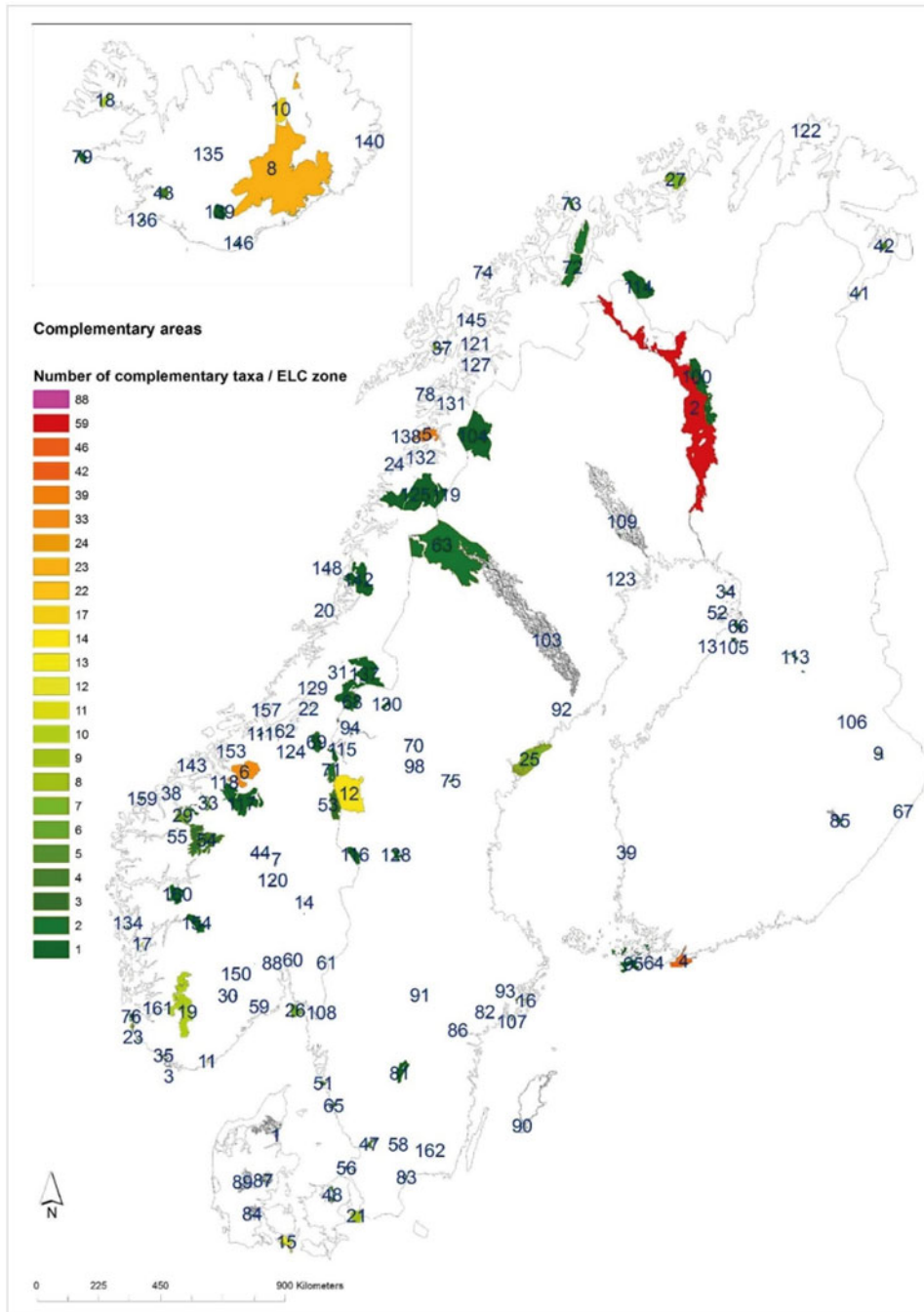
The results of the floristic analysis of the checklist showed that the same species were largely shared across



**Fig. 3.** The grid cell complementary network map for the Nordic priority CWR. This map shows the lowest number of geographical grids that can conserve the intraspecific diversity of the target taxa when the ecogeographic diversity is taken as a proxy for genetic diversity. The top 10 cells, containing the largest number of complementary taxa, are labelled. The colour represents the number of CWR priority taxa found in each grid. Detailed information of the sites and species numbers in each location can be found in Supporting information 6. The ELC data analysis was undertaken using Capfitogen ELC map tool, DIVA (Hijmans *et al.*, 2012) and ArcGIS 10.3.1. (ESRI, 2015). The Nordic region boundary layers are from Natural Earth data (2016).

the Nordic countries and a majority of the prioritized CWR have a wide distribution in the Nordic region. Approximately 80% of the priority taxa are distributed in four or five of the Nordic countries. Similar climate zones and photoperiodic conditions are found across the Nordic countries and the breeding activities and interests are relatively similar. The existence of a working regional

administrative body, the Nordic Council of Ministers, as well as a regional gene bank for *ex situ* conservation, NordGen, adds to the rationale for the Nordic regional approach for planning *in situ* conservation of CWR. However, the integration of national, regional and global CWR conservation strategies, as described by Maxted *et al.* (2015), is important. Ideally, these levels should



**Fig. 4.** The protected area complementary network map for the Nordic priority CWR. This map shows the protected areas where the intraspecific diversity of the target taxa could be conserved when the ecogeographic diversity is taken as a proxy for genetic diversity. The sites are marked in a complementary order, starting from the site which has highest number of species–ELC combinations. Detailed information on the sites and species numbers in each location can be found in Supporting information 6. The colours represent the number of complementary taxa per ELC zone (= ELC category as seen in Fig. 2). The ELC data analysis was undertaken with Capfitogen ELC map tool, DIVA (Hijmans *et al.*, 2012) and ArcGIS 10.3.1. (ESRI, 2015). The Nordic region boundary layers are taken from Natural Earth data (2016).

complement and reinforce each other. Other conservation approaches have previously been successfully integrated into a multi-level system, such as the Natura 2000 network in Europe.

### ***Nordic species checklist and priority list***

The Nordic species checklist is an extensive list including all CWR species connected to food and fodder crops in



the region (Fitzgerald *et al.*, 2017a). It is publically available and can be used both for national planning in each of the Nordic countries and regional planning on the Nordic level as well as into larger scale regional (European) and global conservation planning and analysis.

Prioritizing among taxa on the checklist provided a more cost-effective way to plan *in situ* conservation on both national and regional levels. The most important CWR species of the region, regarding value and utilization potential, have been included in the priority list. We argue that the Nordic region has a collective responsibility to conserve the priority CWR growing in the region. These are, for example, the wild relatives of cultivated berries, forages and vegetable species.

### **Identifying Nordic *in situ* conservation sites**

The results from the complementarity conservation analysis suggest how priority CWR could be conserved *in situ*. A complementarity approach in conservation planning and reserve selection is a widely used method in designing conservation area networks (Rebelo, 1994; Margules and Pressey, 2000; Kukkala and Moilanen, 2012). Genetic reserves are conservation areas set up with the specific purpose of long-term conservation of genetic diversity, and quality standards have been set up on how to best conserve CWR in genetic reserves (Iriondo *et al.*, 2012). We took two approaches in planning the regional *in situ* genetic reserve network for Nordic countries: the grid cell complementary network and the PA complementary network. In both options, we used the ELC map of the region to identify not only complementary areas to conserve target CWR species, but to maximize ecogeographic diversity, to better capture and conserve potential intraspecific diversity based on presumed adaptation to diverse environments.

In the grid cell complementary analysis, many top cells (geographic areas having the highest CWR diversity) were situated near larger cities, a partial result of an observation bias. Overall, the cells were situated relatively evenly over the region. However, the number of cells in southern and western Norway exceeded the number of cells in other countries. Even the least observed area Finnmark, northern Norway, had several complementary cells. This can be attributed to the distribution pattern of ELC zones over the region and Norway having more ELC zones. This may be further explained by Norway demonstrating more variation in the selected climatic, ecological and geographical variables than other countries. Iceland had more ELC categories than either Denmark, Finland or Sweden. Iceland had a relatively large number of complementary cells considering that fewer target species occur in Iceland than in other countries. This was at least partly due to several

unique ELC categories. Whereas the land areas of Sweden and Finland were more homogeneous, there was still a distinct division into several different ELC zones. Denmark, however, is covered by only one ELC zone. In conclusion, it is not possible to aim for even geographic distribution of complementary cells in the analysis as the bioclimatic conditions along with the observation level and distribution of species determine the locations of the cells. If the grid cell approach was to be developed further, a closer look at the urbanization and land use would show where the genetic reserves could be situated since many high diversity cells are located within, or in the vicinity of, larger cities.

The goal of the PA complementary network analysis was to identify sites for genetic reserves within existing PAs. The genetic reserve sites were located relatively evenly around the region. However, the southern and western parts of Norway and Sweden seemed to have a dense network of complementary sites. While the top sites had the highest number of complementary species, the entire network of sites is important because each ELC class represents a specific environment, thus valuable for capturing specific ecotypic variation. Some sites with fewer complementary species nevertheless had a large total number of species. Furthermore, the proposed sites were located within designated PAs. The PA network approach had the advantage that it identified CWR species in already established conservation sites and therefore no new conservation areas need to be established. However, if a PA is to be established as a genetic reserve, a more detailed study would need to be conducted to determine the most appropriate PAs to support such a reserve, validate and inventory CWR species within the PA, identify the most appropriate populations to conserve and establish management and monitoring plans for the populations according to available guidelines (such as Iriondo *et al.*, 2012).

### **Conservation recommendations**

In conclusion, based on the results of the analysis, we suggest the following conservation measures for Nordic CWR:

- Investigate how to continue to harmonize future regional and national conservation actions in the Nordic countries with an aim of implementing more efficient conservation actions;
- Increase efforts to collect distribution data of target species, especially in insufficiently sampled areas and for species which have fewer than five populations in the complementary PA network;
- Assess the suitability of the PAs found to be complementary sites for CWR species, for establishment of genetic reserves;

- As a first step, establish one genetic reserve per Nordic country to gain experience, evaluate currently suggested management plans and policy constraints; and
- Ensure free and open access to CWR data sources for open validation and reuse of species occurrence data for other purposes through platforms such as the GBIF.

Currently, there is an ongoing process to produce a common Nordic report on conservation planning, including recommendations on future *in situ* as well as *ex situ* actions to safeguard the CWR genetic resources in the region. It will be available via the Nordic CWR homepage (<http://www.nordgen.org/cwr>) where other CWR information and conservation planning tools can be found. A policy brief has been produced focusing on CWR and actions needed in the Nordic region to assure long-term conservation of CWR ([http://www.nordgen.org/ngdoc/NordicCWR\\_2016/Policy%20brief.pdf](http://www.nordgen.org/ngdoc/NordicCWR_2016/Policy%20brief.pdf)).

## Supplementary material

The supplementary material for this article can be found at <https://doi.org/10.1017/S147926211800059X>.

## Acknowledgements

We would like to thank the Nordic Council of Ministers for providing funding; Mora Aronsson for providing taxonomic data and assistance; Raino Lampinen, Pawel Wasowicz and GBIF for providing species distribution data; Mauricio Parra-Quijano for technical assistance with Capfitogen tools and Jade Phillips for assistance in diversity analysis.

## References

- Alercia A, Diulgheroff S and Mackay M (2012) *FAO/Bioversity Multi-Crop Passport Descriptors V.2 [MCPD V.2]*. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO); Rome, Italy: Bioversity International, 11 p. Available at [http://www.bioversityinternational.org/fileadmin/user\\_upload/online\\_library/publications/pdfs/FAO-Bioversity\\_multi\\_crop\\_passport\\_descriptors\\_V\\_2\\_Final\\_rev\\_1526.pdf](http://www.bioversityinternational.org/fileadmin/user_upload/online_library/publications/pdfs/FAO-Bioversity_multi_crop_passport_descriptors_V_2_Final_rev_1526.pdf).
- Bebber D, Ramotowski M and Gurr S (2013) Crop pests and pathogens move polewards in a warming world. *Nature Climate Change* 3: 985–988.
- Brown AHD and Briggs JD (1991) Sampling strategies for genetic variation in *ex situ* collections of endangered plant species. In: Falk DA and Holsinger KE (eds) *Genetic and Conservation of Rare Plants*. New York: Oxford University Press, pp. 99–119.
- CBD (2010) *Strategic Plan for Biodiversity 2011–2020 and the Aichi Biodiversity Targets*. United Nations, Montreal, Canada: Secretariat of the Convention on Biological Diversity: <http://cbd.int/sp> (Accessed: 10/09/2017).
- Crop Trust (2016) *The Harlan and de Wet Crop Wild Relative Inventory*. Germany: Global Crop Diversity Trust. <https://www.cwrdiversity.org/checklist/> (Accessed 31/02/2016).
- Dempewolf H, Baute G, Anderson J, Kilian B, Smith C and Guarino L (2017) Past and future use of wild relatives in crop breeding. *Crop Science* 57: 1070–1082.
- Dulloo ME, Labokas J, Iriondo JM, Maxted N, Lane A, Laguna E, Jarvis A and Kell SP (2008) Genetic reserve location and design. In: Iriondo JM, Maxted N and Dulloo ME (eds) *Conserving Plant Genetic Diversity in Protected Areas*. Wallingford: CABI Publishing, pp. 23–64.
- Dyntaxa (2016) *Swedish Taxonomic Database*. <http://www.dyntaxa.se> (Accessed: 15/1/2016).
- ESRI (2015) *ArcGIS Desktop: Release 10.3.1*. Redlands, CA: Environmental Systems Research Institute.
- EU (2016) *Plant Variety Catalogues, Databases & Information Systems for Agricultural and Vegetable species*. EU database of registered plant varieties, European commission. Available at [https://ec.europa.eu/food/plant/plant\\_propagation\\_material/plant\\_variety\\_catalogues\\_databases\\_en](https://ec.europa.eu/food/plant/plant_propagation_material/plant_variety_catalogues_databases_en) (Accessed 7/1/2016).
- FAO (2001) *International Treaty on Plant Genetic Resources for Food and Agriculture, Annex I Taxa*. Food and Agriculture Organization of the United Nations. <http://www.planttreaty.org/> (Accessed 10/9/2017).
- FAO (2005) Alphabetical list of crops with botanical name and crop code. In: *A System of Integrated Agricultural Censuses and Surveys, World Programme for the Census of Agriculture, Volume 1*. Rome: FAO Statistical Development Series, FAO. [http://www.fao.org/fileadmin/templates/ess/documents/world\\_census\\_of\\_agriculture/appendix4\\_r7.pdf](http://www.fao.org/fileadmin/templates/ess/documents/world_census_of_agriculture/appendix4_r7.pdf) (Accessed 1/11/2016).
- FAO (2011) *Second Global Plan of Action for Plant Genetic Resources for Food and Agriculture. Commission on Genetic Resources for Food and Agriculture*. Rome, Italy: Food and Agriculture Organisation of the United Nations, FAO. ISBN 978-92-5-107163-2. <http://fao.org/docrep/015/i2624e/i2624e00.pdf>.
- FAO (2015) *FAOSTAT*. Rome, Italy: Statistics Division, Food and Agriculture Organization of the United Nations. <http://www.fao.org/faostat/en/#home> (Accessed 1/11/2015).
- FAO (2016) *The State of Food and Agriculture – Climate Change, Agriculture and Food Security*. Food and Agriculture Organization of United Nations, FAO. ISBN 978-92-5-109374-0. Available at <http://www.fao.org/3/a-i6030e.pdf>.
- Feedipedia (2016) *Forage Genera List, Animal Feed Resources Information System*. INRA CIRAD AFZ and FAO 2012–2015. <http://www.feedipedia.org> (Accessed 9/1/2016).
- Fick SE and Hijmans RJ (2017) Worldclim 2: new 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology* 37: 4302–4315.
- Fitzgerald H, Aronsson M, Asdal Å, Endresen D, Kiviharju E, Lund B, Palmé A, Rasmussen M, Weibull J and Porbjörnsson H (2017a) *Nordic Crop Wild Relative Checklist Dataset, Version 1.10*. Nordic Genetic Resource Center, NordGen. Available at <https://doi.org/10.15468/itktype>.
- Fitzgerald H, Aronsson M, Asdal Å, Endresen D, Kiviharju E, Lund B, Palmé A, Lund B, Rasmussen M, Weibull J and Porbjörnsson H (2017b). *The Nordic priority crop wild relative gene pool and distribution dataset*. Available at <https://doi.org/10.6084/m9.figshare.5688130.v1>.
- Ford-Lloyd BV, Schmidt M, Armstrong SJ, Barazani O, Engels J, Hadas R, Hammer K, Kell S, Kang D, Khoshbakht K, Li Y, Long C, Lu B, Ma K, Nguyen VT, Qiu L, Ge S, Wei W, Zhang Z and Maxted N (2011) Crop wild relatives – undervalued, underutilized and under threat? *BioScience* 61: 559–565.

- GBIF (2016a) *Norway occurrence data*. GBIF.org (27th May 2016) GBIF Occurrence Download <http://doi.org/10.15468/dl.heawlj>.
- GBIF (2016b) *Sweden occurrence data*. GBIF.org (27th May 2016) GBIF Occurrence Download <http://doi.org/10.15468/dl.z7jfhf>.
- GBIF (2016c) *Denmark occurrence data*. GBIF.org (27th May 2016) GBIF Occurrence Download <http://doi.org/10.15468/dl.i1smvp>.
- GBIF (2016d) *Iceland occurrence data*. GBIF.org (27th May 2016) GBIF Occurrence Download <http://doi.org/10.15468/dl.awmou9>.
- Groombridge B and Jenkins MD (2002) Appendix 2: Important food crops. In: *World Atlas of Biodiversity*. Berkeley, USA: UNEP World Conservation Monitoring Centre, University of California Press, pp. 244–270.
- Hargreaves S, Maxted N, Hirano R, Abberton M, Skøt L and Ford-Lloyd B (2010) Islands as refugia of *Trifolium repens* genetic diversity. *Conservation Genetics* 11: 1317–1326.
- Harlan J and de Wet J (1971) Towards a rational classification of cultivated plants. *Taxon* 20: 509–517.
- Hartvig P ed. (2015) *Atlas Flora Danica, volume 1-3*. Dansk Botanisk Forening, Gyldendal, Denmark. p. 1565. <http://atlasfloradantica.dk/>.
- Helgadóttir Á, Østrem L, Collins RP, Humphreys M, Marshall A, Julier B, Gastal F, Barre P and Louarn G (2016) Breeding forages to cope with environmental challenges in the light of climate change and resource limitations. In: Roldán-Ruiz I, Baert J and Reheul D (eds) *Breeding in a World of Scarcity*. Cham: Springer, pp. 3–14. doi: 10.1007/978-3-319-28932-8\_1.
- Hijmans RJ, Cameron SE, Parra JL, Jones PG and Jarvis A (2005) Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology* 25: 1965–1978.
- Hijmans R, Guarino L and Mathur P (2012) *DIVA-GIS. Version 7.5*. A geographic information system for the analysis of species distribution data. <http://www.diva-gis.org> (Accessed October 2016).
- HWS Database (2012) *Harmonized World Soil Database, Version 1.2*. Rome, Italy: IIASA; Luxembourg, Austria: FAO/IIASA/ISRIC/ISSCAS/JRC. FAO. <http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/> (Accessed 10/09/2016).
- Icelandic Institute of Natural History (2016) *Database of the Icelandic Institute of Natural History*. <http://en.ni.is/botany/>.
- IPCC (2007) Especially affected systems, sectors and regions. In: *Climate Change 2007: Synthesis Report*. A Contribution of Working Groups I, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Geneva, Switzerland: IPCC.
- IPCC (2014) Summary for policymakers. In: Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR and White LL (eds) *Climate Change 2014: Impacts, Adaptation, and Vulnerability*. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University, pp. 1–32.
- IPK (2003) *Mansfeld's World Database of Agricultural and Horticultural Crops*. Leibniz Institute of Plant Genetics and Crop Plant Research. Available from <http://mansfeld.ipk-gatersleben.de/apex/f?p=185:3:0>.
- Iriondo JM, Maxted N, Kell SP, Ford-Lloyd BV, Lara-Romero C, Labokas J and Magos Brehm J (2012) Identifying quality standards for genetic reserve conservation of CWR. In: Maxted N, Dulloo ME, Ford-Lloyd BV, Frese L, Iriondo JM and Pinheiro de Carvalho MAA (eds) *Agrobiodiversity Conservation: Securing the Diversity of Crop Wild Relatives and Landraces*. Wallingford, UK: CAB International, pp. 72–77.
- Jarvis A, Lane A and Hijmans R (2008a) The effect of climate change on crop wild relatives. *Agriculture, Ecosystems & Environment* 126: 13–23.
- Jarvis A, Reuter HI, Nelson A and Guevara E (2008b) *Hole-filled SRTM for the globe. Version 4*, Available from the CGIAR-CSI SRTM 90 m Database. <http://srtm.csi.cgiar.org> (Accessed 10/9/2016).
- Juhola S, Kleinc N, Käyhkö J and Schmid Neset T (2017) Climate change transformations in Nordic agriculture? *Journal of Rural Studies* 51: 28–36.
- Kalliola R (1973) *Suomen kasvimaantiede*. Helsinki: WSOY, 308 p.
- Kang Y, Khan S and Ma X (2009) Climate change impacts on crop yield, crop water productivity and food security – a review. *Progress in Natural Science* 19: 1665–1674.
- Kristinsson HG (1998) *Flowering Plants and Ferns of Iceland*. Iceland: Mal og Menning.
- Kell SP, Ford-Lloyd BV, Magos Brehm J, Iriondo JM and Maxted N (2017). Broadening the base, narrowing the task: prioritizing crop wild relative taxa for conservation action. *Crop Science* 57: 1042–1058.
- Khoury CK, Achicanoy HA, Bjorkman AD, Navarro-Racines C, Guarino L, Flores-Palacios X, Engels J, Wiersema J, Dempewolf H, Ramírez-Villegas J, Castañeda-Álvarez N, Fowler C, Jarvis A, Rieseberg L and Struik P (2013) *Estimation of Countries' Interdependence in Plant Genetic Resources Provisioning National Food Supplies and Production Systems*. The International Treaty on Plant Genetic Resources for Food and Agriculture, FAO, Research Study 8. 26 p. <http://www.fao.org/3/a-bq533e.pdf>
- Kukkala AS and Moilanen A (2012) Core concepts of spatial prioritisation in systematic conservation planning. *Biological Reviews* 88: 443–464.
- Lampinen R and Lahti T (2016) *Kasviatlas*. Helsinki, Finland: Helsinki University, Finnish Natural History Museum. <http://koivu.luomus.fi/kasviatlas>. (Accessed 07/09/2016).
- Lid J and Lid DT (2005) *Norsk flora*, 7th edn. Oslo: Det Norske Samlaget.
- Lesica P and Allendorf FW (1995) When are peripheral populations valuable for conservation? *Conservation Biology* 9: 753–760.
- Lindner M, Maroschek M, Netherer S, Kremer A, Barbati A, Garcia-Gonzalo J, Seidl R, Delzon S, Corona P, Kolström M, Lexer MJ and Marchetti M (2010) Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *Forest Ecology and Management* 259: 698–709.
- Margules CR and Pressey RL (2000) Systematic conservation planning. *Nature* 405: 243–253.
- Maxted N (2003) Conserving the genetic resources of crop wild relatives in European Protected Areas. *Biological Conservation* 113: 411–417.
- Maxted N and Kell SP (2009) *Establishment of A Global Network for the in Situ Conservation of Crop Wild Relatives: Status and Needs*. Rome: Commission on Genetic Resources for Food and Agriculture, FAO. <http://www.fao.org/docrep/013/i1500e/i1500e18d.pdf>.

- Maxted N, Hawkes JG, Hawkes JG and Williams JT (1997) A practical model for *in situ* genetic conservation. In: Maxted N, Ford-Lloyd BV and Hawkes JG (eds) *Plant Genetic Conservation: the in situ Approach*. London: Chapman and Hall, pp. 339–367.
- Maxted N, Ford-Lloyd BV, Jury S, Kell S and Scholten M (2006) Towards a definition of a crop wild relative. *Biodiversity and Conservation* 15: 2673–2685.
- Maxted N, Dulloo E, Ford-Lloyd B, Iriondo J and Jarvis A (2008) Gap analysis: a tool for complementary genetic conservation assessment. *Diversity and Distributions* 14: 1018–1030.
- Maxted N, Magos Brehm J. and Kell SP (2013) *Resource Book for Preparation of National Conservation Plans for Crop Wild Relatives and Landraces*. FAO Commission on Genetic Resources for Food and Agriculture. [http://www.fao.org/fileadmin/templates/agphome/documents/PGR/PubPGR/ResourceBook/TEXT\\_ALL\\_2511.pdf](http://www.fao.org/fileadmin/templates/agphome/documents/PGR/PubPGR/ResourceBook/TEXT_ALL_2511.pdf)
- Maxted N, Avagyan A, Frese L, Iriondo JM, Magos Brehm J, Singer A and Kell SP (2015) *Concept for in Situ Conservation of Crop Wild Relatives of Crop Wild Relatives in Europe*. Wild species conservation in genetic reserves working group, European Cooperative Program for Plant Genetic Resources. [http://www.ecpgr.cgiar.org/fileadmin/templates/ecpgr.org/upload/WG\\_UPLOADS\\_PHASE\\_IX/WILD\\_SPECIES/Crop\\_Wild\\_Relatives\\_of\\_Crop\\_Wild\\_Relatives\\_in\\_Europe.pdf](http://www.ecpgr.cgiar.org/fileadmin/templates/ecpgr.org/upload/WG_UPLOADS_PHASE_IX/WILD_SPECIES/Crop_Wild_Relatives_of_Crop_Wild_Relatives_in_Europe.pdf).
- Natural Earth data (2016) *Admin – Countries, version 3.1.0*. <http://www.naturalearthdata.com/downloads/10m-cultural-vectors/> (Accessed 13/10/2016).
- NordGen (2016) NordGen forage lists: A list of species classified as forages at NordGen and the current list of prioritised forage species from the forage working group at NordGen.
- Parra-Quijano M (2016) *CAPFITOGEN Tools, Program to Strengthen Capabilities in National Plant Genetic Resources Programs in Latin America, Version 2.0*. International Treaty on Plant Genetic Resources for Food and Agriculture, FAO. <http://www.capfitogen.net/en/> (Accessed 10/09/2016).
- Parra-Quijano M, Iriondo JM and Torres ME (2012) Ecogeographical land characterization maps as a tool for assessing plant adaptation and their implications in agrobiodiversity studies. *Genetic Resources and Crop Evolution* 59: 205–217.
- Parra-Quijano M, Torres E, Iriondo JM and López F (2014) *CAPFITOGEN Tools User Manual Version 1.2*. Rome, Italy: International Treaty on Plant Genetic Resources for Food and Agriculture, FAO, 138p. ISBN 978-92-5-108493-9
- 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: 1112–1126.
- Rebello AG (1994) Iterative selection procedures: centres of endemism and optimal placement of reserves. In: Huntley BJ (ed.) *Botanical Diversity in Southern Africa*. Pretoria: National Botanical Institute, pp. 231–257.
- Reuter HI, Nelson A and Jarvis A (2007) An evaluation of void filling interpolation methods for SRTM data. *International Journal of Geographic Information Science* 21: 983–1008.
- Rosenzweig C and Parry ML (1994) Potential impact of climate change on world food supply. *Nature* 367: 133–138.
- USDA (2016) World Economic Plants in GRIN. Online Database, GrinGlobal version 1.9.9.2 <https://npgsweb.ars-grin.gov/gringlobal/taxon/taxonomysearcheco.aspx> (Accessed 10/3/2016).
- Vincent H, Wiersema J, Dobbie S, Kell S, Fielder H, Castaneda N, Guarino L, Eastwood R, Leon B and Maxted N (2013) A prioritized crop wild relative inventory to help underpin global food security. *Biological Conservation* 167: 265–275.
- Worldclim (2016) *Worldclim – Global Climate Data. Version 1.4*. Berkeley: Museum of Vertebrate Zoology, University of California. <http://www.worldclim.org> (Accessed 10/9/2016).
- Whittaker RJ and Fernandez-Palacios JM (2007) *Island Biogeography: Ecology, Evolution, and Conservation*. 2nd edn. New York: Oxford University Press.
- UNEP-WCMC and IUCN (2016) *Protected Planet, the World Database on Protected Areas*. Cambridge, UK: United Nations Environment World Conservation Monitoring Centre (UNEP-WCMC) and IUCN. Available at: [www.protectedplanet.net](http://www.protectedplanet.net) (Accessed 30/11/2016).