

SEED PLANTS IN THE ARCTIC

A prioritisation for seed banking



Egil Skånberg Dahlstedt

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Supervisor: Anne D. Bjorkman, BioEnv & Stina Weststrand, Gothenburg botanical gardens

Examiner: Daniel Zuleta, BioEnv

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Abstract

Seed banking has emerged as a successful strategy to safeguard against the extinction of plant species, as banked seeds are viable for up to hundreds of years and can be used in species reintroductions and habitat restoration. Due to the Arctic warming more rapidly than the global average, which is difficult for conservationists to combat, some plant species growing there may be important targets for seed banks to conserve. The changes brought to Arctic ecosystems by climate change have already been widely documented, but many species-level responses have not been reported. There also remains a considerable gap in the coverage of threatened species in existing *ex-situ* collections. The aim of this study is to inform conservationists of species that should be prioritised for seed collection in the Arctic. I combine red list assessments, data on existing seed bank collections, species' ecological information and socioeconomic relevance. Additionally, I analyse long-term vegetation monitoring data from 38 different sites in the Nordic Arctic using Generalised Linear Mixed Models (GLMMs) and reveal abundance trends for 211 seed plant species. I apply a scoring system to the compiled data to identify gaps and priorities for *ex-situ* conservation. The result was a dataset of 3010 Arctic seed plant species and a ranking of their relative priority. In the abundance-trend analysis, most species exhibited mixed or no trends and more species increased than declined. The trends of rare, vulnerable species were possibly clouded by a lack of data. The prioritisation list can be used to plan seed collection expeditions in the Arctic. Furthermore, the criteria and scoring used to develop the ranking can be tweaked for specific collection foci or be applied to data from other regions in order to support the mission of the world's steadily growing number of seed banks.

Keywords: Seed banking, conservation prioritisation, Arctic ecological change, ITEX analysis, climate change

Introduction

Seed banks and *ex-situ* conservation

The biodiversity of the world's ecosystems is in crisis, as human actions are causing species' populations to decline, reducing their genetic diversity, altering the structure and composition of ecosystems and increasing the global rate of extinction (IPBES, 2019). In addition to the extinctions that have already occurred, there is widespread concern that an extinction debt waits to be repaid following damages done to species populations and habitats, as well as effects of climate change increasing in severity (Kuussaari et al., 2009; Urban, 2024). Climate change is a major threat to biodiversity, especially in Arctic and subarctic environments, which are experiencing warming of two to four times the global average (Conradi et al., 2024; IPCC, 2023; Rantanen et al., 2022). The resulting changes in Arctic plant communities are already being widely recorded (Bjorkman et al., 2020; Elmendorf et al., 2015; García Criado, Myers-Smith, et al., 2025), and continued warming is predicted to cause widespread range contractions and even losses of Arctic and subarctic species (Niskanen et al., 2019). Such changes in Arctic- and tundra vegetation can alter carbon cycles and induce climate feedbacks, potentially with global effects (Callaghan et al., 2004).

Given the large number of techniques available for conserving species, threats of species extinctions could be prevented (Smith et al., 2011). *Ex-situ* conservation is the safeguarding of species at locations other than in their natural habitat, either by maintaining live specimens in zoos or botanical gardens, or by keeping living material such as seeds, sperm, eggs, tissue or genetic material in gene banks (IUCN/SSC, 2014). Storing plant seeds has been part of agricultural practices for millennia, which extended into the previous focus of modern seed banks on crops and economically important species (Cohen et al., 1991; Nair, 2019). Today, however, seed banking is being recognised as an effective resource for the conservation of wild plant biodiversity as well, applied in species reintroductions, habitat restorations and reinforcements of wild populations (Chapman et al., 2019; Sharrock, 2020; White, Ensslin, et al., 2023). Alongside *in-situ* methods, *ex-situ* conservation is included in Target 4 of the current phase of the Global Strategy for Plant Conservation (GSPC), adopted by the Convention on Biological Diversity (CBD; GSPC, 2025). A review of the preceding phase of the GSPC, however, found that progress towards increasing *ex-situ* conservation efforts was limited, partly due to initiatives still not considering their application, despite habitat degradation and loss as well as climate change threatening the future viability of *in-situ* methods for many species (Sharrock, 2020).

Compared with *in-situ* methods, *ex-situ* methods are in many cases more cheaply and effectively able to preserve genetic diversity for the future, with one estimate of them taking 1% of the cost of conserving a species *in-situ*, and seeds being able to germinate after hundreds of years in some cases (Li & Pritchard, 2009). Nevertheless, the effective use of *ex-situ* collections involves them being available to support *in-situ* efforts (GSPC, 2025).

Through storing seeds of Crop Wild Relatives (CWR), seed banks can act as genetic libraries for advanced breeding programmes harnessing genetic resources possessed by wild, naturally evolving populations (Breman et al., 2021). As the changing climate poses a big threat to the global food supply, more resilient cultivars of crops need to be developed (FAO, 2016). This focus for *ex-situ* conservation is likewise encouraged by the previously mentioned Target 4 of the GSPC (GSPC, 2025). Since the Nordic countries constitute the edge of many species' distributions and due to their extreme climatic conditions, it is speculated that populations growing there could potentially harbour unique adaptations, useful to aforementioned programmes (Fitzgerald et al., 2019). With the same reasoning, some Nordic Arctic populations would be particularly important genetically.

The role of seed banks as genetic libraries can also be invaluable to science. By providing a record of the spatial and even temporal diversity of plant species, some collections can be used in studies of short-term evolution, including the effects of climate change (Mattana et al., 2025). Although this also means that resurrected seeds from old collections run the risk of being maladapted to changed conditions since they were collected, especially in quickly changing environments such as the Arctic and alpine regions (Mattana et al., 2025; White, Rosbakh, et al., 2023), highlighting the need to continually replenish collections.

Although the world's seed banks for wild species have already done much for conservation, threatened species are still underrepresented in their collections. A 2017 study reported that over 100,000 species are held in the world's botanical gardens and the seed collections they curate, which amounts to 30% of known plant species (Mounce et al., 2017). The largest of these is the Millennium Seed Bank (MSB) of the Royal Botanic Gardens in Wakehurst, England, and its partnership network, with 40,000 species represented across 97,000 accessions and over 2.4 billion seeds (Royal Botanic Gardens, Kew, n.d.). Albeit impressive coverage, several studies have pointed out that species classified as threatened by global or regional red lists are underrepresented in the world's seed bank collections (Dhanjal-Adams et al., 2026; Mounce et al., 2017; O'Donnell & Sharrock, 2017), despite reasonable notions that these should be a main focus for conservation efforts (GSPC, 2025). A recent study found that a mere 7% of all critically endangered taxa were stored in the MSB or its partnerships, and only 9% of these collected taxa met seed number requirements (Dhanjal-Adams et al., 2026). Seed banks need to store sufficiently large and genetically diverse collections of threatened species for them to be successful in reintroductions and reinforcements (Hoban & Schlarbaum, 2014; Mounce et al., 2017).

Arctic plants and climate change

Arctic and alpine tundra ecosystems are adapted to cold climates and are thus sensitive to increasing temperatures, which in combination with the amplified rate of warming in the Arctic places them at high risk from climate change (Bjorkman et al., 2020; IPCC, 2023; Rantanen et al., 2022). Vegetation monitoring has shown that treelines are advancing and that shrubs are expanding due to climate change (García Criado et al., 2020; Harsch et al., 2009; Myers-Smith & Hik, 2018). Increased shrub cover negatively affects species richness (Boscutti et al., 2018), and threatens to displace rarer, less competitive species (García Criado, Myers-Smith, et al., 2025). Moreover, changes in community structure can alter biotic interactions, potentially leading to even more declines of ecologically important species (García Criado, Myers-Smith, et al., 2025; Myers-Smith & Hik, 2018). Cold-requiring species in alpine environments have been found to be less resilient than more warm tolerant ones (Rumpf et al., 2018). A study analysing 164 Arctic and alpine species' distributional changes in Fennoscandia in response to warming predicted a mean range reduction of 60% by 2100 in the best-case scenario, with the majority of species losing more than half of their range, and some even all of it (Niskanen et al., 2019). The most negatively affected species were those with a range centred in the northernmost part of Fennoscandia.

The threat of climate change to ecosystems poses a different challenge to conservation than the more direct threats of land-use change and overexploitation, for example. The ways in which species can survive climate change are either through migrating to follow the shifting climate, or to adapt to the new conditions, both of which can be constrained by for example dispersal ability and lack of time or genetic variation to adapt (for a review, see Christmas et al., 2016). Conservationists can help through assisted migration (Vitt et al., 2010), but high Arctic and alpine species inhabit the extreme edge; beyond their environments there is no habitat which will be made suitable for them through warming, especially in northern Fennoscandia, which does not extend past 71°N. *Ex-situ* conservation of seeds is a viable safeguard against the complete loss of species

and can be used in translocations to suitable habitats or for long-term storage awaiting better knowledge or conditions (Vitt et al., 2010).

The number of seed banks for wild species and the size of their collections is increasing (O'Donnell & Sharrock, 2017), and with them our capacity to save threatened plant species and populations from extinction. But gaps remain regarding these threatened species (Dhanjal-Adams et al., 2026; Mounce et al., 2017). Collections of non-threatened species can also be very important as genetic resources for crops and for research (Breman et al., 2021; Mattana et al., 2025). Taking such different priorities into account, what species should new collections target to maximise their value? As Arctic and alpine ecosystems are particularly vulnerable to climate change, for which other methods of conservation are limited, they constitute an important area of focus for *ex-situ* efforts. Previous studies of the effects of climate change on Arctic plant ecosystems have mostly looked at changes in ecosystem structure, and do not provide any guidance for conservationists beyond which functional groups are disadvantaged. The aim of this study is to produce a prioritisation list of species for *ex-situ* conservation efforts in the Arctic. By identifying criteria and metrics important for conservation priority and answering questions regarding species-specific responses to global warming, I aim to pinpoint species particularly important for conservationists to target in future seed collections.

Method

Study area

There is no universally agreed upon definition of the Arctic. Here, the geographic boundary of Conservation of Arctic Flora and Fauna (CAFF) was used, whose intersection with the Nordic countries served as the study area (Figure 1).

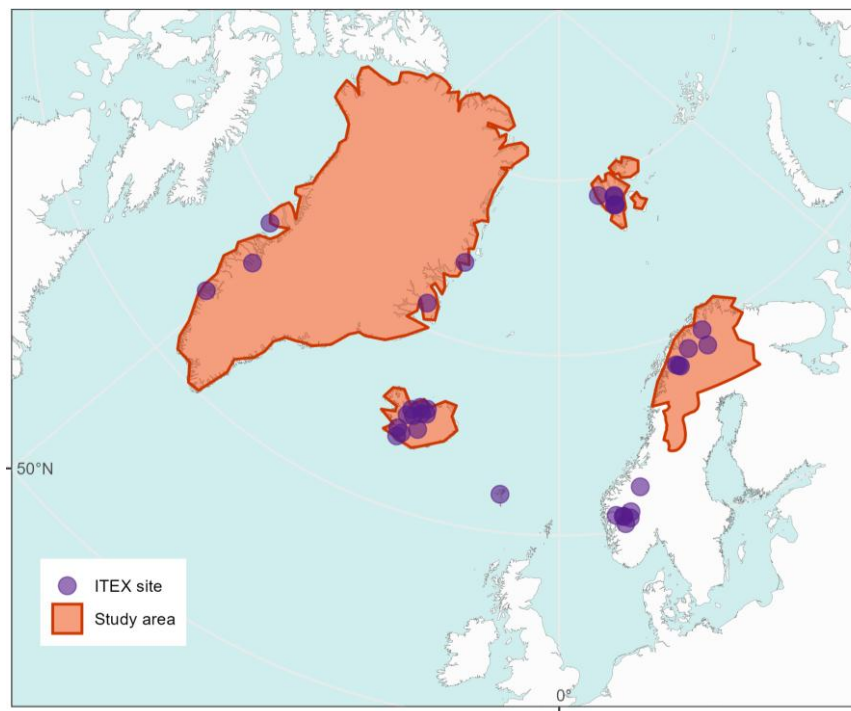


Figure 1 Map of the study area and locations of ITEX sites

Analysis of abundance trends

International Tundra Experiment

In order to estimate species-specific changes in abundance over time, I analysed data from International Tundra Experiment (ITEX; Henry & Molau, 1997), an international long-term collaboration monitoring vegetation change in the Arctic. The data comes from vegetation surveys conducted in different places and time intervals across the Arctic since the 1980s. It is hierarchical in nature; sites located in different countries and at different latitudes contain several subsites, often in different habitat types, which in turn harbour several plots (the sampled unit) of a scale of up to ca 1 m². The original data includes experimentally warmed plots as well as control plots. Here, only the control plots were included, and only sites from the Nordic countries (Greenland, Iceland, Faroe Islands, Svalbard, Norway, Sweden and Finland) were analysed (Figure 1). This included alpine sites in Norway located outside the study area, but as their species pools are very similar to other Scandinavian sites, they were considered valuable to assess the status of these species.

Among the ITEX sites included here, the first survey was from 1984 and the last from 2024, with the median being in 2008. The time interval with which surveys were repeated varied between sites and over time, as some subsites were surveyed every year but only for a short period, and others every five years but across decades, for example.

Sites, and sometimes subsites, used different methods to estimate species abundance. Point frame (PF) methods record the species hit by specific points in regular intervals in the plot, the sum of which for each species measures their abundance. This was done in different configurations; some recorded only the topmost vegetation hit from above, some recorded two layers of points: the topmost vegetation and the ground cover, respectively. Still others used a three-dimensional configuration that recorded everything between the topmost hit and the ground. In some cases, this meant that the total number of hits possible for a plot was dependent on the vertical structure of its vegetation. Other methods for measuring abundance included measuring the percent cover (PC) of a species in a plot, similarly to the Braun-Blanquet (B-B) method, in which species were placed in one of six intervals of estimated percent cover: 75–100%, 50–75%, 25–50%, 5–25%, 1–5% or <1%. The midpoints of these intervals were used for the analysis. Lastly, some sites divided plots into subplots (SP), and reported abundance as the number of these a species occurs in.

Data preparation

The original ITEX data did not include species absences, –i.e. species not observed in a survey were not recorded. To accurately estimate population trends, these had to be reconstructed. In subsites with permanent plots, this was done from the plot-specific species pool; if a species was recorded in a particular plot in at least one survey, it was added with an abundance of zero to every other survey of that plot when it was not recorded. In sites where plots were not permanent, it was done at the subsite level; in surveys of the subsite when a species was recorded in fewer plots than the maximum number it occupied during the entire survey period, as many absence records were added as required to make the number of records equal to this maximum. Thus, if a species was at most recorded in ten plots in one year, and eight plots in the next year, two zero-abundance records would be added to the latter.

Some sites using point frame survey methods indicated species that were present in plot but not hit in the survey by reporting their abundance as a number between zero and one. These were converted to ones to meet model requirements and to distinguish them from absences.

For data quality purposes, the ITEX data were filtered similarly to other published analyses of this dataset (García Criado, Myers-Smith, et al., 2025). Only records of positively identified seed plant species were retained. The data were then divided based on if species in a subsite occurred in either

1–2 or more than two plots in that subsite. For those in more than two plots, a requirement of at least two surveys, five years apart or more was set on the subsite, whereas those in one or two plots, at least three surveys with five years or more between the first and last survey was required. Subsites not meeting these requirements were removed from analysis to ensure model results represent real trends and not short-term fluctuations.

Models

To analyse species' population trends, Generalised Linear Mixed Models (GLMM) from 'glmmTMB' (McGillucuddy et al., 2025) of absolute abundance were fit to each species-subsite combination, with year (centred and scaled) as the sole predictor and plot as random intercept, since data in most plots were too sparse to estimate random slopes. Species that occurred in only one or two plots in a subsite, as well as subsites with non-permanent plots, were analysed without the plot random effect. Initial models with site as random effect had singular fits, and even though subsites within the same site were technically not independent, they are generally established in different habitat types and were therefore assumed to not correlate severely.

GLMMs with different distribution families were used depending on the survey method of the subsite; a zero-inflated Beta model was used for the percent-cover and Braun-Blanquet methods if the species' abundance included any zeros during the survey period. If not, the zero-inflation term was removed. For subsites with point frame methods (for which abundance is the number of hits) a Poisson model was used. Subplot counts were modelled as the frequency of occupied versus unoccupied plots using a binomial distribution. If data of the latter two survey methods were overdispersed (determined using tools from the 'DHARMA' R-package; Hartig, 2016), negative-binomial and Beta-binomial models, respectively, were instead used. If they were zero-inflated, a zero-inflation term was added to the model. This two-step process was done to maximise the convergence rate of the models, as models intended to handle overdispersion (i.e. negative-binomial and Beta-binomial GLMMs) fitted to non-overdispersed data can have convergence problems.

All models were then checked for over- and underdispersion, outliers and uniformity of residuals using tests from 'DHARMA'. Models flagged by the respective tests ($p < 0.05$) were checked visually, aided by 'performance' (Lüdtke et al., 2021), and discarded if the fit was considered inadequate. Models that did not converge were also excluded.

Due to the need to estimate abundance change using different model link functions, the slopes were not directly comparable. Thus, only the sign of the slope estimate (positive/negative) of each model was considered for describing overall population trends of species. Slope estimates with $p > 0.1$ were regarded as showing no trend. Using this, the proportion of subsites in which a species showed positive, negative or no trend, respectively, was calculated. A species was considered declining if it either (1) showed negative abundance trends in more than half of subsites in which it occurred, or (2) showed negative trends in more than one quarter of subsites and declined in more subsites than it increased in. The corresponding criteria for positive abundance trends were used to classify a species as increasing.

Species losses and gains

For an additional metric on change in occupancy not as reliant on the amount of data and therefore able to include the rarer species, species losses and gains were also calculated. In subsites with at least two plots and a survey time of five years or more only, species were considered lost if they were not present in the last survey but had been present in previous ones and gained if they were not present in the first survey but in later ones. From this and the total number of subsites a species had been observed in, the proportions of subsite losses and gains, respectively, was calculated.

However, due to this method not estimating uncertainty, it was given less weight than the trend analysis in the later prioritisation. Species that were lost in more than half of their subsites were classified as “losing”, and those that were gained in more than half of their subsites as “gaining” to simplify comparison.

Other data

Arctic species list

To retrieve a checklist of species relevant to this study, I downloaded data from the Global Biodiversity Information Facility (GBIF; <https://www.gbif.org/>), an online resource cataloguing species occurrence from herbaria, human observation reports etc. Using its R interface ‘rgbif’ (Chamberlain & Boettiger, 2017) and a polygon of the study area generated with R packages ‘rnatuarearth’ (Massicotte & South, 2017) and ‘sf’ (Pebesma & Bivand, 2023), GBIF occurrences of native, non-cultivated (if specified) seed plants within the area of focus were downloaded (for specifics, see GBIF.org, 2026). After removing records close to biodiversity institutions such as botanic gardens and universities with ‘CoordinateCleaner’ (Zizka et al., 2019) which could include exotic plants, the occurrence data were converted into a checklist of species relevant to this study.

Red lists

Red lists, by their own admission following the IUCN standard (IUCN, 2012a), have been published for all Nordic countries except the Faroe Islands, and were accessed from the respective national institutions that publish them (Artsdatabanken, 2021; Boertmann & Bay, 2018; Hyvärinen et al., 2019; SLU Artdatabanken, 2026b; Wasowicz & Heiðmarsson, 2019). The IUCN method uses thresholds of range and population sizes and their trends as estimations of species’ extinction risks, and ranks them in one of five classes: Least Concern (LC), Near Threatened (NT), Vulnerable (VU), Endangered (EN), Critically Endangered (CR) and Regionally Extinct (RE; IUCN, 2012b). A subset of the IUCN Red List including seed plants with ranges in countries intersecting the Arctic was also downloaded (IUCN, 2025).

Ecological indicator values

Tyler et al. (2021) have produced a list of ecological indicator values for all Swedish vascular plants, which was used as information regarding two different factors of *ex-situ* conservation priority for species: the degree of their threat from climate change and their importance to the rest of their ecosystem. The values treated as indicating this were the estimates of species’ temperature optimums as well as an index of biodiversity relevance. The temperature optimum was calculated from the climate at the centre of their Swedish range and represented by an 18-degree scale, with 18 characterising a cold-adapted species. The biodiversity relevance was based on the number of other species directly dependent on the plant (see Tyler et al., 2021 for details). I treated a high value of temperature optimum (i.e. cold-adapted), as indicating a species at increased risk from climate warming, and a high value of biodiversity relevance as a species which would have a disproportionate impact on the ecosystem upon its loss.

For the incredibly species rich genus *Hieracium*, the original dataset listed indicator values at the section level only. To be able to match these to the other datasets, which distinguish *Hieracium* species, a list of all Swedish *Hieracium* species and their sectional membership was downloaded from the Swedish taxonomic database Dyntaxa (SLU Artdatabanken, 2026a), which Tyler et al. (2021) also relied on. This was then used to expand the indicator values for *Hieracium* sections to the species level.

Data on existing seed collections

To evaluate the degree of representation in existing seed banks, information about the collections hosted by the Millennium Seed Bank from the Nordic countries was received. The collections were further classified as being from within the CAFF boundary or not, and relevant metrics were summarised per species from both the whole dataset and the within-CAFF subset, respectively. These included the number of accessions, the number of different localities these were from (assumed to represent the number of different populations sampled), the year of the latest collection and the current total size of the collections, adjusted for the expected viability of the seeds.

Socioeconomic importance

Species' socioeconomic relevance was judged by their inclusion in the World Checklist of Food Plants (WCFP), a large dataset cataloguing plants used as human food, including crops and their wild relatives, provided they have documented use as food by humans (Diazgranados et al., n.d.).

Taxonomic standardisation

Before any analysis or other manipulation of the datasets, their taxonomic nomenclature was standardised against the GBIF Backbone Taxonomy (GBIF.org, 2023) using the 'rgbif' package (Chamberlain & Boettiger, 2017). Due to inconsistencies in the specification of infraspecific taxa between datasets, ranks below species level were removed. Hybrids were also removed. If a species had different values for different subtaxa in a particular dataset, they were for clarity purposes collapsed into a range of the exhibited values.

Compilation and prioritisation

A comprehensive dataset of Arctic seed plants and relevant data for their *ex-situ* prioritisation was produced by combining the global and regional red lists, results from the ITEX analysis, MSB collection data, ecological indicator values for Swedish plants from Tyler et al. (2021), and data on crop wild relatives. Species not represented in the Arctic species list obtained from GBIF occurrences were excluded from the final list.

To rank species' conservation priority, I developed a metric combining the different indications of the many data fields. Across the compiled data, different points were given to field-values regarded as suggesting *ex-situ* conservation priority and summed up into a *priority score* (Table 1). For example, a point from five to ten was given for every red list assessment of Near Threatened (NT) to Critically Endangered (CR), respectively, giving a species listed as vulnerable (VU) in Sweden, (EN) in Finland, and (LC) elsewhere a score of 15 (7 + 8) from the red lists. Additionally, eight points would be added if the species was not in the MSB collections and so forth for the rest of the variables. The scores for criteria regarding seed bank representation were based on relevant directions from the ENSCONET seed collection protocol (ENSCONET, 2009), which gives recommendations for the minimum number of populations and seeds to collect, for example. The scoring is not intended to be final, but to represent an example which considers some general aspects of seed bank prioritisation. A seed collection expedition planner can access the R script and tweak the points to suit their aims, whether they wish to target crop wild relatives or to emphasize the assessment of a particular red list, for example.

Post-hoc analyses

To compare the effect of the different survey methods on the result of the ITEX analysis, I tested if the survey method influenced the respective number of negative and positive trends that models predicted using binomial GLMMs with species and subsite as random effects.

Table 1 Criteria and points applied to each species for the priority scoring. Note that a species cannot fulfil all criteria. E.g. a species not collected within the Nordic countries cannot have been collected within the study area. For the red lists, a corresponding point was given for each assessment as threatened in the five red lists (see text). Note that a high value of temperature optimum indicated a cold-adapted species.

<i>Data source</i>	<i>Criterion</i>	<i>Points given</i>
<i>Red lists</i>	CR or RE	10
	EN	8
	VU	7
	NT	5
<i>ITEX analysis</i>	Declining	6
	“Losing”	3
<i>MSB collections</i>	Not collected within Nordic countries	8
	Not collected within study area	1
	No. of different localities collected < 3	2
	No. of different localities collected > 3 but < 5	1
	Last collection from before 1990	1
	Size of collection < 15000 seeds	2
<i>Ecological indicator values</i>	Biodiversity relevance > 5 (out of 8)	4
	Temperature optimum > 13 (out of 18)	4
<i>WCFP</i>	In the WCFP	2

Results

ITEX analysis

Abundance trends

After filtering the ITEX data, 235 species in 91 subsites (and 38 sites) were left for analysis, corresponding to 1707 subsite-specific trends to which the models were fit. 401 of the models were discarded due to convergence failure or an unsatisfactory fit, yielding 1306 (77%) subsite trends for 211 different species to be included in the prioritisation (Table 2).

The most frequently observed result from the models was that of no trend, followed by positive trend and fewest showing a negative trend (Table 2). The mean survey time of the analysed subsites was 15 years, the mean number of surveys four and, on average, species occurred in eleven plots per subsite.

Most species showed mixed or no trend, and twice as many species increased than declined. After summarising the subsite-specific trends into their relative proportions per species and using the classifications of declining or increasing outlined in the method, 34 species were indicated as declining, 68 as increasing and the remaining majority of species had mixed or no trends (Figure 2). 94 species showed one consistent trend across all analysed subsites, but 58 of these were only analysed in one subsite. The average number of subsites per species was six.

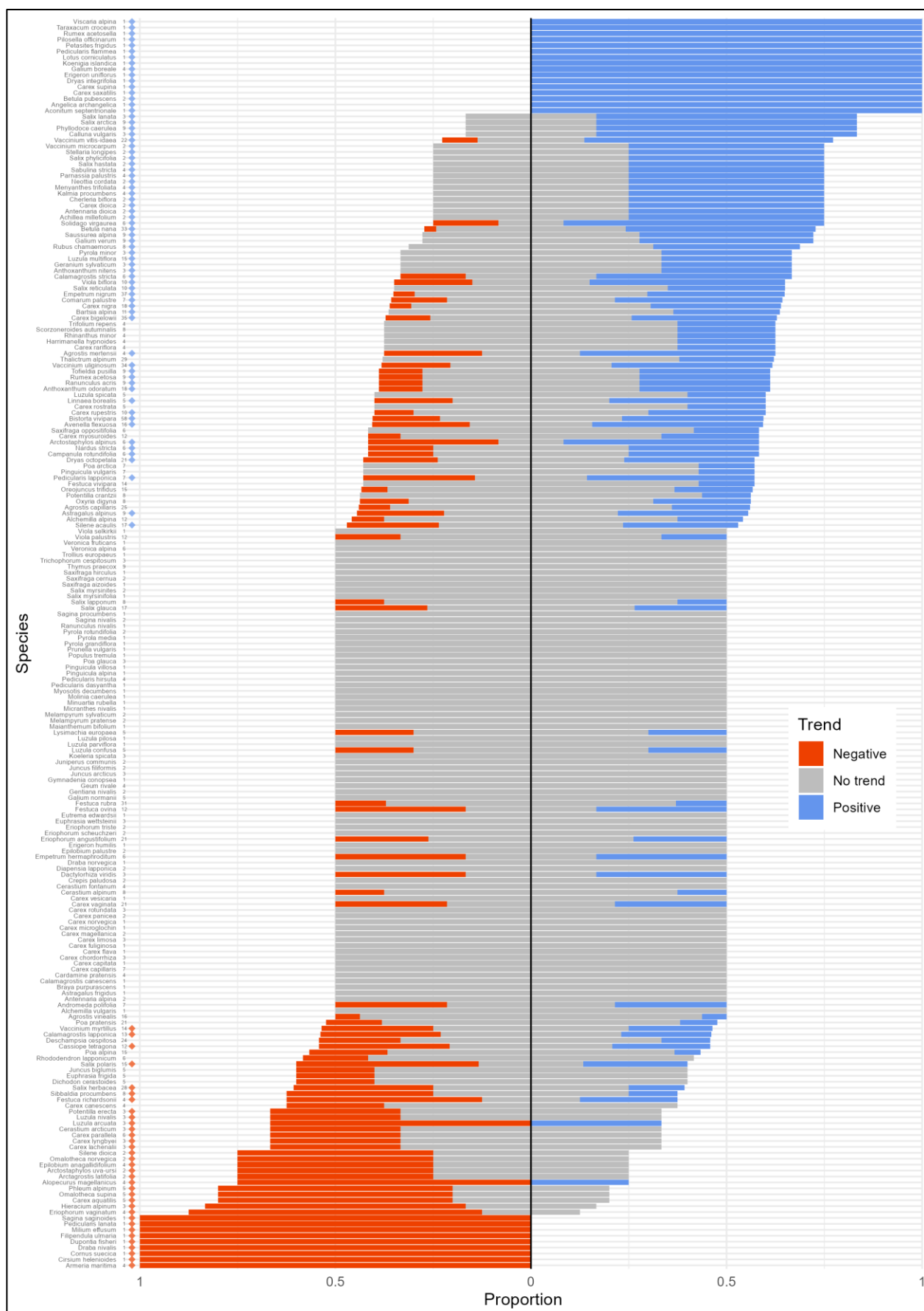


Figure 2 The relative proportions of positive, negative and neutral trends exhibited by species among the subsites they occurred in, obtained from the analysis of ITEX data. The numbers next to the species name indicate how many subsites were analysed. Red symbols denote declining species and blue symbols increasing species, as defined in the method.

Table 2 The number of models fit to each survey method, how many were kept for the prioritisation list and the number of models showing which trend. For the trends, the percentage is of the number of kept models.

	<i>Initial models</i>	<i>Models kept</i>	<i>No trend</i>	<i>Negative trend</i>	<i>Positive trend</i>
<i>PC & B-B</i>	923	546 (59%)	395 (72%)	46 (8%)	105 (19%)
<i>PF</i>	623	607 (97%)	291 (48%)	108 (18%)	208 (34%)
<i>SP</i>	161	153 (95%)	84 (55%)	40 (26%)	29 (19%)
<i>Total</i>	1707	1306 (77%)	770 (59%)	194 (15%)	342 (26%)

The different model structures had different convergence rates (Table 2), with the one used for the percent cover (PC) and Braun-Blanquet (B-B) plot survey methods having the lowest rate. They also varied in the number positive and negative trends predicted. Relative to PC and B-B models, the probability of predicting a negative trend were significantly higher for both point frame and subplot counts ($p < 0.001$). However, no evidence that point frame (PF) and subplot (SP) methods differed from one another was found ($p = 0.51$). PF models also more often predicted positive trends than PC and B-B models ($p = 0.004$).

Losses and gains

As the calculation of species gains and losses from subsites applied other filtering criteria than the abundance analysis, it yielded data for 60 additional species not analysed by the models, for a total of 271 species. Most species were gained or lost in less than half of their subsites (neither gaining nor losing, according to the definitions from the method). But more species were lost in over half of their subsites than were gained (42 and 25 species, respectively). There was limited agreement between the trend analysis and calculation of losses and gains; three species were classified as both declining and losing, three as increasing and gaining, two as increasing and losing, and none as declining and gaining. The average number of subsites from which losses and gains were calculated was eight.

Compiled data and prioritisation

After compiling all data, a list of 3010 species was produced, corresponding to the number of species retrieved from GBIF occurrences after filtering. Eleven unique metrics relevant for *ex-situ* conservation priority were included (for the specific metrics, see Appendix 2). Applying the criteria and their respective points shown in Table 1 to the list, a priority score ranging from one to 42 was obtained for each species (though a higher score was theoretically possible). The median score was eight. I ranked scores in order from highest to lowest and gave equal rank to species with equal scores, which gave 37 different ranks (see Appendix 1 for the topmost ranking species).

A majority of species received the same priority score. 770 of these (26% of the complete list) were not in any of the datasets but the GBIF species list, which due to the setup of the scoring criteria resulted in them all placing 31st in the ranking with eight priority points. An additional 1137 species were also ranked 31st, despite being in one or more dataset (e.g. they were assessed as LC in some or all red lists) for a total of 1907 species (63%, for the number of species each dataset covered, see Appendix 2).

Exemplification of prioritisation list

Three species were chosen to exemplify and illustrate the priority list and some of its incorporated data. They are shown in Table 3. *Dupontia fulva* (Trin.) Röser & Tkach, a perennial grass, received the highest priority score of all species due to not being represented in the Millennium Seed Bank

(MSB) and being threatened in all regional red lists where it was evaluated. *Armeria maritima* (Mill.) Willd., a perennial herb in the family Plumbaginaceae, common along some coasts in Scandinavia, was declining in all four ITEX subsites analysed for this species. Some of its subspecies are red listed, but interestingly not in Iceland, where all the analysed ITEX subsites were located. It was ranked at 10th place with 29 priority points added up from its ITEX trend, lack of representation in the MSB and its subspecies' red list assessments and high values of temperature optimum. *Dryas octopetala* L. is a common dwarf shrub in the tundra. It was found to be increasing in the ITEX subsites and has been collected within the study area. Though two NT assessments, its high value of temperature optimum and presence in the World Checklist of Food Plants (WCFP) added up to a priority score of 18, ranking it at 21st place out of 37.

Seed bank representation of threatened species

I found that a majority of red listed species in the study area had not been collected for seed banking, but almost half of the seed collections were of red listed species. 466 species were red listed as threatened (i.e. assessed as RE, CR, EN or VU) in at least one of the red lists incorporated. Three of them were globally threatened. Of the threatened species, 151 (32%) were represented in the Nordic seed collections of the MSB, amounting to 46% of all species in the collections. None of the three globally red listed species were collected.

Table 3 A selection of the data from the prioritisation list for three representative species: *Dupontia fulva* (Trin.) Röser & Tkach, *Armeria maritima* (Mill.) Willd., and *Dryas octopetala* L. Among the fields excluded are proportions of losses and gains and metrics quantifying the degree of seed bank representation.

	<i>Dupontia fulva</i>	<i>Armeria maritima</i>	<i>Dryas octopetala</i>
<i>IUCN Red List</i>	LC	-	-
<i>Swedish red list</i>	VU	LC	LC
<i>Finnish red list</i>	EN	CR/EN	NT
<i>Norwegian red list</i>	EN/LC	NT/LC	NT/LC
<i>Greenland red list</i>	VU	LC	-
<i>Iceland red list</i>	-	LC	LC
<i>ITEX subsites analysed</i>	None	4	21
<i>Proportion negative</i>	-	1	0,19
<i>Proportion positive</i>	-	0	0,33
<i>Trend</i>	-	Declining	Increasing
<i>Seeds collected in Nordics?</i>	No	No	Yes
<i>Seeds collected in the Arctic?</i>	No	No	Yes
<i>Biodiv. relevance</i>	1	1-2	4
<i>Temp. optimum</i>	14	7-17	17
<i>Has human use?</i>	No	Yes	Yes
<i>Priority score</i>	42	29	18
<i>Priority ranking</i>	1	10	21

Discussion

Trends in Arctic plants

In the analysis of long-term vegetation monitoring data from ITEX, most seed plant species showed mixed or stable trends (Figure 2), agreeing with the heterogeneous ecological trends other analyses of this data have found (Bjorkman et al., 2020; García Criado, Myers-Smith, et al., 2025). The analysis was conducted on a wide geographic scale, and local climatic conditions, functional traits as well as ecological interactions can be important in shaping each plant species' response (Boscutti et al., 2018; Klanderud et al., 2015; Rumpf et al., 2018). Alpine and Arctic plants' responses to change can be complex and difficult to predict (Erkelenz et al., 2025; Henn et al., 2024), emphasising the need to carefully assess and record ongoing change when characterising species' sensitivity.

Twice as many species were found to be increasing than declining and almost twice as many were “gaining” than “losing”, using my criteria for the respective classifications. Similar results were obtained by Rumpf et al. (2018) who studied alpine plants' abundance and range dynamics. As the climate warms, many species benefit due to milder abiotic conditions (Klanderud et al., 2015), and species from warmer habitats expand northward or to higher elevations, termed *borealisation* (García Criado, Barrio, et al., 2025; Rumpf et al., 2018). Shrubs and graminoids have been generally found to be more competitive with warming (Bjorkman et al., 2020; Boscutti et al., 2018), but as mentioned above, trends for individual species can be difficult to predict; representatives of shrubs, graminoids and forbs were found among both increasing and declining species. Nevertheless, since the pool of boreal, more warm adapted species is larger than that of high Arctic and alpine specialists, there are potentially more species benefiting from climate warming than are threatened by it.

Species that only showed one consistent trend were often only analysed in one subsite. Although this can be interpreted as discrediting the trend they exhibit, rarer species, (i.e. species found in less subsites) could be more likely to decline in abundance. For fear of excluding such species, no threshold was placed on the number of subsites. Indeed, 58 species would have been excluded thereby. As collecting the seeds of a non-threatened species is from a conservation standpoint better than not collecting the seeds of a threatened species, a cautionary approach is undoubtedly preferred here.

Limitations of the data and models

The problem of modelling proportional data that contains zeros is well-known in statistics (Douma & Weedon, 2019) and presented difficulties in the analysis of abundance from the percent cover and Braun-Blanquet survey methods. The many different models available for such data are demanding and were unstable when fitted to the ITEX data, and the large number of models built did not permit individually tweaking models according to the nature of each subset. The zero-inflated Beta GLMM had the best convergence rate and fit compared to other models for proportional data containing zeros, but only 59% converged. As the majority of subsites in the ITEX data used PC or B-B survey methods, the poor performance of their models had a considerable impact on the total yield of adequate models. This may also have biased results as species' trends in PC and B-B subsites were less likely to be detected due to more of their models being discarded.

Different plot survey methods also have different strengths and weaknesses, which may bias results. Subplot counting has been found to be better at detecting rare species and their trends than percent cover and point frame methods (Mamet et al., 2016). Here, the models fit to subplot count and point frame data were more likely to predict negative trends compared to PC and B-B methods,

and PF models detected more positive trends than the other two. This could reflect the lower stability and potentially higher uncertainty of the PC models, increasing the likelihood of them producing false negatives. If sites or subsites using a particular survey method consistently underdetect rare species, their results could be biased toward only showing trends for common species which are less likely to be declining. Though invaluable to studies of ecological dynamics, plot-level monitoring on the whole may not either be optimal for measuring the abundance of rare species occurring at a low frequency in the landscape (Morrison, 2016), for which more directed surveys may be needed. This could possibly bias the entire result toward the common species and thus explain the prevalence of increasing trends.

Findings from the prioritisation list

Representation of threatened species

Like other studies (Dhanjal-Adams et al., 2026), I found that seeds of almost two thirds of threatened species in the Nordic Arctic remain unrepresented in the Millennium Seed Bank. I only examined seed collections from the Nordic countries, and thus threatened species included in my data may still exist in collections from other regions. However, as these would represent non-native populations, they are not as relevant for conservation in the Nordic countries (Hoban & Schlarbaum, 2014). Although more than two thirds of threatened species are unrepresented in seed collections, 46% of collections were of red listed species. This relatively high proportion compared to other studies' findings can mean that collecting targets have been largely appropriate in the Nordic Arctic, but that more collecting need to be undertaken to cover a larger portion of the red listed species.

Priority of common species

For many species that received priority points for their red list status, one or more of their subtaxa were red listed rather than the species as a whole, resulting in some unexpectedly high-ranking species such as *Armeria maritima* (Table 3). Since datasets did not always specify species' infraspecific membership, infraspecific ranks were removed to set the taxonomic resolution to the lowest mutually shared rank and increase the overlap of the datasets. However, it may also have resulted in surprising priority rankings, when very common species received high scores owing to rare subspecies. Different taxonomic conventions can also disagree on the rank of particular taxa, classifying them either as separate species or subspecies, the latter of which would here result in the taxa losing their distinction. Therefore, using a different taxonomic backbone could lead to different results being obtained. Nonetheless, as data for infraspecific taxa were retained but simply merged and displayed at the species-level, the prioritisation list did not risk overlooking taxa important for conservation for this reason. As previously discussed, a cautionary approach is often preferred from a conservation standpoint.

Data-lacking species

26% of species in the prioritisation list were not on any of the datasets used for the priority scoring, and thus all received a score of eight for not being represented in the MSB (see Table 1). Many of these could have been included in the list due to the relatively indiscriminate method of using GBIF occurrences for producing the Arctic species checklist, as some cultivated and non-native taxa were observed among the data-lacking species. Many GBIF records are from potentially erroneous human observations, and their means of establishment (i.e. native, introduced, cultivated) are seldom specified. The datasets incorporated in the prioritisation list are mostly oriented towards native, wild species, and do not cover other species. This is inconsequential as introduced and cultivated species are not relevant for conservation prioritisation. However, some of the data-lacking species are wild and native and may potentially have received higher priority rankings if more data on them were available (see Bachman et al., 2024). These species therefore constitute

targets for data collection and red list assessment to safeguard against otherwise preventable extinctions.

Adaptability of prioritisation method and use of list

Human actions are threatening biodiversity in many if not all regions of the world, but through *ex-situ* conservation, there is no reason why species should go completely extinct (Smith et al., 2011). Although the selection of data used here is tailored for an analysis of Arctic species' conservation priority, similar data for other regions can be combined using the same method to prioritise *ex-situ* conservation efforts in other regions.

Many countries now produce red list assessments of their native floras following the IUCN guidelines. An analysis of abundance trends in long-term monitoring data such as from the international LOTVS initiative (Sperandii et al., 2022), can complement them. Alternatively, GBIF occurrence data or other geographical range data can be used to compute Area of Occupancy (AOO) and Extent of Occurrence (EOO), two statistics used by the IUCN to make preliminary red list assessments (IUCN, 2012b; Pelletier et al., 2018). Either on their own or in combination with other covariates to threat probability, they can be used to make informed predictions of threat assessments for large numbers of taxa (e.g. Bachman et al., 2024; Pelletier et al., 2018). A third option usable for assessing climate change impacts is species distribution modelling, using environmental variables and their projected changes (see Niskanen et al., 2019). These range-based methods of threat predictions might even be preferred considering the limitations to plot-level abundance analyses discussed above.

The use of ecological indicator values to characterise species environmental requirements can be adopted for other environmental changes than climate warming, which may not be the most severe threat elsewhere than the Arctic. For example, Tyler et al. (2021) included measures of species' sensitivity to or requirement of light and management regimes in their dataset of indicator values, as both encroachment of woodland in ancient meadows and pastureland as well as intensive forestry are respectively threatening many species in Sweden. Depending on regional threats to biodiversity and the availability of ecological indicator values for local species, different indicators can be used to identify at-risk species.

As some plants produce so called recalcitrant seeds that do not tolerate storage using traditional methods, data on seed characteristics and viability can be incorporated here or in similar prioritisations to highlight species that are more easily stored *ex-situ*. Though other methods such as cryopreservation have been developed to facilitate the banking of such species as well (Li & Pritchard, 2009), for seed banks that lack resources for these methods, species with recalcitrant seeds may be meaningless to collect, and deprioritisation of them might be desirable. However, such species also constitute an important part of biodiversity and neglecting them would not be inconsequential (Dhanjal-Adams et al., 2026).

As stated earlier, the priority scoring used can be tweaked depending on local conditions or particular aims of a seed collector. For example, a Swedish collection programme may wish to emphasise species' threat status in Sweden over other countries red lists and therefore give more points for a Swedish CR assessment than an Icelandic one. A species' regional and global threat status should still be considered, however, since it impacts the importance of local populations' persistence to the survival of the entire species. Conservation priorities can be complex, and different seed banks can have different foci, often having objectives on the national level. This analysis was conducted across a broad geographical range, and all species included are not present

everywhere within it. Therefore, national conservation initiatives may also wish to filter the prioritisation list to only include the local species.

Conclusion

Here, I have produced a prioritisation list highlighting species in the Nordic Arctic in need of seed collection. This compilation of data reveals gaps suggesting that more collection needs to be undertaken, with a continued focus on threatened species. More data also needs to be gathered to ensure plants unrecognised as threatened are not overlooked by conservationists. Although the analysis of Arctic species' abundance trends was possibly underdetecting negative trends, a prevalence of increasing species may reflect the borealisation of Arctic communities due to climate warming. The analysis nevertheless identified some declining species thus deserving higher conservation priority. The Arctic prioritisation list can be used as it is to plan collection expeditions or be tweaked for more specific objectives. Moreover, this relatively simple method of data compilation followed by a scoring of priority points can be applied to other regions to make conservation prioritisations that consider the local conditions. With 45% of all 330 000 flowering plant species estimated to be threatened with extinction (Bachman et al., 2024), ex-situ conservation needs to intensify and prioritise efforts. Biodiversity is being lost and time left to save it is dwindling. Through prioritisation, seed banks are able to focus their efforts, maximise the value of their collections and save species from irreversible extinction.

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Appendix 1

Species with topmost priority

Note: results from the abundance trend analysis were removed as none of these species were analysed by the models.

Data source		ITEX			MSB collections						WCFP	Red lists						Indicator values				
			N subsites - Losses, gains	Prop. Lost	Prop. Gained	Collected - Nordics	Collected - Study area	N collections	N localities	Year - latest collection	Tot. collection size	In WCFP	IUCN	Sweden	Finland	Norway	Greenland	Iceland	Biodiv. relevance	Temp. optimum	Priority score	Priority rank
Order	Family	Species																				
Poales	Poaceae	DuPontia fulva	-	-	-	No	No	-	-	-	-	No	LC	VU	EN	EN/LC	VU	-	1	14	42	1
Lamiales	Plantaginaceae	Hippuris tetraphylla	-	-	-	No	No	-	-	-	-	Yes	LC	CR	VU	VU	-	VU	1	11	41	2
Rosales	Rosaceae	Rosa spinosissima	-	-	-	No	No	-	-	-	-	Yes	NT	RE	-	VU	-	VU	5	6	39	3
Ranunculales	Ranunculaceae	Ranunculus sulphureus	-	-	-	No	No	-	-	-	-	No	-	EN	CR	VU/LC	LC	-	1	17	37	4
Asparagales	Orchidaceae	Hermidium monorchis	-	-	-	No	No	-	-	-	-	No	-	VU	RE	CR	-	-	1	7	35	5
Boraginales	Boraginaceae	Buglossoides arvensis	-	-	-	No	No	-	-	-	-	No	-	VU/NT	EN	CR	-	-	2	4	33	6
Brassicales	Brassicaceae	Draba subcapitata	-	-	-	No	No	-	-	-	-	No	-	CR	-	CR/NT	LC	-	1	18	32	7
Caryophyllales	Caryophyllaceae	Sagina caespitosa	-	-	-	No	No	-	-	-	-	No	-	NT	-	EN	LC	VU	1	18	32	7
Poales	Cyperaceae	Carex hartmaniorum	-	-	-	No	No	-	-	-	-	Yes	-	VU	EN	VU	-	-	4	7	32	7
Asparagales	Orchidaceae	Malaxis monophylos	-	-	-	No	No	-	-	-	-	No	-	VU	EN	EN	-	-	1	10	31	8
Caryophyllales	Caryophyllaceae	Spergula arvensis	1	1	0	No	No	-	-	-	-	No	-	NT/LC/RE	LC/RE	LC	-	-	3	6	31	8
Saxifragales	Saxifragaceae	Micranthes foliolosa	-	-	-	No	No	-	-	-	-	No	LC	LC	NT	VU/NT	LC	VU	1	17	31	8
Asterales	Asteraceae	Arnica angustifolia	-	-	-	Yes	Yes	1	1	2024	282	No	-	VU	EN	NT/LC	LC	-	1	17	30	9
Brassicales	Brassicaceae	Camelina alyssum	-	-	-	No	No	-	-	-	-	Yes	-	RE	RE	-	-	-	1	-	30	9
Brassicales	Brassicaceae	Draba fladriensis	-	-	-	No	No	-	-	-	-	No	-	NT	EN	NT	LC	-	1	18	30	9
Caryophyllales	Caryophyllaceae	Arenaria norvegica	1	0	1	No	No	-	-	-	-	No	-	NT	EN	NT	-	LC	1	17	30	9
Ericales	Primulaceae	Primula scandinavica	1	1	0	Yes	Yes	2	2	2022	9556	No	NT	VU	-	NT	-	-	2	16	30	9
Poales	Cyperaceae	Carex helenastes	-	-	-	Yes	Yes	3	2	2021	8472	No	DD	VU	VU	NT	-	VU	4	13	30	9

Appendix 2

Dataset coverage and fields

	<i>Number of species</i>	<i>Fields</i>
<i>GBIF species list</i>	3010 (100%)	Order Family
<i>ITEX analysis</i>	271 (9%)	Trend analysis Losses and gains
<i>IUCN red list</i>	431 (14%)	Threat status globally
<i>Swedish red list</i>	1435 (48%)	Threat status in Sweden
<i>Finnish red list</i>	923 (31%)	Threat status in Finland
<i>Norwegian red list</i>	1087 (36%)	Threat status in Norway
<i>Greenland red list</i>	410 (14%)	Threat status in Greenland
<i>Iceland red list</i>	487 (16%)	Threat status in Iceland
<i>MSB collections</i>	331 (10%)	Location of collection (within Arctic or not) Number of collections Number of different localities collected Year of latest collection Size of collection
<i>Indicator values</i>	1682 (56%)	Biodiversity relevance Temperature optimum
<i>WCFP</i>	2616 (87%)	Use as human food