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Research article

Horizon scanning of potential invasive alien plant species and their distribution in Norway under a changing climate

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Invasive alien plant species can cause considerable ecological, economic, and social impacts, and the number of impactful species will likely increase with globalisation and anthropogenic climate change. Preventing potentially invasive alien plant species from becoming introduced is the most cost-effective way to protect Norway's ecosystems from future invasions. We developed and applied a new method for horizon scanning to identify high-risk potentially invasive alien plant species that are not yet present in Norway but could be introduced and become naturalised and invasive in the future. Starting with 16 866 species known to be naturalised somewhere globally, we employed a simple and novel method for assessing the climate match of each species' known distribution to Norway's climate, then used economic and environmental impact data to narrow them down further. Of the species identified, we implemented species distribution models to predict the potential distribution of these high-risk species in Norway under both current and projected future (2060–2080) climate scenarios. A total of 265 plant species were identified as posing a high invasion risk to Norway. Under the current climate, their distributions were mostly limited to the southeast and coastal regions of Norway. However, under future climate change scenarios, the species' potential distribution increased significantly, with their ranges expanding northwards and further inland. Several invasion hotspots containing large numbers of species were identified close to urban areas such as Oslo, which is of particular concern as urban areas are amongst the most highly invaded environments globally. We strongly recommend that the import into Norway of species identified in this study be closely monitored and/or restricted to reduce the risk of invasions and to safeguard Norway's native biodiversity. We have also presented a novel and widely

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applicable method of horizon scanning with a particular focus on climate matching between species and the area of interest for both current and future climate scenarios.

Keywords: climate change, horizon scanning, naturalisation, non-native species, Norway, species distribution modelling

Introduction

Invasive alien species are known to be a major component of local and global environmental change, with a wide range of impacts on biodiversity, ecosystems, and economies (Chornesky and Randall 2003, Essl et al. 2011, Welch and Leppanen 2017, Dueñas et al. 2018, IPBES 2023). Among invasive alien species, plants are typically the most numerous, and they can transform ecosystems through, for example, changes in vegetation structure, pollinator populations, nutrient cycling, and hydrology (Weidenhamer and Callaway 2010, Pyšek et al. 2012, Bezemer et al. 2014, Weidlich et al. 2020). Plants can be intentionally or unintentionally introduced via many different pathways, but especially through trade in ornamental plants (Reichard and White 2001, Beaury et al. 2021). Other key industries (such as forestry and agriculture) may be responsible for the introduction of fewer species globally but involve planting species in high numbers and in multiple locations, across large areas of landscape (Richardson 1998). Furthermore, it is predicted that recent increases in global trade will result in greater levels of plant naturalisation in the future due to a lag between trading activity and non-native species accumulation (Seebens et al. 2015). The most cost-effective way to prevent future invasions is to identify species that pose a high risk of invasion to a recipient region and to prevent their introduction (CBD 2010, Shine et al. 2010, Essl et al. 2011, Ahmed et al. 2022). Identification and prevention of the introduction of high-risk plant species are easier to achieve for intentionally introduced species, e.g. through the creation of legislation and enforcement that would ban imports for established economic use.

The impacts of invasive alien plants are likely to be exacerbated under climate change, which is predicted to increase invasive alien species' ability to invade new areas while simultaneously decreasing native species' ability to resist invasions (Thuiller et al. 2007). More specifically, climate-change-induced warming enables non-native plants to move to higher latitudes (Walther et al. 2009, van der Putten et al. 2010, Schweiger et al. 2010) and elevations (Walther et al. 2009, Petitpierre et al. 2016), where increased performance and longer growing seasons are likely to enhance invasion success. High-latitude countries, such as Norway, are therefore likely to become more vulnerable to plant invasions in the future because rates of temperature increase are higher towards the poles (IPCC 2014). Norway is already home to over 1000 naturalised non-native species, 71% of which are plants (Sandvik et al. 2019, Norwegian Biodiversity Information Centre 2023a), and, according to a recent inventory, 3% of all stably reproducing species in Norway are non-native (Sandvik et al. 2019).

While a wide range of evidence-based weed risk assessment and risk analysis systems have been developed (outlined below) and implemented to evaluate invasion risks and inform biosecurity legislation, the sheer number of plant species that could be introduced to a country and become invasive now or in the future demands a more rapid approach. In fact, reducing the introduction of invasive alien species by 50% is listed as one of the 2030 targets by the Kunming–Montreal Global Biodiversity Framework (CBD 2022). Horizon scanning is a systematic method of evaluating future potential threats (Roy et al. 2014), and recently, several horizon scanning approaches have been developed and tested to rapidly identify high-risk invasive alien plant species. These either involve consensus-building methods (Sutherland et al. 2008, Roy et al. 2014, Gallardo et al. 2016, Peyton et al. 2019) or decision trees that consider suitability, such as the notable example of the Australian Weed Risk Assessment (WRA) proposed by Pheloung et al. (1999), which has been utilised to identify high-risk species in Spain (Bayón and Vilà 2019) and to determine 'weediness' (invasive potential) in South Africa (Cheek et al. 2021). However, the suitability of climate for a species in the location in question has rarely been assessed with great accuracy in horizon scanning studies. One exception is the European Plant Protection Organisation (EPPO), which carries out Pest Risk Assessments for a number of species and integrates current and potential future distributions in its analysis using climatic niche modelling (EPPO 2023). Other methods used in the literature have been varied. Bayón and Vilà (2019) compared the temperature tolerances of each species with the climatic extremes of Spain to assess species' survivability. Matthews et al. (2017) recommended the Köppen–Geiger Climate Classification, whereby the world is split into broad climatic zones that are used to determine where a plant could survive based on its known distributions (Rubel and Kottek 2010). Finally, Sandvik (2020) used data on species' biogeography according to Plants of the World Online (POWO 2022) to predict species' climatic tolerances. These approaches do not consider the specific climatic niche of each species individually or, importantly, how climate suitability may change in the future, and how these changes will affect whether and where introduced plant species could pose a higher invasion risk.

In this study, we developed and applied a novel method of horizon scanning to identify which potentially invasive alien plant species could pose a threat to Norway. Here, we define 'invasive alien' species according to the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) definition as 'a subset of established alien species that spread and have a negative impact on biodiversity, local ecosystems, and species' (IPBES 2023). We

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considered the economic use and environmental impact of a large starting pool of species, with a particular focus on the climatic suitability of Norway for each species. Furthermore, we investigated how climate suitability for these species will likely change in the future and which areas of Norway are most at risk under both the current climate and predicted future climate change scenarios.

Methods

In our horizon scanning study, we first established a set of criteria and used these to assess an initial list of 16 866 plant species to determine which could pose a risk to mainland Norway (Fig. 1). We chose these assessment criteria to determine whether a plant could survive in Norway if introduced (climatic suitability), if it was likely to become introduced (economic use), and if it was likely to harm Norwegian ecosystems if established (environmental impact). Here, we summarise the different stages of the framework, which is outlined in Fig. 1; for a full description of the methods, please see the Supporting information. All data handling in this and the following sections was completed in R ver. 3.6.1 (www.r-project.org).

Does a species have the ability to naturalise outside its native range?

We downloaded a list of global, currently known naturalised or invasive alien non-native vascular plants from the Global Naturalized and Alien Flora (GloNAF) database (van Kleunen et al. 2019) in December 2019 as our initial pool of species. We removed non-native species that already occur in Norway and Norwegian native plant species from the list, using native species lists obtained from the Germplasm Resources Information Network (GRIN; USDA Agricultural Research Service 2015) and the Norwegian Biodiversity Information Centre (2023b).

Could a species survive in Norway if introduced?

Assessing the suitability of the climate for a species is key to determining whether that species could survive if introduced to Norway. Dynamic range boxes are a tool to quantify the size and overlap of n-dimensional hypervolumes (Junker et al. 2016), a set of points representing biologically relevant variables represented in an n-dimensional space (Hutchinson 1957). We used this method to compare the hypervolumes of Norway's climate and the species' climatic niche. Analyses of climatic niche overlaps showed that they were a fair predictor of a species' ability to become naturalised in Norway (Supporting information).

To construct species' climatic niche hypervolumes, hereon called 'climatic spaces' due to the use of only three variables (see below), global occurrence data were first required for all species. We obtained these data from the Global Biodiversity Information Facility (GBIF 2022), using the R package 'rgbif' (Chamberlain et al. 2020). Species' occurrences were included regardless of whether they were in the native or non-native range, following recommendations by Bocsi et al. (2016). Please see the Supporting information for details on how occurrence records were filtered. For occurrence download citations, see the Derived dataset (2024, https://doi.org/10.15468/dd.6f7jfc).

We downloaded the global current climate data at a 5-minute resolution from WorldClim (Fick and Hijmans 2017), for all of the 19 bioclimatic variables described on WorldClim, using the R package 'raster' (Hijmans and van Etten 2012). This resolution was selected as a compromise between detail and computational ability. We applied a principal component analysis (PCA) to all 19 variables within Norway to select the bioclimatic variables that best explained the total variation in Norway's climate. The first axis (62.7% of total variance) correlated with precipitation variables. The second axis (16.3%) correlated mostly with temperature variables, and the third axis (8.3%) correlated with precipitation seasonality. Together, these variables explained 87.5% of the total bioclimatic variation across Norway. For each principal component, we chose a variable that was strongly correlated with each PC axis. The resulting three variables were annual precipitation (mm; AP), mean temperature of the warmest quarter (°C; TWQ), and precipitation seasonality (coefficient of variation (CV); PS), respectively. These variables were also chosen to represent the Norwegian climate in a study by Speed and Austrheim (2017), who employed a similar technique. We tested the correlation and collinearity between the variables by calculating Spearman's rank correlation and the variance inflation factor (VIF). The results indicated minimal correlation and low collinearity, which are below reported correlation and collinearity thresholds (Pradhan 2016), supporting the inclusion of these variables in the climate analysis (AP and TWQ: $\rho^2 = 0.06$, $p < 0.05$, VIF = 1.10; AP and PS: $\rho^2 = 0.11$, $p < 0.05$, VIF = 1.12; and TWQ and PS: $\rho^2 = -0.01$, $p < 0.05$, VIF = 1.01).

To predict species' future climate suitability across Norway, CMIP6 (Coupled Model Intercomparison Project Phase 6) climate predictions were acquired from WorldClim (Eyring et al. 2016, Fick and Hijmans 2017). We downloaded bioclimatic variable data at a 5-minute resolution for SSP2-45 and SSP5-85 for eight different general circulation models (GCMs) for the years 2061–2080, to represent both an intermediate and the most severe greenhouse gas emissions scenarios for climate change, respectively. This time period was chosen to represent a medium-term timescale, which would still be relevant to national planning while capturing the potential climatic shifts that could lead to changes in climatic suitability for species. We calculated a mean bioclimatic variable value across all GCMs for all grid cells, each for SSP2-45 and SSP5-85.

To determine whether a species could survive in Norway based on climatic suitability, we calculated the climatic niche overlap between each species' climatic niche (using climate data extracted from each occurrence point) and Norway's

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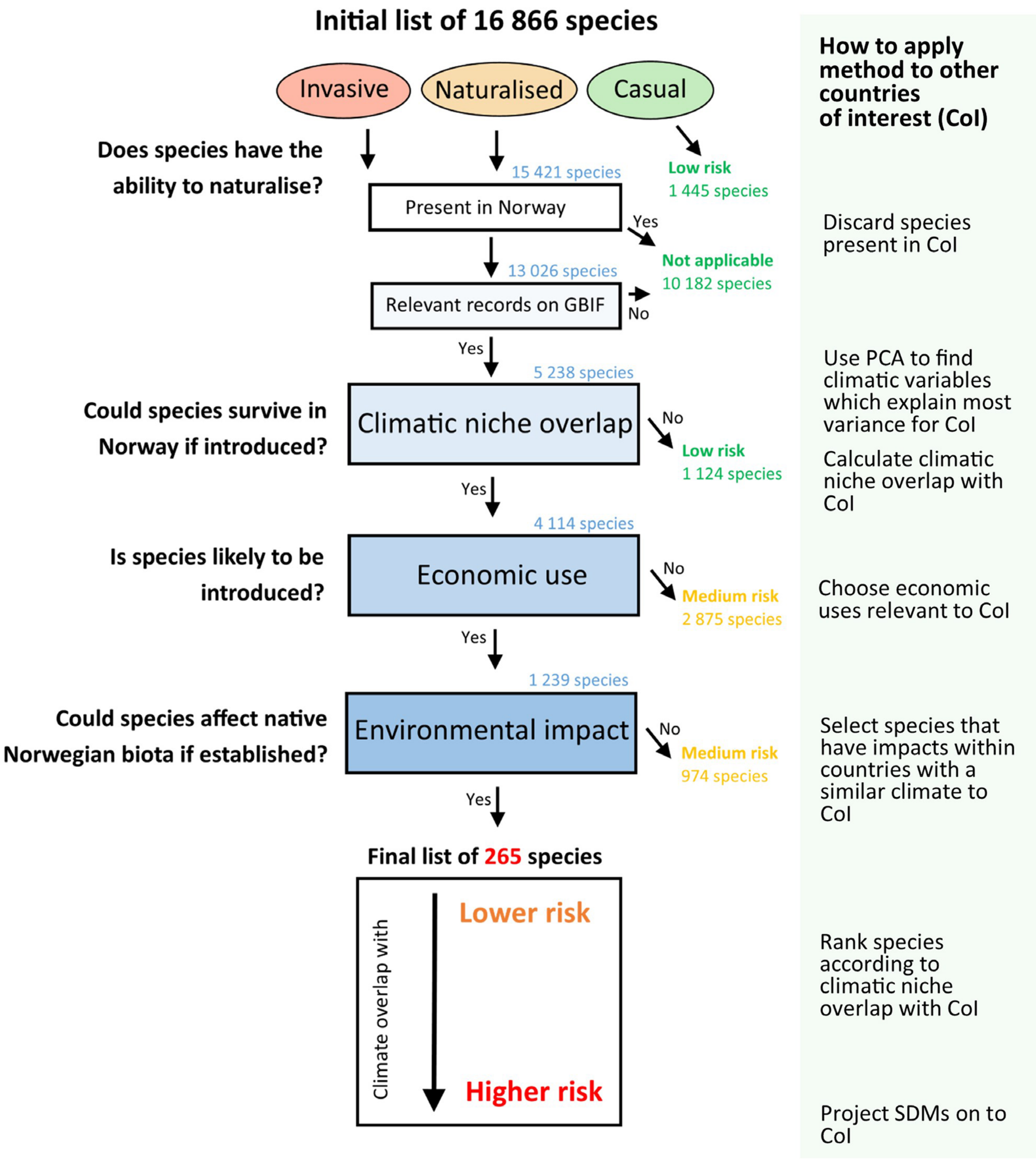

Figure 1. Framework used to assess species to determine which could pose a risk to Norway. Key questions are in bold and are addressed in each method's section below. Blue boxes represent how questions were addressed. Numbers indicate how many species fulfilled each category and how many were discarded at each stage. Low-risk (green) species are very unlikely to become a risk to Norway due to their inability to naturalise outside their native ranges and the climatic unsuitability of Norway. Medium-risk (yellow) species are unlikely to pose a threat to Norway, as they are not used in local industries and are therefore unlikely to be introduced, and, with no known environmental impacts, they are also unlikely to harm Norwegian biota if introduced. Right-hand panel shows how methods can be adjusted to be used for other countries of interest.

current climate for all species using the 'dynRB' R package (Junker et al. 2016). We employed a method in which, if there was zero overlap within any one dimension of the climatic space, the overall mean overlap was zero. All species with a climatic niche overlap above zero with Norway's current climate were selected. Climatic niche overlaps with climate scenarios SSP2-45 and SSP5-85 were also calculated for all species.

Is species likely to be introduced?

Plants are often introduced to non-native areas for economic purposes, and the naturalisation success of non-native plants is more likely if the plant has economic value (van Kleunen et al. 2020). We therefore chose economic use as a proxy for the introduction pathway. We obtained data describing the global economic uses of plant species

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from the World Economic Plants database, accessed via the Germplasm Resources Information Network (USDA Agricultural Research Service 2015) of the US National Plant Germplasm System. We selected the three most common economic uses of 129 non-native species already in Norway that were deemed to be high or very high risk by the Norwegian Biodiversity Information Centre (2023a) – horticulture, animal fodder, timber – and listed plants with at least one of these economic uses as those that could be purposely introduced to Norway.

Could species harm native Norwegian biota if introduced?

An invasive alien non-native plant is defined as a naturalised plant that harms biodiversity, ecosystems, or species in its invaded ecosystems (Hellmann et al. 2008, CBD 2010, IPBES 2023). We therefore included this factor in our horizon scanning study, as our aim was to identify potentially harmful invasive alien species rather than just non-native species. The Global Register of Introduced and Invasive Species (GRIIS) database contains information on whether a non-native species has a documented ecological impact and in which country this impact has occurred (Pagad et al. 2018). To determine whether these environmental impacts occurred in places with a climate similar to that of Norway, we compared the climatic spaces of each country's climate and Norway's climate using the 'dynRB' package (Junker et al. 2016). Countries with a climate overlap greater than zero shared some climatic characteristics with Norway. Only species that had a known ecological impact in countries with some climatic overlap with Norway were selected.

Application of methods to other countries

We have presented a novel method for horizon scanning of high-risk species in Norway. However, this method could be applied to any country with some minor adjustments. Firstly, species that occur in the country or region of interest should be removed (both native and non-native). Secondly, a PCA of current climate data can be carried out to identify which of the nineteen bioclimatic variables explain the most vari-ation in climate for the country of interest. These climate data can then be used in a climatic space analysis and any species distribution model projections. For the analysis of which economic uses might result in a species' import into the country of interest, a list of naturalised or invasive alien species in the country of interest can be obtained. In this study, we used the Norwegian Biodiversity Information Centre (2023a); however, plant species data recorded in other countries can be obtained from national databases, or global ones such as GloNAF (van Kleunen et al. 2019). The main economic uses of these species can then be matched using the Germplasm Resources Information Network (USDA Agricultural Research Service 2015). Finally, climate overlap between the country of interest and countries where species have an environmental impact can be calculated to determine whether this environmental impact is likely to occur in the country of interest. These adjustments are shown in Fig. 1 at the appropriate stages of the framework.

High-risk species in Norway

In summary, the final list of species considered to pose a high invasion risk to Norway included species that: 1) have a known global occurrence distribution with non-zero overlap with Norway's current climate, 2) have at least one of the three top economic uses important to Norway, and 3) have known impacts in other regions with climates similar to that of Norway. A total of 265 species met these criteria. However, while these shortlisted species are deemed 'high-risk', the extent of their risk will vary partly due to the climatic suitability of Norway. We therefore ranked them according to their climate overlap with Norway's current climatic conditions (Supporting information, Table 1). To determine whether climatic niche overlap was affected by climate change, paired t-tests were conducted to compare climatic niche overlap scores of these high-risk species under current, SSP2-45, and SSP5-85 scenarios. To assess the importance of climate matching in the current dynamics of plant invasion, we compared the climatic niche overlap of these species with that of 45 species listed as invasive in Norway with severe impacts on Norwegian ecosystems, according to the Norwegian Biodiversity Information Centre (2023a). Current climate data for their occurrences were downloaded in the same manner as for the species in our horizon scanning study, and the climatic space overlap was calculated.

Climate overlap sensitivity analysis for high-risk species

Climatic variables associated with occurrence records may not be accurate in areas with high climatic variation within a single grid cell, such as in mountainous regions and may misrepresent the true climatic niche of a species. Therefore, we carried out a climatic overlap sensitivity analysis for the five high-risk species with the highest climate overlap with Norway (*Gunnera tinctoria, Muehlenbeckia complexa, Petasites pyrenaicus, Senna multiglandulosa* and *Persicaria nepalensis*) by removing outliers of the temperature variable TWQ and repeating climatic niche overlap calculations (Supporting information).

Mapping the potential current and future distributions of high-risk plant species

The potential distributions of the 265 high-risk species were projected across Norway using species distribution models (SDMs) (Fig. 2). All SDMs were computed using the R packages 'biomod2' (Thuiller et al. 2009) and 'dismo' (Hijmans et al. 2015). We chose to use the same climatic variables as those used in the climatic niche overlap

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Table 1. Top 10 species identified in the horizon scanning study ranked according to climatic niche overlap between species' climatic niche and Norway's current climate using climatic spaces. Native and invasive ranges are according to POWO (2022) and the number of countries with reported impacts are according to GRIIS (Pagad et al. 2018). For predicted distributions of these across Norway see the Supporting information.

Species	Family	Current overlap	SSP2-45 overlap	SSP5-85 overlap	Economic use	Where is it native?	Where is it invasive?	No. countries with reported impacts
Gunnera tinctoria	Gunneraceae	0.31	0.53	0.66	Ornamental	South America	NW Europe, S Australasia, N America	9
Muehlenbeckia complexa	Polygonaceae	0.24	0.34	0.38	Ornamental	New Zealand	N America, S America, Western Europe	8
Petasites pyrenaicus	Asteraceae	0.23	0.46	0.61	Ornamental	Mediterranean Europe	NW and S Europe, S Australasia, N America	7
Senna multiglandulosa	Fabaceae	0.23	0.32	0.36	Ornamental	Central and South America	S Asia, S Australasia, Africa, N America	7
Persicaria nepalensis	Polygonaceae	0.20	0.32	0.39	Ornamental	Africa, Asia	N America, S America, NW and SE Europe	17
Prunus lusitanica	Rosaceae	0.20	0.36	0.41	Ornamental	SW Europe, N Africa	N America, UK, Australia	8
Cupressus lusitanica	Cupressaceae	0.19	0.33	0.39	Ornamental, forestry	Central America	NW and S Europe, Himalayas, E Africa	16
Symphytum caucasicum	Boraginaceae	0.18	0.38	0.59	Ornamental	E Europe	W Europe	7
Trachycarpus fortunei	Arecaceae	0.17	0.32	0.43	Ornamental	China	E Asia, UK, S Europe	12
Dahlia imperialis	Asteraceae	0.17	0.28	0.34	Ornamental	Central America	S America, S Asia, Australia, Portugal	6

calculations (TWQ, AP and PS). We selected generalized linear models (GLM), generalized additive models (GAM), random forests (RF) and boosted regression trees (GBM), as in Dullinger et al. (2017) and Bagchi et al. (2013), to represent two classical regression models (GLM and GAM) and two machine-learning models (RF and GBM). These algorithms all require both presence and absence data. To generate pseudo-absence data, we created circles with a 200 km radius around each presence point and sampled pseudo-absences from outside these radii (Dullinger et al. 2017). For GLM and GAM, we sampled 1000 pseudo-absence points, and for RF and GBM the number of pseudo-absences we selected equalled the number of presence points, following Barbet-Massin et al. (2012). Pseudo-absences were sampled ten times per species to control for any potential sampling bias. When fitting models, we used a five-fold cross-validation approach, training models using 80% of the data and testing them on the remaining 20%. To minimise the impacts of spatial autocorrelation (SAC) (Dormann 2007), we created cross-validation samples using a blocking method (Bagchi et al. 2013). For this, we downloaded a world map of ecoregions according to WWF (Olson et al. 2001), which we then grouped into five blocks, each with a similar mean and variance for the three bioclimatic variables selected for the SDMs. For each training run, four of these five blocks were selected for model calibration, and the final block was used for model evaluation. We evaluated the resulting models using the relative operating characteristic (ROC) curve procedure, which produces an area under the curve (AUC) metric. Models with an AUC below 0.7 were rejected in accordance with Zhang et al. (2015), who state that evaluation scores below 0.7 are considered poor, 0.7–0.9 moderate, and above 0.9 good. Successful models were created using all four modelling techniques for all species except *Allium neopolitanum, Cereus jamacaru, Cestrum parqui, Lathyrus tingitanus, Opuntia ficus-indica* and *Pinus radiata.* These species had no GLMs with ROC values above 0.7, so only the three model types GAM, RF and GBM were used (Supporting information). Four different models (GLM, GAM, RF, GBM) with ten pseudo-absence sampling runs, each with five training runs, resulted in up to 200 models (or up to 150 for species with no successful GLMs) in total per species.

Model projection and mapping

We projected each of the 200 models using current (1970–2000) and future (2061–2080) climate data across Norway (both intermediate (SSP2-45) and severe (SSP5-85) climate change scenarios) (Fig. 2). Unlike the climatic space calculations, each of the eight future climate GCMs was projected individually instead of using the mean value for each scenario. Up to 3400 projections were therefore computed for each species (200 current and 200 each of 16 future predictions, with some removed due to low AUC scores). To create an ensemble model, we calculated the mean of each projection across all models (GAM, GLM, GBM and RF) for each of the climate scenarios for all raster cells, resulting in one

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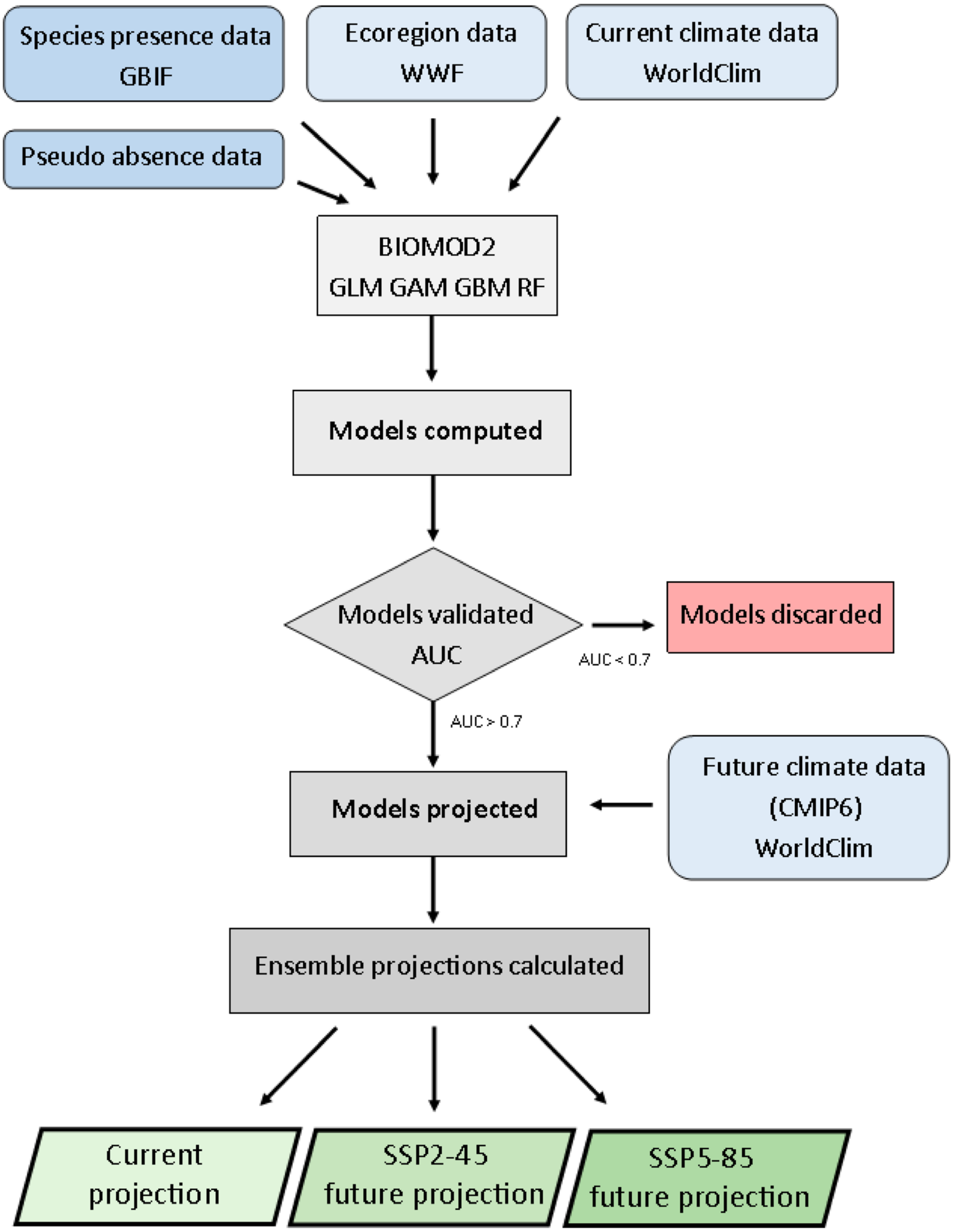

Figure 2. Framework used to carry out species distribution models (SDMs) on 265 high-risk species identified by horizon scanning study. Blue boxes represent input data, grey boxes represent model processes, and green boxes represent model outputs.

ensemble model for each species under each climate scenario: current, SSP2-45 and SSP5-85. Averaging was unweighted as all models with an AUC below 0.7 were discarded. We converted these mean model predictions into binary presence/absence predictions by applying a threshold that optimised the true skill statistic (TSS) metric (Allouche et al. 2006). We then calculated the sum of all species' presence/absence scores to give the number of species with potential distribution in each 5-minute grid cell (equal to 9 km^2 at the equator) for all three climate scenarios, and mapped to identify 'hotspot' regions of invasion risk under current and future climates, which contained a high number of species.

Analysis of model results

For each species and each climate scenario, we determined the percent cover of Norway by calculating the proportion of grid cells in Norway that contained presence predictions. Species' northern limits were also determined as the highest latitude that contained presence predictions. We then compared these values for all species between climate scenarios using paired t-tests to determine how the range cover of Norway and latitudinal limits might be affected by climate change.

Finally, to determine whether climatic niche overlaps were a good predictor of species distribution model results,

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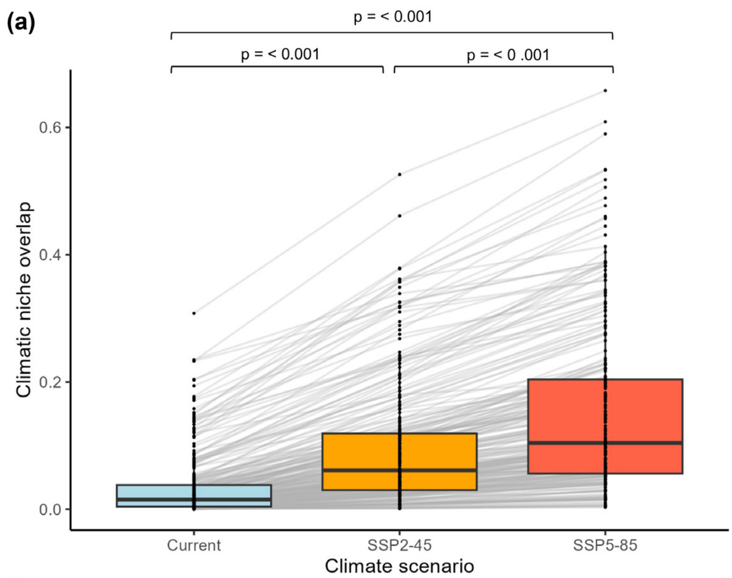

(b)

Test	Estimate	T statistic	Parameter	Conf. interval	p-value
Current vs SSP2-45	-0.061	-19.541	267	-0.067 to -0.055	**< 0.001**
Current vs SSP5-85	-0.117	-20.907	267	-0.128 to -0.106	**< 0.001**
SSP2-45 vs SSP5-85	-0.056	-21.028	267	-0.061 to -0.051	**< 0.001**

Figure 3. (a) Climatic niche overlap scores calculated between high-risk species' climatic niches and Norway's climate under current and future (SSP2-45, SSP5-85) climate change scenarios, and (b) paired t-test results comparing climatic space scores between each climate scenario.

we carried out a Pearson correlation analysis between all 265 species' climatic niche overlaps and the proportion of grid cells in Norway that contained presence predictions for each climate scenario.

Results

A total of 265 potential non-native species were identified as high-risk to Norway based on climatic niche overlap, economic use, and ecological impact (Table 1; Supporting information). These species are currently mostly distributed across western Europe, Central America and the USA, South Africa and southeastern Australasia (Supporting information). The high-risk species belonged to 75 families, the most common being Fabaceae with 34 species, followed by Poaceae with 25 species and Asteraceae with 18 species (Supporting information). A total of 239 species are used as ornamental plants, 38 for timber and 30 as animal fodder (note that some species have multiple uses). Climatic niche overlap of high-risk species ranged from < 0.01 to 0.31 with a mean of 0.04 (0.004 lower quartile (LQ) to 0.04 upper quartile (UQ)) under current climate conditions, and overlap increased significantly by 2061–2080, both from the current climate to SSP2-45, which had a mean of 0.10 (0.03 LQ to 0.12 UQ), current climate to SSP5-85, which had a mean of 0.15 (0.06 LQ to 0.20 UQ), and between SSP2-45 and SSP5-85 (Fig. 3). The species with the highest climatic niche overlap in all climate scenarios was *Gunnera tinctoria*, the Chilean rhubarb, native to Chile and Argentina.

We compared the climatic niche overlap of species currently invasive within Norway to that of our shortlisted species. The invasive species generally had much higher climatic niche overlaps, with an average of 0.33 (0.25 LQ to 0.39 UQ) overlap with Norway's current climate. Only one invasive species had an overlap of < 0.1 (*Parthenocissus quinquefolia*) (Supporting information).

In terms of species' potential distributions under the current climate, all grid cells within Norway contained at least one shortlisted species, with a maximum of 76 species predicted to occur in any one grid cell. The distributions of high-risk species were mainly clustered around the southern and western coasts of Norway (Fig. 4). Of these, 139 species were not predicted to occur anywhere in Norway under the current climate, with corresponding climatic niche overlap scores of < 0.001–0.120 (Supporting information). Under the future climate scenario SSP2-45, there was a maximum of 221 species in any one grid cell. The highest number of species was predicted to occur near Oslo, with a further cluster north of Trondheim in the boreal rainforest region (DellaSala et al. 2011; Supporting information). Under scenario SSP2-45, only 23 high-risk species were not predicted to occur anywhere in Norway, with corresponding climatic niche overlap scores of < 0.001–0.021. Under SSP5-85, there was a maximum of 233 species predicted to occur in any one location. The area containing more than 200 species increased to cover a wider region in the south, around

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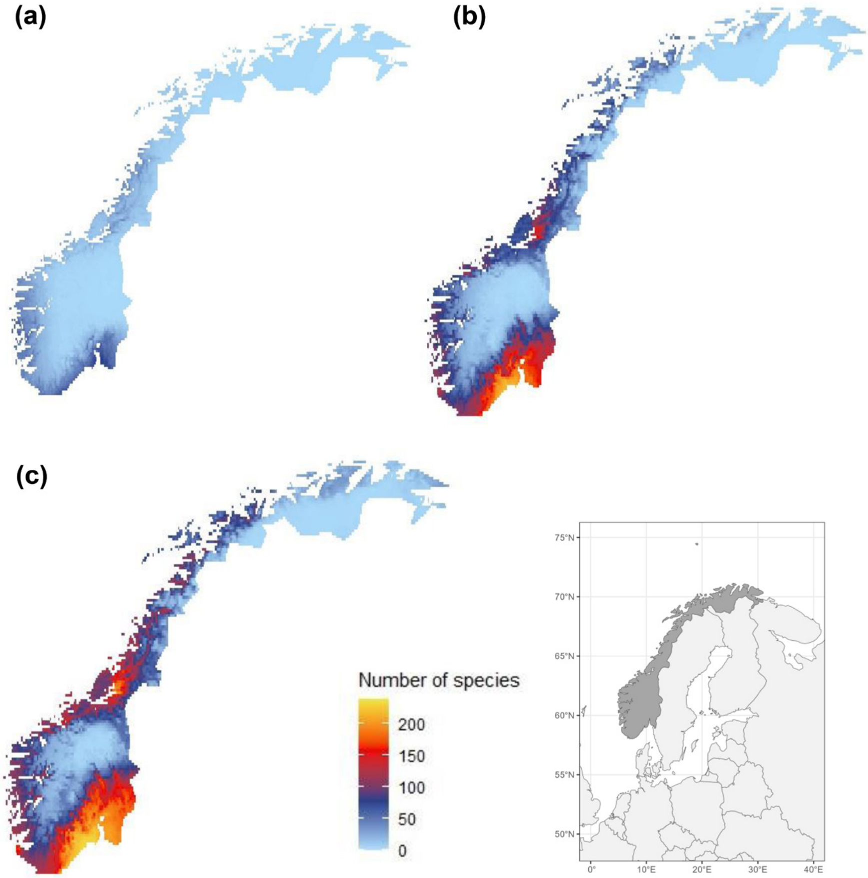

Figure 4. Potential distribution of 265 species identified as high-risk for Norway by a horizon scanning study under (a) current climate, (b) predicted climate for SSP2-45, and (c) predicted climate for SSP5-85.

Oslo, and in the boreal rainforest north of Trondheim. Few species were predicted to have potential distributions in the Arctic and alpine regions of Norway under both current and future scenarios (Fig. 4). Only 15 high-risk species were not predicted to occur anywhere in Norway under SSP5-85, with corresponding climatic niche overlap scores of < 0.001–0.020. Invasion 'hotspots', here defined as areas containing at least 20 high-risk species, more than doubled in size from 20.3% under the current climate to 53.3% under SSP2-45, and increased again to 70.0% under SSP5-85.

The average potential range for all species, calculated as the mean of the percentage of Norway's grid cells in which each species is predicted to occur, increased from covering 5.2% (3.0% LQ to 7.4% UQ) of Norway under the current climate to 17.1% (6.4% LQ to 27.9% UQ) under SSP2-45, and to 25.3% (10.5% LQ to 40.1% UQ) under SSP5-85 (Fig. 5a, Supporting information). There were two species with potential ranges covering over 70% of Norway under current conditions (*Pinus radiata* and *Senna multiglandulosa*). Species potential ranges shifted within Norway from an average latitude of 63.9°N under current climate conditions to 66.0°N under SSP2-45 and 67.8°N under SSP5-85 (Fig. 5). Only the two species with the largest percentage cover of Norway (*P. radiata* and *S. multiglandulosa*) were predicted to occur at the northernmost point in Norway (71.04°N) under current conditions, but under climate change scenarios, the number of species predicted to occur at Norway's northern limit increased to eight species under SSP2-45 and 25 species under SSP5-85 (Supporting information). Both species' potential range sizes and their northernmost range limits increased significantly from the current climate to SSP2-45, current climate to SSP5-85, and between SSP2-45 and SSP5-85, calculated using paired t-tests (Supporting information).

The correlation analysis carried out between climatic niche overlap scores and the proportion of Norway covered by each species showed fair to good correlations within each climatic scenario ($R = 0.57$, 0.75 and 0.74, respectively, for current, SSP2-45 and SSP5-85 climate scenarios; Supporting information).

Climate overlap sensitivity analysis

Removing outlying TWQ values for the five high-risk species with the highest climate overlap resulted in greater climate overlap for two of the five species (*P. pyrenaicus* and *S. multiglandulosa*) and lower climate overlap for two (*G. tinctoria* and *M. complexa*). There was very little change for *P. nepalensis,* with the exception of SSP5-85, in which climate

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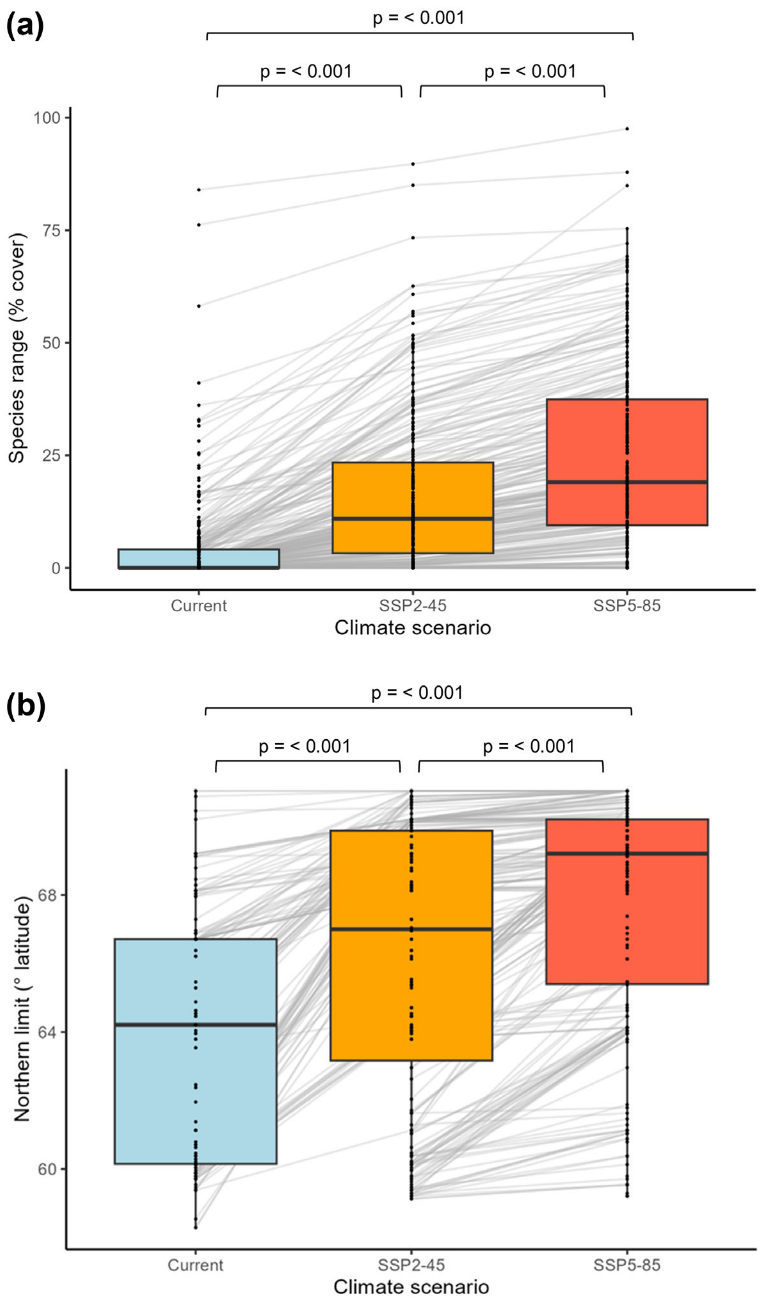

Figure 5. (a) Predicted species ranges (% cover of Norway) and (b) northern limit of species' predicted ranges (° latitude) under current climate conditions and predicted future climates SSP2-45 and SSP5-85. Grey lines join each species across different climate scenarios. Some species are not predicted to occur in Norway using SDMs, so some lines are missing in plot (b).

overlap was reduced when outliers were removed. The species with the greatest change in climate overlap when outliers were removed was *S. multiglandulosa*, where removing outliers resulted in an overlap increase from 0.23 to 0.32 under the current climate, from 0.32 to 0.35 under SSP2-45, and from 0.36 to 0.43 under SSP5-85 (Supporting information). This suggests that the 'core' climatic niches of these five species do indeed show some overlap with Norway's climate, and that including even potentially inaccurate outliers does not considerably affect climate overlap.

Discussion

High-risk species

This study used a novel method of horizon scanning to identify potential high-risk species for future plant invasions in Norway, with a particular focus on climatic suitability. We identified 265 species that fulfilled all of our horizon scanning criteria and predicted their potential distributions across Norway under current and future climatic conditions. Our

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key finding was that the distribution range of our high-risk species in Norway was predicted to increase significantly from the current climate to future climate projections, and this increase was more pronounced under the high-end future climate scenario SSP5-85 than under the intermediate scenario SSP2-45. In addition, our results suggest that species are likely to expand their ranges further north under climate change and that the overall number of invasive alien species will increase. These findings are consistent with, but expand on, those of Sætersdal et al. (1998), who predicted an increase in climatic suitability for many native species in Scandinavia under climate change, particularly in the southern boreal regions, and with Petersen et al. (2022), who predicted an increase in tall, woody species in Norway under climate change, which applies to most species highlighted in Table 1. Our results suggest that invasive alien species richness will increase across the southern regions of Norway, which may have substantial negative environmental and ecological implications.

The impacts of the introductions of a number of our identified high-risk species have already been documented in the literature. For example, *Gunnera tinctoria* impacts have been discussed in Ireland, where its presence reduces seed biodiversity in soil banks (Gioria and Osborne 2009), and it has spread rapidly around disturbed areas of land (Skeffington and Hall 2011). *Gunnera tinctoria* is also widespread across the Azores (Silva et al. 1996) and New Zealand, where it occurs in dense populations and displaces endangered native plants (Williams and New Zealand Department of Conservation 2005). In addition, *G. tinctoria,* along with *Prunus lusitanica,* was chosen by Thomas (2010) as two of the most 'critical' or 'urgent' risk species to Great Britain, a landmass relatively close to Norway, where these species are already naturalising. EU Regulation 1433/2014 also included *G. tinctoria* as one of several species of 'Union concern' – that is, species whose movement and breeding are restricted within the European Union. *Petasites pyrenaicus* is classed as invasive in the UK (Jones et al. 2022) and Ireland (Carlier et al. 2020), with low-growing dense leaf canopies that exclude light from native species (Jones et al. 2022). The fact that multiple studies within northern Europe have identified the same few high-risk species using different methods further reinforces the risk status of these species.

Distribution of species

We observed a prevalence of high-risk species around the coasts of Norway but very few high-risk species inland. This pattern was present across both current and future climate scenarios (Fig. 4–c) and is potentially due to the mountains that cover much of inland Norway (Supporting information). Of the three bioclimatic variables used in this study, the variable that showed the largest difference between the climate of mountainous and coastal regions of Norway was the mean temperature of the warmest quarter (TWQ; Supporting information), which suggests that temperature is the limiting factor preventing species from expanding their ranges. However, under SSP2-45 and SSP5-85 scenarios, species are predicted to occur inland at higher elevations, suggesting that these mountainous regions will become more hospitable to high-risk species in the future. This trend supports predictions that plants will move to higher elevations under climate change (Walther et al. 2009, Petitpierre et al. 2016).

One of the most prominent high-risk 'hotspots' occurred near Oslo, with further high numbers of species predicted around the southeast and southwest coastlines where other larger cities are located (Bergen, Stavanger; Supporting information), a link that may be explained by these cities being built in more temperate and hospitable environments. These hotspots are concerning because plants used for horticultural purposes are usually first imported and widely planted in urban areas (Smith et al. 2006, Niinemets and Peñuelas 2008). Urban sites are among the most invaded types of land (Lonsdale 1999, Chytrý et al. 2012), and cities often have increased plant species richness due to the introduction of alien species (Kühn and Klotz 2004, McKinney 2008). Furthermore, the spread of invasive alien plants often begins in urban areas (Dehnen-Schmutz et al. 2007) due to higher propagule pressure, e.g. by plants that may 'escape' from their garden environments and ultimately become naturalised (Niemiera and Holle 2009). This means that these species are more likely to be introduced into these cities than into less populated areas in Norway. Additionally, if introduced, these species are more likely to 'escape' from gardens due to the suitable climate surrounding these cities. Our models did not take land use into consideration, but it has been shown that non-native plants are more abundant in disturbed land where they are able to colonise more quickly (Almasi 2000, Hansen and Clevenger 2005, Dickson et al. 2012). In addition, a further 'hotspot' was located in the boreal rainforest region of central Norway. This ecosystem is categorised as 'vulnerable' by the Norwegian Biodiversity Information Centre (2023c), and in fact, a relatively high proportion of non-native species already exists in this region compared with native species (Olsen et al. 2017). This means that preventing further invasions is even more important in order to protect this vulnerable region.

Methodology

We incorporated the economic use of plants as a key stage in our framework and did not look at accidental pathways, such as stowaways, though we acknowledge that unintentional introductions are important to consider. However, van Kleunen et al. (2020) found that plants with economic value are 18 times more likely to become naturalised and that naturalisation success is highest for ornamental plants and plants used as animal fodder, both of which were identified as being of importance in our study. Ornamental plants were found to be the main introduction pathway of non-native plants into Europe (Arianoutsou et al. 2021).

In 2021, an expert committee was tasked by Artsdatabanken (the Norwegian Biodiversity Information Centre) to produce a list of potential 'door knocker' species that may pose a risk to Norway, further developing methods

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described by Sandvik (2020) and Sandvik et al. (2020). This species list formed the basis for subsequent horizon scanning and ecological risk assessments, and now forms part of the most up-to-date Alien Species List (Norwegian Biodiversity Information Centre 2023a). Of their unpublished draft list of 1392 plant species (Westergaard unpubl.), 90 overlapped with the 265 species that we identified. Our analyses highlighted that our approach identifies species with a broader climatic niche, therefore complementing the expert committee who identified plants whose risk is potentially more immediate. However, this list was not considered as part of our horizon scanning study, as we aimed to develop a widely applicable and quantitative method that could be adaptable for use elsewhere. For example, the list produced by the Norwegian Biodiversity Information Centre employed an expert committee, which, although a very valuable resource, may not be available in other countries. For details of this analysis please see the Supporting information.

We compared the climatic niche of our shortlisted high-risk species with the climatic niche overlap of a set of species currently invasive in Norway. Our species generally had much lower overlaps than those of current invaders, suggesting that they might not currently be able to naturalise within Norway's climate to the same degree as the invasive alien species. However, when using predicted future climate data, the climatic niche overlaps of our high-risk species increased and became more similar to those of Norway's invaders under current conditions (Supporting information). It is therefore important to consider preventing the introduction of these species before Norway's climate becomes more suitable, providing the conditions required for these species to become established.

Limitations

While our horizon scanning framework is relatively straightforward, there are some limitations. Specifically, our methods rely solely on online databases with the assumption that these databases contain all relevant species information. We reduced the chance of using inaccurate occurrence data by discarding records with some degree of uncertainty, but it is possible that key populations of species may have gone unrecorded, which would affect climatic niche overlap values and predicted species' distributions. Furthermore, we can only include species in our framework that are present in the World Economic Plants database (USDA Agricultural Research Service 2015) and the GRIIS database of environmental impacts (Pagad et al. 2018), and therefore may miss key species whose economic use or impact are unknown. It is therefore of vital importance to continually add emerging species knowledge to these online resources so that we can ensure that horizon scanning and species risk assessments stay up-to-date.

Conclusions

We have presented a novel and widely applicable method of horizon scanning, with a particular focus on climate matching between species and the area of interest under both current and future climate scenarios. This study has identified a group of plant species that could pose an invasion risk to Norway, as well as areas within Norway that are most at risk. Horizon scanning studies are a valuable tool to identify risk species before they become an economic, environmental, or human/animal health problem. Based on this study, we recommend that the identified high-risk species be fully screened as part of Norway's biosecurity policy to evaluate the potential costs of introducing these species into Norway. Predicting future invasion risk is increasingly important as climate change renders Norway's climate more habitable for introduced species and expands their suitable range to higher latitudes. In addition, the impacts of climate change on native biota (e.g. loss of species, range shifts) mean that native communities will be in flux, and therefore more susceptible to the impacts of invasive alien species (Thuiller et al. 2007). Early detection and prevention of invasion is always more cost-effective than trying to eradicate or manage an invasion post-introduction (CBD 2010). By acting now to implement laws that will monitor the import of such species, Norway's ecosystems and their biodiversity can be preserved for future generations.

Finally, here we have presented a relatively simple protocol for rapidly screening large numbers of species based on their potential for introduction, naturalisation, and environmental impact, which could complement a full-scale invasive alien plant risk assessment and analysis. Our method of climate matching is arguably more accurate than other widely used methods and, in addition, accounts for both current and future climate scenarios, which has not been done before in horizon scanning studies. This approach can be easily adapted and implemented for different countries or regions and would provide quantitative support for established, consensus-based horizon scanning projects.

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Author contributions

Katy Ivison: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Methodology (equal); Visualization (equal); Writing – original draft (lead). **Christine Howard**: Formal analysis (equal); Methodology (equal); Visualization (equal); Writing – review and editing (equal). **Lisa Baldini**: Conceptualization (equal); Methodology (equal); Writing – review and editing (equal). **Franz Essl**: Resources (equal); Writing – review and editing (equal). **Petr Pysek**: Resources (equal); Writing – review and editing (equal). **Wayne Dawson**: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Methodology (equal); Supervision (equal); Visualization (equal); Writing – review and editing (equal). **James D. M. Speed**: Conceptualization (equal); Formal

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analysis (equal); Methodology (equal); Supervision (equal); Visualization (equal); Writing – review and editing (equal).

Transparent peer review

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Data availability statement

Data are available from the Figshare Digital Repository: https://doi.org/10.6084/m9.figshare.c.7631387 (Ivison et al. 2025).

Supporting information

The Supporting information associated with this article is available with the online version.

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