

Research Article

The potential area of occupancy of non-native plants across a warming high-Arctic archipelago: Implications for strategic biosecurity management

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Abstract

The terrestrial high-Arctic has, so far, escaped the worst impacts of non-native plant establishment. However, increasing human activity and changing climate raise the risk of introductions and establishment, respectively. The lack of biosecurity in the terrestrial Arctic is thus of concern. To facilitate the development of biosecurity measures on the rapidly warming and highly trafficked archipelago of Svalbard, we generated ecological niche models to map the bioclimatic niche potential of 27 non-native established or door-knocker vascular plant species across Svalbard, identify species with a high risk of widespread occupancy, and locate hotspots of potential current and future invasions. Under the current climate the three species with the highest threat in terms of broad potential area of occupancy and known invasion potential were *Deschampsia cespitosa*, *Ranunculus subborealis* subsp. *villosus* and *Saussurea alpina*. However, under future climate, most of the considered species have potentially wide distributions across the archipelago. Remote eastern islands were a hotspot region for broader potential establishment of non-native species under the current climate. Our results suggest that many non-native plant species have a broader macroclimatic niche on Svalbard than they currently occupy, and that other factors probably limit both dispersal and establishment outside their current localised distributions. Environmental management on Svalbard has a limited window of opportunity to act early in containing and preventing the spread of non-native plant species beyond the few settlements where they currently exist. Moreover, preventing introductions and establishments on the remote and rarely visited islands of Edgeøya, Barentsøya and Bjørnøya could be also a priority action to safeguard sanctuaries of the archipelago's natural ecosystems.

Key words: Bioclimate, Climate change, Distribution, Neophyte, Svalbard, Tundra



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Introduction

Biodiversity redistribution processes related to the Anthropocene are rearranging regional biotas to higher and cooler elevations and latitudes (Pecl et al. 2017). The spread of non-native species is a major threat to biodiversity and ecosystem functioning (Vilà and Hulme 2017; IPBES 2019). The establishment of multiple non-native species can lead to facilitatory and accumulating changes in habitats known as invasional meltdown (Simberloff and Von Holle 1999). Invasional meltdown

processes disproportionately threaten remote, species-poor ecosystems with low biotic resistances to invasions (limited functional redundancies). Meltdown is thus expected to manifest in species-poor systems such as islands (Moser et al. 2018), but remains poorly documented in polar systems (Perterra et al. 2023). Identifying the most vulnerable areas to the establishment of multiple non-native species and potential impacts or meltdown can be narrowed down using macroecological principles: identifying 'areas of risk' with highest aggregated suitable establishment potential by the pool of alien species introduced to a site. In this regard species distribution models (SDMs) are a foundation for identifying regions of concern for potential invasions, facilitating further research and management.

The terrestrial Arctic is characterised by species-poor communities under strong ecological determination by abiotic conditions (Daniëls et al. 2013; Ims et al. 2013). The Arctic is undergoing a higher degree of warming than anywhere else on Earth (Serreze and Barry 2011; Box et al. 2019). At the same time, increasing human activity within the Arctic (Meier et al. 2014) increases both propagule pressure and ecosystem disturbance, respectively facilitating the introduction and establishment of non-native species. Non-native vascular plant species are continually arriving in the Arctic, yet to date, most have not established (i.e. transient or casual species) roughly following the rule of tens (Williamson and Fitter 1996). However, with warming more species can be expected to establish (Alsos et al. 2015). Amelioration of climatic conditions may proceed beyond a point of no return (a tipping point), where the stressors are no longer limiting factors for wider establishment of non-native vascular plants and their associated biota, potentially leading toward invasional meltdown of the Arctic tundra ecosystem. Wasowicz et al. (2020) found that 341 non-native vascular plant species have been recorded in the Arctic, of which 188 are considered naturalised in at least one of the 23 floristic regions of the Arctic. Only 11 taxa are currently considered invasive, and they are only known from Alaska and Iceland.

Svalbard is a high-Arctic archipelago, located between 73 and 81°N. Svalbard is undergoing a high degree of climatic warming, with annual mean temperatures predicted to increase by between 3 °C and 10 °C from 1971–2000 to 2071–2100 and annual precipitation predicted to increase by 40% to 60% over the same time period (Hanssen-Bauer et al. 2019). It is heavily trafficked relative to other high-Arctic regions. The combination of warming and human activity in a remote, species-poor ecosystem (Duffy et al. 2017), places Svalbard at high risk of invasional meltdown. To date, there are more than 100 species of non-native vascular plant species that have been reported from Svalbard (Alsos et al. 2015; Wasowicz et al. 2020) although only 13 have established as of 2023 (Artsdatabanken 2023; Table 1) and these are limited to Svalbard's few settlements and around old cabins, all on the main island of Spitsbergen. About 75% of the introduced species are considered seed contaminants imported with livestock fodder, animal bedding, shipping of goods (Artsdatabanken 2018) and transported on visitors shoes (Ware et al. 2012). While the intentional introduction of non-native species is forbidden on Svalbard (Svalbardmiljøloven 'Svalbard environmental protection act'; Klima- og miljødepartementet 2001), there are no biosecurity measures in place to prevent unintentional introductions. This is in stark contrast to other polar (i.e. Antarctica; Hughes and Perterra 2016) and remote (e.g. Australia; Anderson et al. 2017) regions where stringent measures have been put in place to limit import of non-native species. Importantly, island systems harbour a distinct biota under processes of isolation and speciation with low biotic resistance,

making them highly vulnerable to the arrival of non-native species. Indeed, Svalbard has several endemic and near-endemic vascular plant species (Elven et al. 2022).

To facilitate policy development on Svalbard, identification of regions suitable for future establishment of non-native species is required. By encompassing the entire pool of non-native species currently known from the region, broad scale patterns can be identified that can be related to potential ecosystem impacts. The objective of this study is to carry out a risk assessment of macroclimate suitability for non-native vascular plant species on Svalbard by identifying regions within the potential bioclimatic niche under both current and future climates. We aim to: 1. Rank non-native species based on both bioclimatic suitability and current ecological impact assessment category (from the 2023 alien species list; Artsdatabanken 2023). 2. Identify regions with high numbers of potential non-native species under current and future climate scenarios, in order to determine areas where increased vigilance or management is required. 3. Detect low risk zones under both present and future conditions which are less bioclimatically suitable for the focal non-native species and could be considered for reinforced protection. 4. Identify assemblages of non-native species in different regions of the archipelago, in order to understand potential bioregionalization of non-native species and potential impacts.

Methods

Study region and species

This study focused on the high-Arctic archipelago of Svalbard (Norway). Svalbard is geographically isolated with a small number of permanent settlements and research stations, although it is relatively easily accessible, with heavily-used traffic connections to lower latitudes including daily scheduled air routes and regular shipping. Three out of five Arctic bioclimatic subzones occur in Svalbard, including the middle Arctic tundra zone, the northern Arctic tundra zone and the Arctic polar desert (Elvebakk 1997; Elvebakk 1999). Despite its high-Arctic position, the North Atlantic Current reaches the western part of the archipelago, providing a relatively mild climate.

In total, 27 non-native vascular plant species were included in this study (Table 1). This includes all species ecologically impact assessed for Svalbard by a vascular plant committee for the Norwegian Alien Species List 2023 (Artsdatabanken 2023; Suppl. material 1: table S1). The assessments included the invasion status (stage of establishment) of each species using the categories introduced by Blackburn et al. (2011), further specified for Norwegian inventories by Sandvik et al. (2019) and Sandvik et al. (2020). The 13 non-native vascular plant species considered established in Svalbard were categorised as C2, C3, D1, or D2, while the 14 door-knockers (i.e., transient/casual species not currently reproducing in Svalbard, but which can be expected to do so within 50 years) were categorised as A, C0, or C1.

Model training

To train climate suitability models, we used species occurrences from GBIF (GBIF.org 2023a), retrieved using scientific names with authors as accepted by the Norwegian Biodiversity Information Centre (Table 1). We used global occurrence

Table 1. List of non-native vascular plant taxa from Svalbard used in the study, with authors. Accepted species names follow Artsnavnebase (Norwegian Nomenclature Database; Artsdatabanken). GBIF species names are also provided to link to the source data. The status of each species in Svalbard is given as either established or door-knocker (not currently reproducing in Svalbard, but can be expected to do so within 50 years; Sandvik et al. 2020), and their establishment class (Blackburn et al. 2011, as specified by Sandvik et al. 2019). The ecological impact category is given as either LO (low impact) or NK (no known impact; Suppl. material 1: table S1).

Accepted species name in Norway	GBIF species name	Status Svalbard	Impact category
<i>Achillea millefolium</i> L.	<i>Achillea millefolium</i>	Established (D1)	LO
<i>Alchemilla subcrenata</i> Buser	<i>Alchemilla subcrenata</i>	Established (C3)	LO
<i>Alchemilla wichuræ</i> (Buser) Stefánsson	<i>Alchemilla wichuræ</i>	Door-knocker (C0)	LO
<i>Anthriscus sylvestris</i> (L.) Hoffm.	<i>Anthriscus sylvestris</i>	Door-knocker (A)	LO
<i>Barbarea vulgaris</i> W.T.Aiton	<i>Barbarea vulgaris</i>	Established (D2)	LO
<i>Capsella bursa-pastoris</i> (L.) Medik.	<i>Capsella bursapastoris</i>	Door-knocker (C0)	LO
<i>Deschampsia cespitosa</i> subsp. <i>cespitosa</i>	<i>Deschampsia cespitosa</i>	Established (C3)	LO
<i>Festuca rubra</i> subsp. <i>rubra</i>	<i>Festuca rubra</i>	Established (C3)	LO
<i>Lepidotheca suaveolens</i> (Pursh) Nutt.	<i>Matricaria discoidea</i>	Door-knocker (A)	NK
<i>Poa annua</i> L.	<i>Poa annua</i>	Established (C3)	NK
<i>Poa humilis</i> Ehrh. ex Hoffm.	<i>Poa humilis</i>	Established (C3)	LO
<i>Poa palustris</i> L.	<i>Poa palustris</i>	Door-knocker (C1)	NK
<i>Poa pratensis</i> L.	<i>Poa pratensis</i>	Established (C3)	LO
<i>Ranunculus acris</i> subsp. <i>friesianus</i> (Jord.) Syme	<i>Ranunculus acris</i>	Established (C3)	LO
<i>Ranunculus repens</i> L.	<i>Ranunculus repens</i>	Established (C2)	LO
<i>Ranunculus subborealis</i> subsp. <i>villosus</i> (Drabble) Elven	<i>Ranunculus propinquus</i>	Door-knocker (C1)	NK
<i>Rumex acetosa</i> L.	<i>Rumex acetosa</i>	Established (C3)	LO
<i>Rumex longifolius</i> DC.	<i>Rumex longifolius</i>	Door-knocker (C0)	NK
<i>Saussurea alpina</i> (L.) DC.	<i>Saussurea alpina</i>	Door-knocker (C1)	NK
<i>Stellaria media</i> (L.) Vill.	<i>Stellaria media</i>	Door-knocker (C1)	LO
<i>Tanacetum vulgare</i> L.	<i>Tanacetum vulgare</i>	Door-knocker (C1)	LO
<i>Taraxacum</i> sect. <i>Ruderalia</i> Kirschner, H.Øllg. & Stepánek	<i>Taraxacum ruderalia</i>	Established (C3)	LO
<i>Trifolium pratense</i> L.	<i>Trifolium pratense</i>	Door-knocker (C0)	NK
<i>Trifolium repens</i> L.	<i>Trifolium repens</i>	Door-knocker (C0)	NK
<i>Tripleurospermum maritimum</i> (L.) W.D.J.Koch	<i>Tripleurospermum maritimum</i>	Door-knocker (C0)	LO
<i>Urtica dioica</i> subsp. <i>dioica</i>	<i>Urtica dioica</i>	Door-knocker (C1)	LO
<i>Veronica longifolia</i> L.	<i>Veronica longifolia</i>	Established (C2)	LO

records for each species, including native and non-native ranges (i.e. the realised niche of the species). Some taxa belong to taxonomically complex groups; however, leaning towards the precautionary principle we retrieved all records under the accepted names according to GBIF backbone taxonomy. We removed records of *Deschampsia borealis* (Trautv.) Roshev. from *D. cespitosa* as this synonym likely includes records of *D. sukatschewii* subsp. *borealis* (Trautv.) Tzvelev which is native to Svalbard. Occurrence records of *Taraxacum* sect. *Ruderalia* Kirschner, H.Øllg. & Stepánek were retrieved as *Taraxacum ruderalia*.

Species occurrence data was subsequently cleaned (Gueta and Carmel 2016) following these steps: 1. We removed records lacking geographic coordinates or with geographic coordinate precision above 5 000m. 2. We removed occurrences with coordinates of 0°, 0°. 3. We removed records dating from before 1990 to ensure that occurrences were recent. 4. We removed duplicate occurrence records,

retaining a maximum of one record per species within 2.5' raster cells to prevent pseudoreplication. Suppl. material 1: fig. S1 shows the distribution of occurrences used for each species. A total of 9 239 240 species occurrence records were retrieved. After cleaning, 952 465 remained (most were removed as duplicates within 2.5' grid cells). The number of occurrence records ranged from 142 for *Ranunculus subborealis* subsp. *villosus* to 106 102 for *Achillea millefolium*.

Models were run using pseudo-absence data. Since the GBIF data used for species presences suffers from geographic and environmental biases (Petersen et al. 2021), we accounted for these biases in selecting pseudo-absence data. We selected 100 000 pseudo-absences through a weighted random sampling, where the total number of vascular plant (Tracheophyta) records on GBIF per 2.5' grid cell was used as the weighting (Suppl. material 1: fig. S2; GBIF.org 2023b).

Climatic suitability was modelled using WorldClim2.0 bioclimate variables (Fick and Hijmans 2017). We selected a subset of the 19 bioclimate variables for modelling based on a combination of ecological relevance and selecting variables only with $|r_p| < 0.7$ (Suppl. material 1: fig. S3). Since the 27 species have mostly temperate to boreal and arctic-alpine ranges (Suppl. material 1: fig. S1), we selected variables of ecological relevance in these seasonal environments and important to survival in Arctic conditions. The selected variables included three temperature variables: bio10 (temperature of the warmest quarter; i.e. growing season temperature), bio2 mean diurnal range (the mean of monthly difference between maximum temperature and minimum temperature; i.e. temperature variability), and bio7 (maximum temperature of warmest month). Two precipitation variables were also selected; bio18 (precipitation of the warmest quarter: i.e. growing season precipitation) and bio15 (precipitation seasonality – coefficient of variation of monthly precipitation).

Climate suitability modelling was implemented using ensemble species distribution modelling within the biomod2 package (Thuiller et al. 2023) within the R Statistical Environment (R Core Team 2023) running in a Linux environment. We selected a suite of six widely used models, namely generalised linear models (GLM), generalised additive models (GAM), generalised boosted regression (GBM), random forest (RF), maximum entropy (MaxEnt) and surface range envelope (SRE, also known as BIOCLIM). Each model was run 10 replicate times, each replicate taking a random sample of 80% of the species data for training and 20% for testing. Model evaluation statistics are shown in Suppl. material 1: fig. S4. Ensemble models were calculated, weighting on the AUC (area under the receiver operator characteristic curve ROC) but omitting poorly-fitted models with AUC of < 0.7 .

Model projections

The climate suitability models were projected across the archipelago of Svalbard at 30" resolution. Projections were at higher resolution than the training data in order to adequately visualise local variation. This is due to the limited extent of the projection (Svalbard) compared to the training range (global) and the need to mask out fjords and glaciers from the climate suitability projections. Each model was projected with both current climate conditions and a moderate and a severe future climate scenario. For the future scenarios we used the period 2061–2080 (chosen for relevance to the typical 50-year horizon of Norwegian ecological impact assessments of non-native species), and SSP2-45 (as a moderate scenario) and SSP5-85 (as an upper boundary). We used the model HadGEM3-GC31, although

note that there is very high correlation between different models. Future climate data was also downloaded from WorldClim (Fick and Hijmans 2017).

Ensemble models were projected as climatic suitability, bounded between 0 and 1. To estimate potential area of occupancy for each species across Svalbard, models were thresholded to binary projections using a threshold prediction level for each species that maximized the true skill statistic (TSS, maximising the sum of the specificity and sensitivity). The modal value across all 60 models per species was then taken across the model methods and replicates (if tied – i.e. 30 models predicting presence at one location, we assumed predicted presence, leaning toward precaution). Potential non-native species richness was estimated as the number of species with potential occupancy (modal threshold value = 1) for each cell. Glaciers and ice-covered areas were masked out from model projections, using GLIMS data (GLIMS Consortium 2005) to mask ice-covered regions.

Finally, we classified the model projections to determine potential bioregionalization of non-native vascular plant species on Svalbard. Using the package NBClust (Charrad et al. 2014), we first determined the optimum number of groups for both current and future assemblages, using the majority rule approach, kmeans clustering and Euclidean distances within the NBClust function, with a minimum and maximum number of clusters of 2 and 10. For both current and future climates the optimum number of clusters was three, hence cells were grouped into three clusters using kmeans clustering. Clustering was carried out using scaled model projections.

Results

Climate suitability models were trained for all 27 species based on global occurrences, and these were projected across Svalbard. Model evaluation scores varied between species and modelling methods. Generally, the machine learning methods (RF and GBM) had the highest AUC and TSS values, whilst the simplest method, surface range envelopes, had the lowest evaluation scores (Suppl. material 1: fig. S4). The species split roughly into two groups; one with relatively high evaluation scores (median AUC across models of >0.8 and median TSS of >0.5), and another group with relatively low evaluation scores (Suppl. material 1: fig. S4). The species with the higher evaluation scores were generally those with more restricted geographic ranges while globally widespread species had lower evaluation scores by both AUC and TSS (Suppl. material 1: figs S1, S5).

For some species, one of the bioclimatic variables was by far the most important in determining the distribution. For example, temperature of the warmest quarter for *Saussurea alpina*, mean diurnal range for *Tripleurospermum maritimum* and maximum temperature of the warmest month for *Veronica longifolia* (Suppl. material 1: fig. S6). While for other species, multiple variables are of roughly equal importance (Suppl. material 1: fig. S6). Many species had a unimodal or negative response to growing season temperatures, and a positive response to temperature annual range and a negative response to mean diurnal range (Suppl. material 1: fig. S7).

Under current climate, climate suitability varied across species (Fig. 1). Some species have high potential niche suitability across much of Svalbard such as *Deschampsia cespitosa*, *R. subborealis* subsp. *villosus* and *Saussurea alpina*. When the projections were thresholded to maximize TSS (Suppl. material 1: fig. S8), these

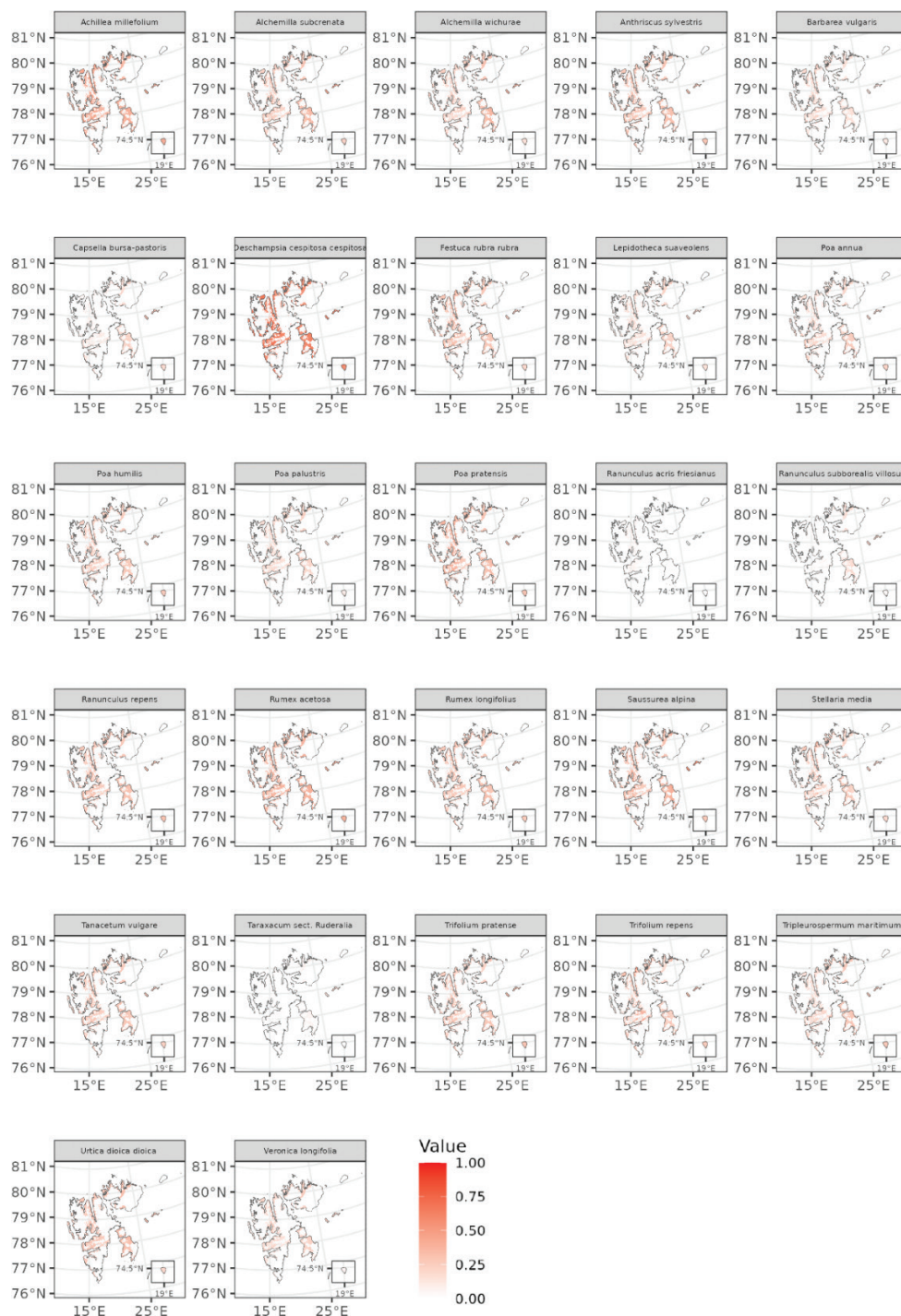


Figure 1. Ensemble projections of the potential macroclimatic niche distribution of all non-native vascular plant species across the archipelago of Svalbard under current climate. Species labels follow Artsnavnebase (Species Nomenclature Database; Artsdatabanken). See Table 1 for scientific names corresponding to the data downloaded from GBIF.

were also the species predicted to be most widespread, with an area of potential occupancy of 100% of the non-glaciated parts of Svalbard for *D. cespitosa* and *R. subborealis* subsp. *villosus* and 75% for *S. alpina* (Fig. 2, Suppl. material 1: table S2). However, of these three species, only *D. cespitosa* has an invasion potential (Suppl. material 1: table S1, Artsdatabanken 2023), thus this is ranked as the top risk species, followed by *Alchemilla wichuriae* and *Alchemilla subcrenata*, also assessed to have invasion potentials (Fig. 2). In contrast, climate suitability for other

species is very low under current climate including *Poa pratensis*, *Taraxacum* sect. *Ruderalia* and *Achillea millefolium*.

For most species the climate suitability is predicted to be higher under both future climate scenarios than under the current climate (Suppl. material 1: figs S9, S10). However, *Poa palustris* and *Ranunculus acris* do not have suitable climate available in Svalbard under neither present nor either of the future scenarios (Fig. 2, Suppl. material 1: figs S11, S12). The area of potential occupancy for several species including *Poa annua*, *Poa pratensis*, *Ranunculus repens*, *Rumex longifolius*, *Trifolium pratense* and *Trifolium repens* increases from around 0% under current climate to almost 100% of the non-glaciated regions of Svalbard under both future scenarios (Fig. 2). In contrast, the area of potential occupancy of *Saussurea alpina* decreased by around 3000 km² under the severe future climate scenario, but increased under the moderate future climate scenario by around 5000 km² compared to the current. Meanwhile the potential occupancy of *Veronica longifolia* decreased from a current potential area of around 5000 km² to below 500 km² under both future scenarios (Fig. 2).

Potential richness of non-native vascular plant species is greatest in the remote eastern islands of the Svalbard archipelago such as Edgeøya. The current climate here is suitable for up to 13 non-native vascular plant species (Fig. 3). Current climate is suitable for fewest species in the eastern part of the main island of Spitsbergen and northern Nordaustlandet, with some parts having suitable climate for only two species (*Deschampsia cespitosa* and *R. subborealis* subsp. *villosus*). The southern island of Bjørnøya also has suitable climate for many non-native species (Fig. 3).

The potential non-native species richness was far higher under both future climate scenarios than under the current climate. Some regions including Edgeøya had suitable climate for 25 non-native vascular plant species, out of a pool of 27 species under both future scenarios (Fig. 3). Potential species richness increased the most between current climate and the future scenarios in the central Spitsbergen region, where human activity is greatest (Fig. 3).

The projected models indicate a clear bioregionalization of potential assemblages of non-native species, with Eastern, Central Fjord and Western clusters being apparent under both current and future climates (Fig. 4). The cluster prevalent in the central region has lowest climate suitability for most species under both current and future climates (Suppl. material 1: fig. S13). The Western cluster had high climate suitability for *Poa pratensis*, *Festuca rubra* and *Achillea millefolium* under all climate scenarios, while the Eastern cluster was widespread with high climate suitability for many species under the current climate. However, under the future climate scenarios, the geographic extent of the Eastern cluster was further to the East (Svenskøya and around), and the climate suitability was low for most species, and the island of Edgeøya shifted from being grouped with the Eastern cluster under the current climate, to the Western cluster under future climate scenarios (Fig. 4).

Discussion

Biological invasions are a growing threat in polar ecosystems, where milder temperatures and increasing human activity heighten the risk for introduction and establishment of many globally invasive species (Duffy et al. 2017). The relative simplicity of communities in polar ecosystems increases the likely ecological impacts of establishing non-native species. So far Svalbard, in the high-Arctic, has largely

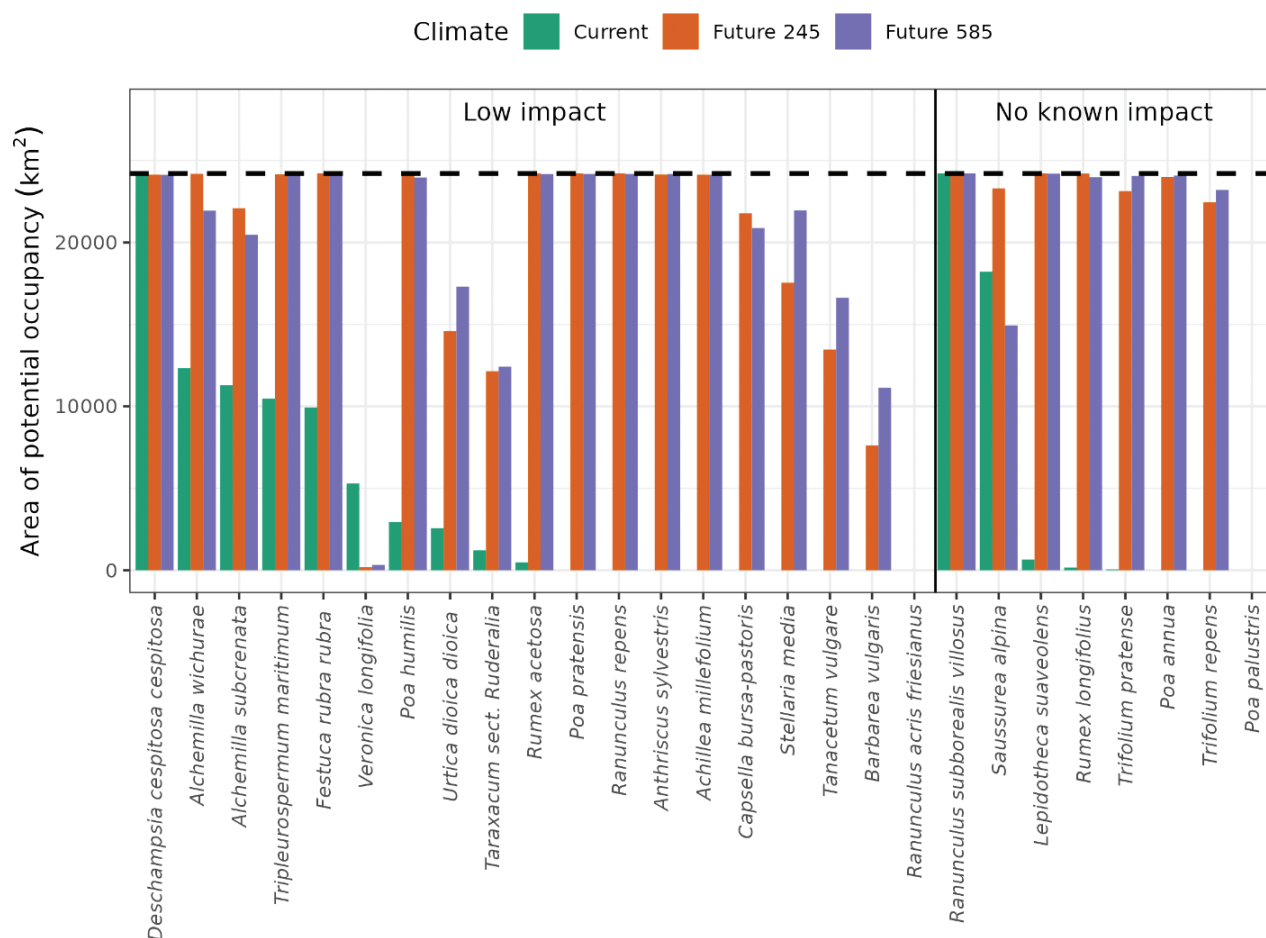


Figure 2. Area of potential range occupancy of 27 non-native vascular plant species across the Svalbard archipelago under current and future (SSP2-45 and SSP5-85) climate scenarios (see Suppl. material 1: figs S7, S9 for the corresponding maps). These are estimated using 30' second rasters. The total ice-free area of non-glaciated land available using this dataset is 24 210 km² and is denoted by a dashed horizontal line. Species are ranked first by their ecological impact category (and separated by a vertical line), next by the current area of potential range occupancy and lastly by the area of potential occupancy under the future intermediate climate scenario. All Low impact (LO) species score 1 for ecological effect (range 1-4) except *Anthriscus sylvaticus* (3, not currently present in Svalbard), *Festuca rubra* subsp. *rubra* and *Stellaria media* (both 2; Suppl. material 1: table S1, Artsdatabanken 2023). The areas and percentages of the non-glaciated parts of Svalbard are included in Suppl. material 1: table S2. Species labels follow the Norwegian Artsnavnebase (Species Nomenclature Database; Artsdatabanken). See Table 1 for scientific names corresponding to the data downloaded from GBIF.

escaped impacts of non-native vascular plants despite a relatively high number of species' introductions. All established or identified door-knocker species are currently confined to disturbed soils in settlements or around cabins, and all are assessed to present low impact or no known impact (Table 1, Suppl. material 1: table S1). There is thus an opportunity for preventive biosecurity management measures to be applied. To facilitate this, we mapped the current and future macroclimatic niche potential of the non-native vascular plants on Svalbard. We found that many species have a wide potential climatic niche on Svalbard today, with a high number of potential niches in some regions of the archipelago beyond the current sites of occurrence. Under future climate change many more non-native vascular plant species have a broad potential climatic niche across Svalbard.

The finding that many of the non-native species considered here are inside their realised climate niche on Svalbard today, shows that factors other than macroclimate likely limits these species occurring more widely across the archipelago

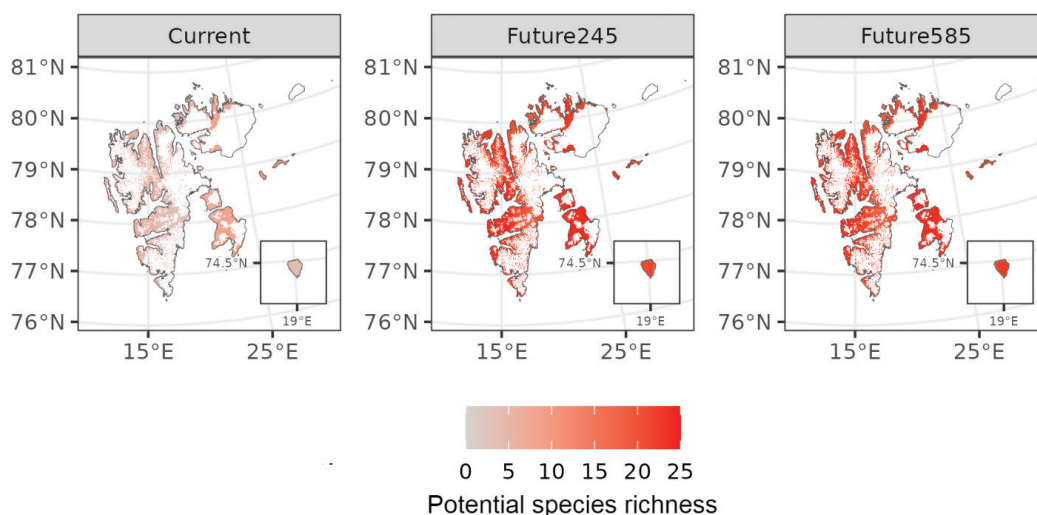


Figure 3. Potential species richness of non-native vascular plant species across Svalbard under current and two future climate scenarios. Potential species richness is estimated as the sum of species with potential occurrence based on thresholding of model predictions maximizing the true skill statistic.

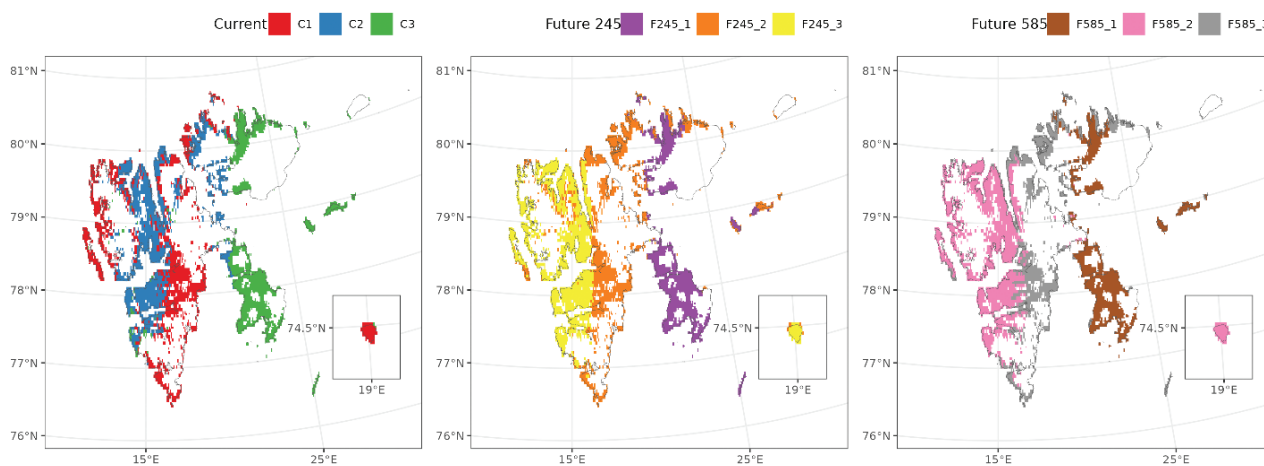


Figure 4. Potential non-native vascular plant species assemblage clusters across Svalbard under current and future climate scenarios. For all, the optimum number of clusters was three. These are illustrated using colours. The clustering was undertaken independently for each scenario, and the cluster groups have no direct correspondence between present and future climate scenarios. Species associations with clusters are shown in Suppl. material 1: fig. S11. The southern island of Bjørnøya is shown as an inset and ice-covered regions are excluded.

than their current distribution. Previous studies in Antarctica indicated that species like *Poa annua* and *Poa pratensis* were living at the farthest ends of their niche centroids (Perterra et al. 2017); our results suggest that many non-native vascular plant species are not at their climate niche limits on Svalbard. In contrast, under current climatic conditions, *Deschampsia cespitosa*, *Ranunculus subborealis* subsp. *villosus* and *Saussurea alpina* have the widest potential distribution on Svalbard, while *Deschampsia cespitosa*, *Alchemilla wichuriae* and *Alchemilla subcrenata* are the top ranked risk species with known invasion potential (Fig. 2, Suppl. material 1: table S1).

All species of non-native vascular plants on Svalbard have highly localised current distributions, on nutrient-enhanced and/or disturbed soils within the settlements and around some remote cabins. The introduced non-native plants on Svalbard may possibly still be under a lag phase of acclimatation-adaptation where

their dispersal capabilities are limited. Lag phases are not uncommon in polar ecosystems; for example Pertierra et al. (2013) showed that *Poa pratensis* struggled to flower in Antarctica, while it flowers so late in the season in Svalbard that seed-production may not always be possible (Elven et al. 2020; Westergaard et al. 2023). In contrast, the discovery of colonies of *Poa annua* in Antarctica from the 2010s (Molina-Montenegro et al. 2014) suggests that *P. annua* has overcome a lag phase of 30–40 years, and without the strict biosecurity and eradications in place, it could be more firmly established and spreading in Antarctica (Pertierra et al. 2023). Understanding lag phases in establishment in Svalbard is even more important considering future climate scenarios, where 19 of the 27 considered species have climatic potential to spread to over 75% of the non-glaciated parts of the archipelago.

The potential richness of non-native plants on Svalbard was found to be greatest in Eastern regions such as the large island Edgeøya, as well as the island of Bjørnøya, far south of the main archipelago. These parts of Svalbard are remote and more rarely visited than the central fjord regions. The high number of non-native vascular plant species with potential climatic ranges here suggests that these regions may be at greater risk of establishment by several non-native plant species. Importantly, the potential number of non-natives escalate the risk of causing functional disturbances to native plant communities (Beaury et al. 2023). There is thus a need to increase vigilance measures in these regions. For example, they could potentially be designated as sanctuary regions with limited human visits and increased biosecurity requirements. Future climate change will increase the number of species that can potentially survive in the central regions of Spitsbergen around the largest settlements (which are also the main potential import sites), notably Longyearbyen and Barentsburg. Thus, the key risk areas under future climate overlap with zones under different land-use such as settlements, heavily visited tourism and research sites and protected areas. The difference in potential species richness was greater between current conditions and the moderate future scenario, than between the moderate and severe future scenarios, indicating that non-native vascular plant species are likely to be an increasing issue in the high-Arctic, regardless of the magnitude of climatic change.

Clustering of the non-native species potential distributions across Svalbard revealed assemblages separated on the longitudinal axis. This clustering reflects the Svalbard's bioclimate sections (i.e. continentality-oceanity gradient representing oscillating temperature and precipitation) more closely than the bioclimatic zonation (temperature gradient representing thermal limits) (Elvebakk 1997). For some species (for example *Trifolium repens* and *Ranunculus acris*), precipitation variables were as, or more, important than temperature variables in the distribution models (Suppl. material 1: fig. S6). These results suggest that future precipitation patterns are also important in determining the distribution of non-native vascular plant species, and composition of non-native assemblages in the Arctic in the future. There are parallels here with importance of soil moisture, in addition to temperature, in driving shrub establishment in the tundra (Myers-Smith et al. 2015). It remains to be studied whether the clusters would also implicate different functional pressures (Beaury et al. 2023).

In this study we only included non-native species assessed for their ecological impact by the vascular plant committee for the Norwegian Alien Species List 2023 (Artsdatabanken 2023). We have not considered species which have never been observed or identified as potential door-knockers by the committee, which was

expert-led and based on monitoring data and a literature-based horizon scan (Suppl. material 1: table S1). However, many other species could find suitable climatic niches on Svalbard, and a full, data-driven horizon scan is required. Such exercises have been carried out for lower latitude regions including both climate suitability and import potential (Bayón and Vilà 2019).

Our study focussed on macroclimatic niche potential. In harsh environments, the microclimatic conditions that plants experience can substantially differ from macroclimatic conditions. In many cases this can offer refugia for species originating from less harsh environments (Lembrechts et al. 2018), thus our results may actually underestimate potential occupancy. Furthermore, species may undergo climatic niche shifts in their non-native ranges (Bates and Bertelsmeier 2021). Climate is unlikely to be the only factor limiting species potential establishment. Other limiting factors like soil development and nutrients (Doetterl et al. 2022), soil disturbance and biotic interactions with native species will play a major role in determining establishment potential for many non-native species. In addition, wind and other dispersal vectors will shape the speed of niche filling within the archipelago from the established non-natives. While our study presents the potential climate niche of the species (based on the global realised niche), the realised niche on Svalbard is likely to be far smaller. Conversely, some species such as *Achillea millefolium*, *Barbarea vulgaris*, *Poa palustris* and *Ranunculus acris* are identified as having no suitable current climate on Svalbard, yet all exist and disperse locally within settlements, so here the Svalbard realised niche is broader than the potential climatic niche. Microclimate as well as other factors, such as soil nutrients, disturbance or enemy release may lie behind this. It should also be noted that Svalbard's current climate differs from the current ranges of the species considered here, particularly in having a cooler summer temperature. Therefore, the models represent some degree of extrapolation in climatic space.

There are also taxonomic challenges in using global occurrence data to model regional distributions. Three of the most taxonomically complex groups in the northern hemisphere are included in this study. Firstly, Norwegian material of *Poa pratensis* s.lat. is considered to include five closely related species, all present in Svalbard: the native *P. alpigena* and *P. colpodea*, and the introduced *P. angustifolia*, *P. humilis*, and *P. pratensis* s.str. (Elven et al. 2022). Our data comprises *Poa pratensis* s.str. and our results show *P. pratensis* climate suitability is very low under current climate.

Secondly, *Festuca rubra* is not only one of the most widely distributed grasses of the northern hemisphere, but also among the taxonomically and morphologically most complicated of all northern grasses. Its main Arctic subspecies *richardsonii* is consistently accepted and is considered widely distributed in a wide range of habitats in Svalbard. Morphological characterization of the Svalbard material into two subspecies (the alien *F. rubra* subsp. *rubra* and the native *F. rubra* subsp. *richardsonii*) is, however, ambiguous, with potential transitional forms between the subspecies (Elven et al. 2020). The introduced *F. rubra* subsp. *rubra* is known from areas within the settlements and around old cabins, but has in recent years only been found in Longyearbyen, Pyramiden and Barentsburg. In addition, there are some morphologically less studied native populations in bird-cliffs along the west coast of Spitsbergen that may belong to *F. rubra* subsp. *rubra*. Our results suggest that both current and future Svalbard climates are suitable for *F. rubra*, and the species shows an affinity for the western clustered assemblage.

Thirdly, *Taraxacum* sect. *Ruderalia* (or *T. officinale* aggregate; Elven et al. 2020) is a large and taxonomically difficult section of dandelions consisting of cosmopolitan

weeds and many apomictic microspecies. In mainland Norway alone, more than 150–200 microspecies have been named, and there have not been any attempts to identify the Svalbard plants to microspecies. Occurrence records were therefore retrieved as *T. ruderalia* (GBIF synonym for *T. sect. Ruderalia*) to include data from the accepted section according to the Norwegian Nomenclature Database, to avoid including irrelevant occurrences, but with an unavoidable caveat of missing some relevant occurrences. Our results suggest low current climate suitability for *Taraxacum* sect. *Ruderalia*, but this will increase in the future.

In summary, the use of large datasets of species observations must accept the accompanying taxonomic uncertainty for individual data points. The precautionary principle suggests that leaning towards inclusivity of records is best, particularly where the focus is placed on aggregated results across species, such as this study. In many of the species, the limited number of current occurrences indicates that only a few lineages have established and thus their potential for adaptation to the high-Arctic can be limited by their genetic diversity. Hence our models could be over-predicting the potential distribution beyond the existing occurrences (Maclean and Early 2023). However, there is a high risk for repeated introductions in the future, thus the models provide a precautionary estimate of potential distributions. Even so, processes of adaptation to novel conditions with niche shifts are also documented for non-native plants (Bates and Bertelsmeier 2021; Häkkinen et al. 2022). Therefore, our models might in some cases even under-predict potential distributions.

Risk assessments of non-native species often focus on aspects of invasion potential and ecological impacts. This study estimates the potential area of occupancy of non-native species based on their realised niche, complementing quantitative ecological impact assessment (Sandvik et al. 2019; Artsdatabanken 2023). It also complements systematic, ongoing field monitoring of non-native vascular plant species (Ravolainen et al. 2019; Bartlett et al. 2021). Our results identify species that could be prioritised for early detection of local dispersal and rapid management response. However, it is clear that mechanistic studies, considering source pools of species, introduction pathways, establishment, and the ecological impact of single and multiple non-native species, are required to address the potential ecological impact of non-native plant species on Svalbard.

Biosecurity and implications for management

Non-native species continue to accumulate in novel ranges (Seebens et al. 2017; IBPES 2023), with invasive species causing irreversible changes to biodiversity particularly on islands. Yet, to date there is minimal biosecurity on Svalbard or other Arctic islands, in contrast with other remote island regions and polar regions. The Arctic Invasive Alien Species Strategy and Action Plan (CAFF and PAME 2017) priority actions include improving the knowledge base for well-informed decision making on options for preventing invasive alien species, and to undertake prevention and early detection and rapid response initiatives. Our results have implications for policy development on Svalbard where strategic biosecurity planning could play a preventative role. Our results suggest that the Eastern parts of Svalbard, including Edgeøya and Barentsøya, as well as the southern island of Bjørnøya, have high climatic suitability for many non-native vascular plant species: These already fall within Sørøst-Svalbard and Bjørnøya nature reserves, but minimising introductions to these regions by further limiting human activity should be

considered. Inaction in the control and management of non-native species often results in exponential costs as prevention and early eradication are cheaper than management of established and spread invasions (Hughes and Convey 2014; Epanchin-Niell 2017). As the climate continues to change, the number of potentially establishing species will only increase.

Conclusions

The terrestrial Arctic has been fortunate to escape widespread impacts from non-native vascular plants. However, climate change will exacerbate potential establishment whilst increased human activity will favour dispersal and wider establishment opportunities at disturbed regimes. Our study maps the potential climate niche of non-native vascular plant species across Svalbard, finding that climate does not prevent the distribution of many species today, and will prevent the distribution of even fewer in the future. Environmental management on Svalbard has a window of opportunity to take proactive steps to minimise new introductions and establishment of non-native plants and avoid further dispersal of already established non-native species.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

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Author contributions

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

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Supplementary material 1

Supporting information

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Data type: docx

Explanation note: **table S1**. References with species-specific strings and permanent links for each of the studied 27 non-native plant species' ecological impact assessments. **table S2**. The total area of potential occupancy (km²) of the 27 non-native species across the Svalbard archipelago under current and future (SSP 2-45 and 5-85) climate scenarios (data from Fig. 2, also see figs S8, S11 and S12 for the corresponding maps). **fig. S1**. GBIF spatial occurrence records downloaded for the plant species used in the study (GBIF.org, 2023a). **fig. S2**. The number of GBIF spatial occurrence records across the world for vascular plants (Tracheophyta) per 2.5' grid cell, used as a bias weighting in sampling pseudo-absences (GBIF.org, 2023b). **fig. S3**. Pearson correlation matrix used to evaluate the colinearity of the 19 global bioclimate variables and select the five representative macroclimate variables used for the distribution modelling. **fig. S4**. Evaluation statistics of the models predictive performance across all species. **fig. S5**. Evaluation statistics (TSS and ROC) of the models predictive performance plotted against the number of occurrence records per species. **fig. S6**. Variable importances of the macroenvironmental predictors estimated across modelling methods and replicates for each species and bioclimatic variable. **fig. S7**. Response curves to the five macroenvironmental predictors per species and model algorithm. **fig. S8**. Thresholded binary species predictions of potential distribution under the current climate conditions. **fig. S9**. Model predictions for each species potential distribution under future climate (SSP2-45, 2061-2080). **fig. S10**. Model predictions for each species potential distribution under future climate (SSP5-85, 2061-2080). **fig. S11**. Thresholded model predictions for each species local potential distribution under future climate (SSP5-45, 2061-2080). **fig. S12**. Thresholded model predictions for each species local potential distribution under future climate (SSP5-85, 2061-2080). **fig. S13**. Species associations within the assemblage clusters under current and future scenarios (the clustering was independent within each time period so the cluster number is not comparable between scenarios).

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