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Future protective forests: a regional forecast on potential natural conditions of woody species impacted by climate change along the Austrian railway corridor

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Introduction: Railway corridors, as linear landscape structures, are highly exposed to natural hazards. In alpine regions intact protective forests form a key basis for safeguarding the route network by complementing technical protection measures through forest-related ecosystem services. From a long-term perspective, these benefits are only generated by resilient and vital forest stands. To maintain sustainable services and benefits under climate change, an understanding of the biological system and its future developments is essential. Difficulties lie in long reaction times of forest stands to management actions and a broad range of species, that need to be considered.
Methods: The method used in this study focuses on the extrapolation of potential natural stands based on basic climate parameters by developing a two-dimensional climatic space, describing natural stands for 46 species in all 26 operational units of the Austrian railway corridor. First, we analyzed the current distribution of woody plant species using a climate-envelope modeling approach. Secondly climatic conditions of the Austrian railway network were evaluated and modelled for future climate change scenarios. In the synthesis of steps one and two, potential natural stands were detected, quantified, contextualized and compared to the reference period 1961–2020.
Results: Several promising species were detected for future climate scenarios and European wide trends were confirmed on the regional scale. Especially *Castanea sativa*, *Ulmus minor*, and *Sorbus torminalis* can help generating vital stands that can deliver the protective functions we are aiming for.
Discussion: The results mark an initial step toward climate-change-adapted protective forest management by detecting changes in natural site conditions and predicting vulnerable areas along the Austrian railway corridor, offering a management tool for infrastructure operators to guide future species selection and assess risks to protective forest functions.

KEYWORDS
biodiversity, climate change mitigation, ecosystem services, forest management, natural hazard, nature based solutions, protective forests, Woody vegetation

1 Introduction

Large parts of Austria's extensive rail network run through mountainous terrain dominated by forest vegetation in the Alps. In these areas natural hazards occur frequently, and resilient protective forests are vital for the safe operation of rail traffic. Meteorological conditions and extreme weather events can lead to various hazardous events such as floods, debris flows, landslides, avalanches, rockfalls, rock avalanches and mudslides that endanger the railway infrastructure (Ludvigsen and Klæboe, 2014; Nogal et al., 2016). Railway systems are especially exposed and there are limited rerouting possibilities (Mattsson and Jenelius, 2015). Therefore, hazard prevention measures and limitation of vulnerability are of significant importance. Especially in the alpine track management natural disaster risk mitigation and protection of railway infrastructure has always been an important topic. These aspects are amplified as the Alps are particularly affected by climate change (IPCC, 2022; IPCC, 2021; IPCC, 2019). There is a strong indication that natural hazards respond to meteorological alterations. Consequently, the frequency of natural hazards will increase (Enigl et al., 2019; Matulla et al., 2018; Schlögl and Matulla, 2018; Schlögl et al., 2020). Among others these changes are driven by climate change (Glade et al., 2020). The scientific community discusses the impacts of climate change, its resulting phenomena and strategies to face them within railway operations (e.g., Koetse and Rietveld, 2009; Ludvigsen and Klæboe, 2014; Rosetti, 2002).

Besides technical and operational hazard management actions, healthy ecosystems can provide resilience and protective functions by reducing the risk of natural events. At the same time, vegetation along the tracks safety zone can pose a risk or damage technical facilities (Bíl et al., 2017). The security of railway networks bordered by vegetation has been under discussion and observation for a long time, showing the need for holistic vegetation management strategies for railway corridors (Hoerbinger et al., 2020; Hoerbinger et al., 2018). In the alpine regions, intact protective forests are the fundamental basis for protecting the extensive route network and can support technical hazard protection facilities through various effects. Due to their diverse functions, forests can provide essential protective effects in terms of retention mechanisms, stabilization processes or energy reduction (Beniston, 2003; Florineth, 2012; Irauschek et al., 2017; Keenan, 2015; Kleemayr et al., 2020; Schiechtl and Stern, 1992; Schiechtl and Stern, 1992; Seppälä, 2009). Many studies showed the positive effects of protective forest stands on mitigating rockfall events (Dorren et al., 2005; Stoffel et al., 2006). These effects are related to retention and energy dissipation issues (Dorren and Berger, 2006), while stabilization processes through woody vegetation counteract shallow landslides and erosion processes. The root system, including fine to strong roots, armors and stabilizes the upper soil horizons (Arnone et al., 2016; Graf and Frei, 2013; Preti and Giadrossich, 2009; Schwarz et al., 2016; Schwarz et al., 2010). Additionally, vegetation plays a crucial role in regulating increased precipitation rates, through interception and retention of precipitation and the resulting time lag in discharge patterns (Kleemayr et al., 2020; Markart et al., 2006). Therefore, it affects the entire river systems by regulating runoff, influencing hydromorphological processes, and impacting hazardous risks of floods and fluvial sediment transport (Kleemayr et al., 2020; Müller et al., 2022). Vegetation can reduce high pore-water pressures, that may trigger landslides and debris flow in unstable rock and debris masses. This reduction is done by extracting water from the system through interception and transpiration (Rickli et al., 2004). Without claiming completeness, the vegetation effects discussed constitute key ecosystem services that deliver protective functions and thereby reduce management pressure within the Austrian railway corridor. Within this context, attention must be paid to the fact that vegetation structures are constantly changing due to the given physical, biological and artificial conditions (Keenan, 2015), which brings particular challenges in their maintenance. Climate change is fundamentally altering the prevailing vegetation stands. Although much research has been conducted and reviewed within this field (Boisvenue and Running, 2006; Keenan, 2015), many questions remain open. Key challenges are the long response time of forest systems and the high variety of tree species involved. Additionally, adaptation strategies might not be able to cope with the total amount of required actions, as they were developed under different climatic aspects (Seppälä, 2009). Climate change will severely impair the protective function, especially in yet vulnerable even-aged forests with low biodiversity (Makino et al., 2021; Moos et al., 2023). As a result of past forest management, stands like this are widely spread over Austria (Prskawetz and Gschwantner, 2011). Site conditions are changing due to alterations in precipitation amounts and distribution, which impact the soil water balance (Boisvenue and Running, 2006; Farkas et al., 2014). Stronger storms and increasing droughts exert additional stress, thereby facilitating the spread of diseases and pest infestations (Battisti, 2008; Keenan, 2015; Regniere, 2009). In response to changing climate conditions, species adapt in morphology, behavior, phenology and migration to more suitable climatic zones (Theurillat and Guisan, 2001; Weiskopf et al., 2020). The individual response of species is highly variable. For accurate predictions of a species' distribution, it is necessary to consider microclimatic conditions directly linked to macroclimatic changes and changes in forest structure and composition (Hylander et al., 2022; Lexer et al., 2002; Matulla et al., 2002; Zellweger et al., 2020). Invasive alien plant species tend to benefit more from higher average temperatures and CO2 concentrations in the atmosphere than native plants (Liu et al., 2017) and can threaten the ecosystem's capacity to provide the regulating services essential for efficient protection against natural hazards. The provision of ecosystem services is associated with resilient, vital forest stands (Dorren et al., 2004), which implies that natural conditions prevail for the species at the site (Frehner et al., 2005; Schuler et al., 2017).

This study was therefore based on the assumption that for a resilient supply of ecosystem services, at least the fundamental niche defined by Hutchinson (1957) must be provided. It is assumed that even minor climate changes severely impact service provision (Leemans and Eickhout, 2004; Irauschek et al., 2017). As protective forests are usually managed and strongly influenced by humans (Kleemayr et al., 2020), the studied areas in the railway corridor do not correspond to the natural landscape, making some principles related to the distribution of species in undisturbed nature (e.g., the Volterra-Gause principle) irrelevant, as human actions suspend them. In this article, the ecological niche of woody species is defined by basic climate parameters in the form of climate envelopes. Many studies have applied climate envelope models for a range of purposes such as forestry, biodiversity, risk analysis, species distribution and conservation policy (Harrison et al., 2006; Kölling, 2007; Thuiller, 2003). Often the focus lies on converting field data in point format into spatially continuous data (Kadmon et al., 2003). The prevailing study went beyond this scope and investigated the development of potential natural conditions for 46 woody species on a regional scale along the Austrian railway corridor. It included a reference period (1961–2020),

two future periods (2036–2065 and 2071–2100) and four socio-economic pathways representing different climate change scenarios. Future distributions with potential natural sites for the respective species were compared with their distribution in the past. This way, risks deriving from changes in the conditions of the protective functions due to the loss of species as well as opportunities from changes in the species composition can be identified. Results may serve as a basis in specifying the needs for action in protective forest management. This research is motivated by the urgency that vegetation provides ecosystem services as a protective function against natural hazards over major parts along the Austrian railway corridor. It contributes to reducing the vulnerability of critical infrastructure and the damage potential (Kleemayr et al., 2020). To maintain these services and benefits under climate change aspects, an understanding of the system and its future developments is essential.

2 Materials and methods

The study area refers to the Austrian railway corridor, which shows a length of 7,900 km across the country (see Figure 1). It is divided into 26 operational units, varying in length between 184 and 480 km. A total of 1,500 km of this railway network is covered by forest within a 30 m lateral zone. Extending this zone in lateral direction the dimension even rises. The 1 km buffer of the single operational units function as area of observations for the prevailing research. High speed rail network is considered as well as local railway lines. Density of the railway corridor is highest in the northeast of Austria, related to relatively flat terrain, lower precipitation rates and milder climate. While in the alpine parts the extent of railway corridors is limited to valley bottoms or selected mountain routes, influenced by higher altitudes, steeper terrain and colder climatic conditions.

The method used in this study focuses on the extrapolation of potential natural stands based on basic climate parameters and is done in three working steps (see Figure 2). In the first part, the current distribution of woody vegetation species is analyzed, and climactic variables along given distribution data are defined in the style of climate envelope models, representing a two-dimensional climatic space. Secondly, the climatic parameters of the operational units along the Austrian railway network were analyzed and modelled for future climate change scenarios. In the synthesis of steps one and two potential natural stands were detected and quantified. They were contextualized and compared to the reference period 1961–2020. In total 9,568 models have been set up, combining 46 species, 26 operational units, four climate change scenarios and two future 30-year periods. The observed species show a broad spectrum of plant physiological and biogeographical attributes. 78% belong to deciduous trees and 22% to conifers. 50% of the observed species can build up a shrubby habitus, while five species are exclusively related to shrubby habitus, and 18 species can form shrub or tree habitus. Of the species observed, 72% have the ability to resprout and are therefore suitable for use in coppice stands.

Modelling was performed using climate envelope models. They describe the set of climatic conditions for species habitat by approximating the climatic niche (Hijmans and Graham, 2006). To achieve this, a bioclimate envelope is characterized based on prevailing species distribution data (Pearson and Dawson, 2003). In our study the current species distribution was defined by presence-only data across geographical Europe, generated by Commission European and Centre Joint Research (2022) and Caudullo et al. (2017). The climatic parameters used, were mean annual temperature and annual precipitation. Several steps of data transformation, cleaning and reduction were

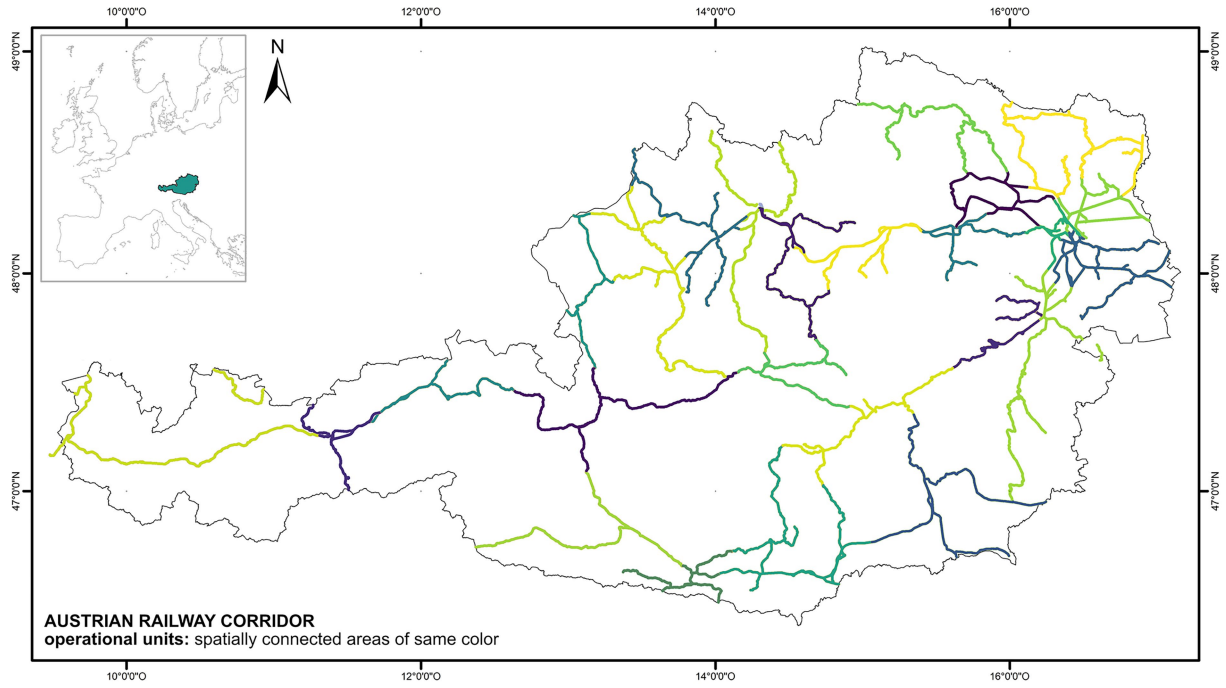


FIGURE 1
Area of observation: Corridor along the Austrian railway network divided into 26 operational units. Spatially connected areas of same color build an operational unit. [own illustration based on BEV (2025) and EuroGeographics (2025)].

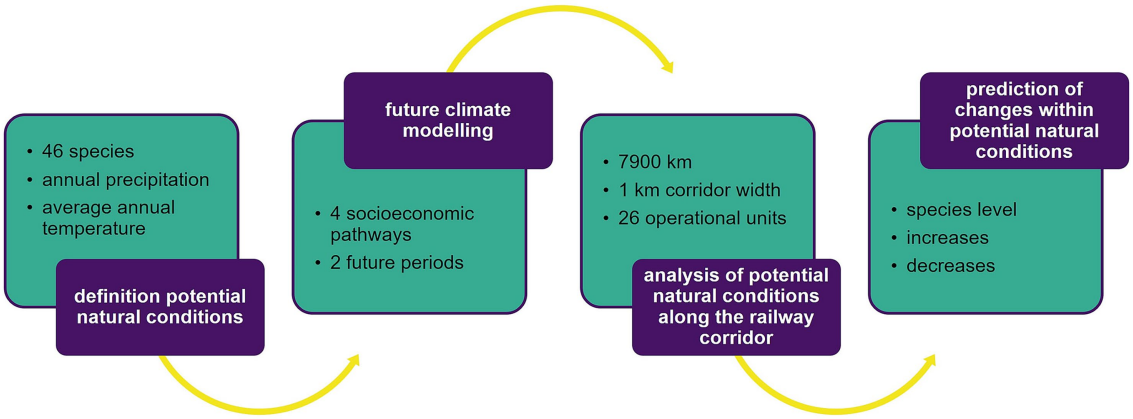


FIGURE 2
Workflow and method used within the study in four steps: Including the definition of potential natural conditions, climate modelling, analysis and resulting in a prediction of future changes within potential natural conditions under climate change impact.

carried out. First, the data was transformed from polygon shape information into a raster of points, resulting in a 200 m resolution. A spatial delimitation was carried out to geographical Europe. Information on altitude based on a digital elevation model (DEM) (EEA, 2016) was extracted for each raster point. Species-specific elevation limits were introduced according to literature references (Commission European and Centre Joint Research, 2022; Florineth, 2012; Forster et al., 2019; Stimm et al., 2014; Leder and Wolff-Metternich, 2018; Schiechtl and Stern, 1994; Schiechtl and Stern, 1992). The point cloud was reduced by removing points representing areas outside the expected species altitude classes. For the cleaned distribution raster points, mean annual temperature and annual precipitation data were extracted from Worldclim 2 bioclimatic variables (Fick and Hijmans, 2017). To derive the envelopes, a two-dimensional frequency distribution was calculated via the cid2d tool based on gplots package in R Studio (Gregory et al., 2022). Outliers were eliminated by considering 95% of the data points for further calculations and validation.

To adequately represent future climatic processes at the local scale, meteorological data from General Circulation Models (GCMs) were downscaled to a regional resolution. Observational reference datasets were required for both the large-scale and local-scale representations: ERA5 was used for the large-scale reference (Hersbach et al., 2020), while SPARTACUS provided local-scale observations (Hiebl and Frei, 2016, 2018). Both datasets cover the period from 1961 to 2020. The climate projections were based on four Shared Socio-economic Pathways (SSPs) from the Coupled Model Intercomparison Project Phase 6 (CMIP6): SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. These scenarios span a wide range of possible future developments, from a climate mitigation oriented pathway (SSP1-2.6) to a fossil fuel intensive pathway (SSP5-8.5), thereby enabling a comprehensive assessment of potential climate change impacts under different socioeconomic trajectories. The downscaling approach adopted in this study is based on the analogue method (Matulla et al., 2008; Zorita and von Storch, 1999). Near-surface temperature fields were downscaled using temperature and geopotential height at 850 hPa level as predictor variables. These predictors were extracted consistently for all GCMs and for ERA5. Precipitation fields were downscaled using temperature, geopotential height, and specific humidity at the 500 hPa level as predictors and again applied uniformly across GCM and ERA5 datasets. For SPARTACUS, only near-surface temperature and precipitation totals were required, as these variables served as predictands in the downscaling framework. All datasets were available at daily temporal resolution. Observational data (ERA5 and SPARTACUS) cover the period 1961–2020, while GCM simulations extend from 1961 to 2100. The spatial resolution of the GCMs varies by model and ranges approximately from 100 to 150 km, whereas ERA5 provides a resolution of about 30 km and SPARTACUS of 1 km. All large-scale datasets (GCMs and ERA5) were spatially constrained to the domain bounded by 20–70° N and −40–30° E. GCM data were obtained via the Earth System Grid Federation (ESGF; Cinquini et al., 2014), and ERA5 data via the Climate Data Store (Hersbach et al., 2018). A principal component analysis model was adopted to find statistically nearest neighbors between daily GCM fields and daily ERA5 fields. The statistically linked ERA5 field then yields the corresponding date for the best fit. SPARTACUS data from the same date can then be extracted, representing the downscaled field for a particular day. This process is repeated for every day in the GCM data thereafter, yielding the fully downscaled GCM data for one model run. The whole process is repeated for every GCM run to be downscaled.

The climate envelopes created were used to quantify potential natural vegetation sites, and their changes over the course of climate change were analyzed. Separately for all observation areas, species, scenarios, and two future periods, the percentage of those grid points within and outside the calculated potential natural range (based on annual precipitation and average annual temperature) was calculated. The amount of potential natural sites of each species was classified into five categories describing the presence of potential natural conditions for each operational unit: (0–5%) no potential natural conditions, (5–35%) mostly no potential natural conditions, (35–65%) partly potential conditions, (65–95%) mostly potential natural conditions. Further on, changes compared to the reference period 1961–2020 were categorized into three classes: (−100 to −5%) decreases of potential natural conditions, (−5 to 5%) minor changes in potential natural conditions, (5–100%) increases of potential natural conditions. Subsequently, the information was generalized at the species level: information on the observation units was summed up over the entire railway corridor by their amount of increases and decreases. From this, frequencies of observation units with increasing or decreasing potential natural site conditions were obtained.

3 Results

3.1 Downscaled climate data along the railway corridor

The results based on the downscaling of climate model data along the Austrian railway corridor are presented in Figure 3. The trend of increasing temperatures is visible for most scenarios, whereby the specific amount of the temperature rise depends on the particular socio-economic pathway. The increases are generally higher in the second period, 2071–2100. While scenario SSP1-2.6 is relatively stable, comparing the two climate periods for the middle and the end of the century, scenarios SSP2-4.5, SSP3-7.0 and SSP5-8.5 show continuous increases with time and hence unstable climatic conditions. The annual precipitation trends are not as definitive but still offer a solid tendency to increase precipitation with higher global warming. However, compared to the observational data, the changes in amplitude are not as significant as for temperature increases.

3.2 Potential natural conditions of woody vegetation

The potential natural conditions of woody species referring to the Austrian railway corridor in the reference period 1961–2020 show apparent differences between conifers and deciduous species (see Figure 4). The latter have significant higher frequencies in classes representing primarily or potential natural conditions. Except for *Castanea sativa*, all deciduous species exceed a frequency of 40% for the class 95–100% of area of operational units shows potential natural conditions. Only for *Alnus viridis* and *Castaniea sativa* a few units were assigned to the classification "no potential natural conditions." The overall picture for the conifers is contrasting: *Abies alba*, *Cedrus libani, Larix decidua*, *Picea abies*, and *Pinus nigra* show a broad spectrum, including operational units in all five classes. *Pinus sylvestris* and *Taxus baccata* find wide potential natural conditions. While *Pinus* species, naturally present at higher altitudes, show opposite tendencies. *Pinus cembra*, *Pinus mugo unc*. and *Pinus mugo rot*. Were classified as "no potential natural conditions" over most operational units. Conifers with the ability to build out a shrubby habitus (*Pinus mugo rot.* and *Pinus mugo unc*., *Taxus baccata*) show deviating trends from conifers related to erect habitus only. The absence of potential natural conditions for *Pinus mugo* is caused by missing observation units in their natural range of altitude and cannot be associated with shrub form. While *Taxus baccata* occupies a broad ecological niche in general, independent of individuals with shrub or erect habitus.

Ulmus glabra and *Pinus mugo unc.* Are both representing only one class. *Ulmus glabra* finds potential natural conditions in the range of 95–100% of the area's overall operational units, while *Pinus mugo unc.* Follows a similar pattern concerning the class 0–5%.

3.3 General trends along the whole Austrian railway network

Observing the Austrian railway corridor as one spatial unit, several trends and tendencies were detected for future scenarios. Deciduous species generally showed better forecasts than conifers, with higher decline rates on potential natural sites. At the same time, more significant regional differences were found for deciduous tree species.

With climate change, the majority of species present today lose area under potential natural conditions. Nevertheless, some species show increasing areas of potential natural conditions. Figure 5 summarizes the frequencies of operational units with increases and decreases in potential natural conditions. Stable conditions were not included. A spatial shift in potential natural sites is observed for several species characterized by spatially differentiated increases and

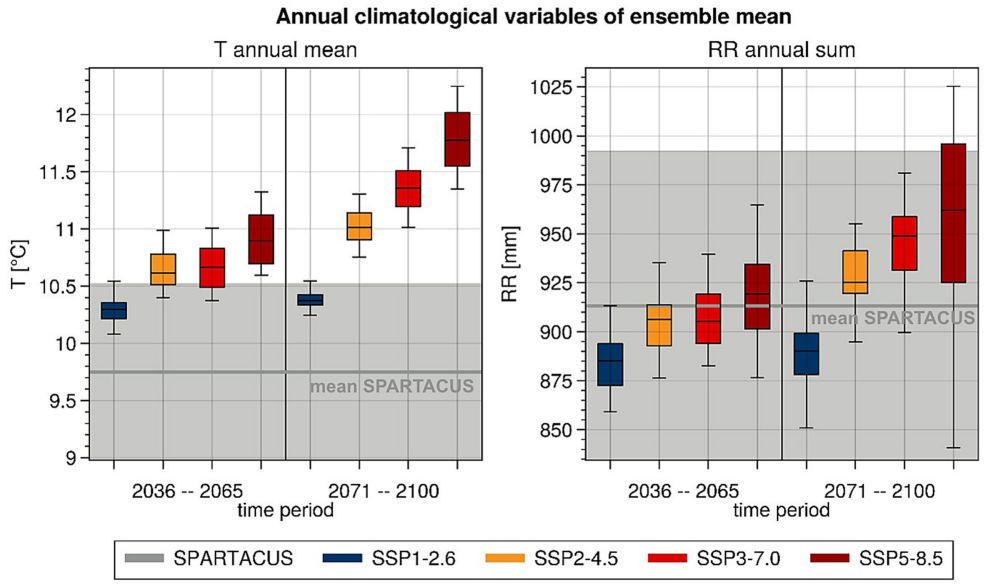


FIGURE 3
Climatic characteristics along the Austrian railway corridor: annual mean temperature [°C] (left) and mean annual precipitation [mm] (right) for the reference period 1961–2020 (SPARTACUS) and downscaled data for 2036–2065 (f1) and 2071–2100 (f2) based on socio-economic pathways (SSP1-2.6, SSP2.4.5, SSP3-7.0, and SSP5-8.5). The boxplots show the distribution of annual quantities of the GCM ensemble means, while the solid gray line shows the mean reference value of measured Spartacus dataset.

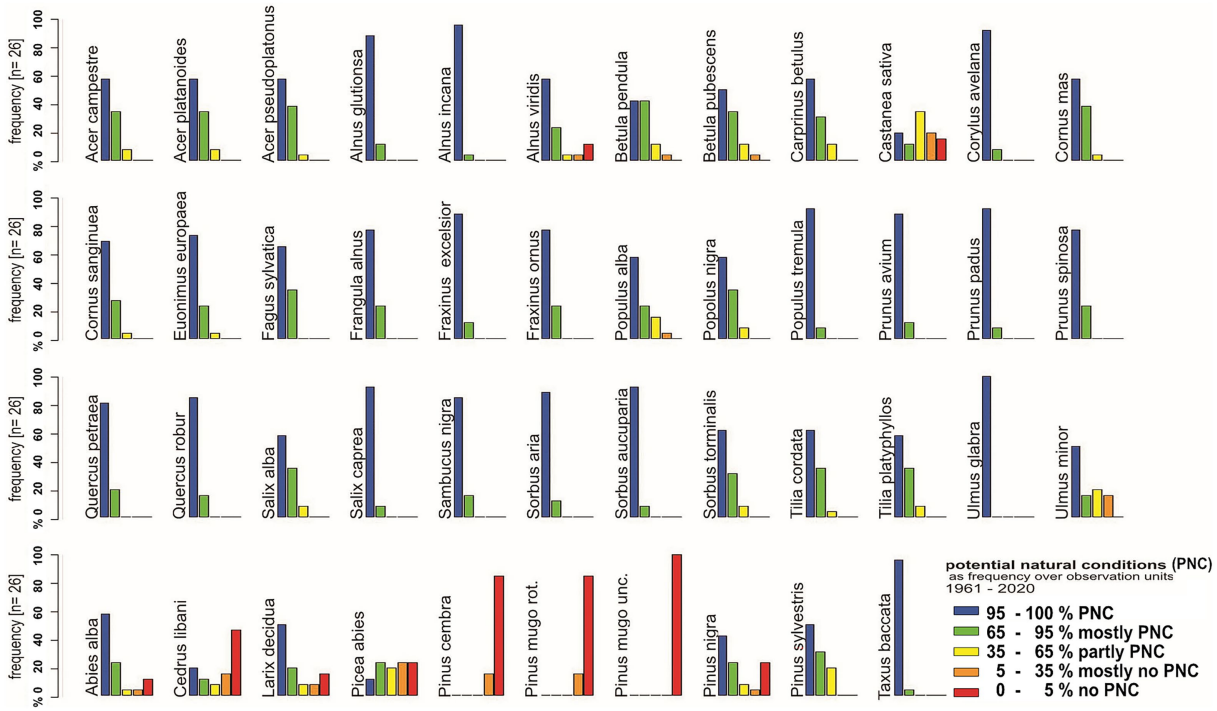


FIGURE 4
Current potential natural conditions of the observed species along the existing railway corridor based on the measured climate data in the period of 1961–2020 and plotted as frequency over all 26 operational units.

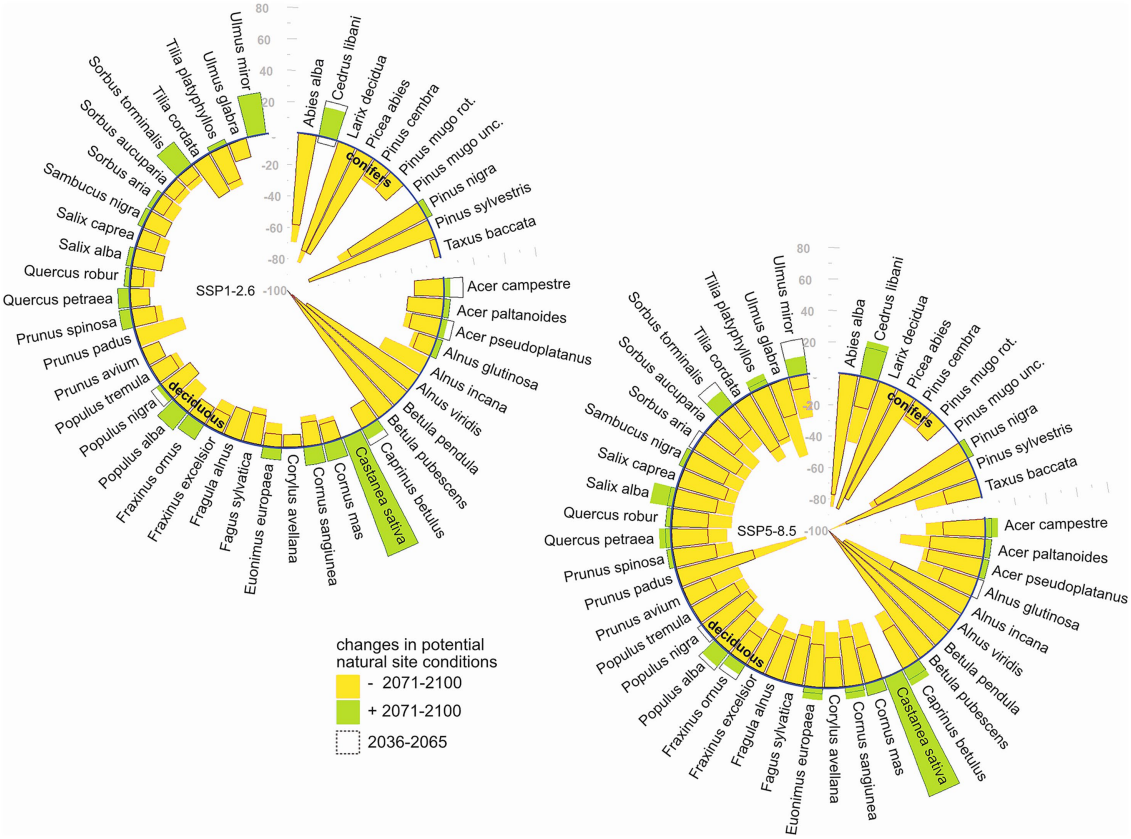


FIGURE 5
Changes in potential natural site conditions for the 46 species investigated in the climate change scenarios SSP1-2.6 and SSP5-8.5. The plotted frequencies are related to operational units, which divide the Austrian railway corridor into 26 segments with variable lengths and 1 km width.

decreases. The declining trends already observed in the comparison between the reference period and the most moderate climate change scenario SSP1-2.6 were significantly amplified by applying socio-economic pathways leading to more substantial climatic changes.

Additionally, the patterns seem to be strengthened for the far future (2071–2100) compared to the near future (2036–2065). Increasing trends do not follow the same scheme. The correlation with the intensity of climate change seems to be related to specific species. Two species that exclusively grow in scenario SSP1-2.6 are *Castanea sativa* and *Ulmus minor*. For the former, continuously increasing conditions were detected in all pathways with a maximum of available potential natural conditions in SSP5-8.5. The latter is projected to have increasing declines starting with scenario SSP2-4.5 and predominating in SSP5-8.5. A similar pattern can be observed for *Cedrus libani*.

Conifers are already heavily affected by SSP1-2.6, with more than one-half of the species facing forecasted decreasing frequencies over 80% of the investigated area. Based on different starting points in the reference period, the effects on frequencies of an absence of potential natural conditions are most severe for *Picea abies* and *Larix decidua*. For the far future period of scenario SSP5-8.5, more than 80% of the operational units are classified by 0–5%. Three observed conifer species seem to be minor impacted: *Pinus cembra*, *Pinus mugo rot*. and *Pinus mugo unc*. However, this stability is related to the wide absence of potential natural conditions during the reference period. Based on widespread potential natural conditions in the reference period, *Taxus baccata* can deal with growing decreases and remains in a position comparable to the average of deciduous species.

In the spectrum of deciduous species, only three species (*Alnus viridis*, *Betula pendula* and *Betula pubescens*) show similar decreases in potential natural conditions. In scenario SSP5-8.5 two further deciduous species (*Alnus incana* and *Prunus padus*) follow this strong trend. For the same pathway, the majority of observed deciduous species show decreases of 20–35% in 2036–2065, rising to 40% in 2071–2100. Comparing the changes in potential natural conditions of deciduous species with their distribution in the reference period (see Figure 2), climatic changes of scenario SSP1-2.6 lead to the introduction of the class, representing 35–65% of the area with potential natural conditions. Due to the further intensification of changes, the frequency of broadleaf tree species will decrease in scenario SSP5-8.5 (class 5–35%).

Looking at individual species, *Castanea sativa* is particularly noticeable. From an originally even distribution in the observation period, it was found in the climate change projections in up to 80% of the observation units with a frequency of 95–100%. Another deciduous species showing good forecasted values, but starting from a wider distribution in the reference period is *Corylus avellana*. While it indicates similarly high values as *Prunus avium*, *Sorbus aria*, *Sorbus aucuparia*, *Ulmus glabra*, and *Taxus baccata* in SSP1-2.6, *Corylus avellana* is ranked second for the far future period of scenario SSP5-8.5. For *Castanea sativa,* all operational units were classified by the upper two classes (65–95% and 95–100% of the area showing potential natural conditions) in the far future period of the pathway SSP5-8.5. *Corylus avellana* builds, together with *Frangula alnus*, *Prunus avium* and *Quercus robur,* a group of species with absent lower classes (0–5% and 5–35% of the area show potential natural conditions) in this scenario.

3.4 Results grouped by their genus

- For the genus *Acer*, the species show a similar pattern for various scenarios based on comparable starting points. *Acer platanoides* show more substantial decreases than its related species with proceeding climate change impacts.
- *Alnus glutinosa* and *Alnus incana* show similar distributions of potential natural conditions in the reference period, while the latter is more heavily impacted by changing climate. Starting in the far future period of pathway SSP2-4.5, decreases exceeding 70% are forecasted. *Alnus viridis* shows even higher decreases over all scenarios resulting in most observation units having no potential natural conditions for SSP5-8.5.
- Both species of the genus *Betula* had medium conditions in the past reference period and have to face a severely decreasing area of potential natural conditions, starting with minor changes in climatic conditions and ending in prominent absence in scenario SSP5-8.5.
- *Cornus* were not counted as the highest-ranked species in the past, but they can enlarge their area of potential natural conditions even under proceeding scenarios. Therefore, parallelly occurring decreases can be buffered, leading to a pretty good performance of the genus *Cornus* for the pathway SSP5-8.5.
- Between *Fraxinus excelsior* and *Fraxinus ornus* slight differences were detected. The former has a wider range of potential natural conditions in the reference period. At the same time, the latter shows lower decreases over all scenarios. Depending on the future period and the pathway, 5–10% of increases result in minor advantages for *Fraxinus ornus* in the far future period SSP5-8.5.
- Within the genus *Populus*, *Populus tremula* showed the biggest areal of potential natural conditions in the past. *Populus nigra* was ranked second and was closely followed by *Populus alba*. Remarkable increases were detected for *Populus alba* over all scenarios. Minor increases were assigned to *Populus nigra*, temporarily located mainly in the near future period. Accompanying decreases for *Populus tremula* lead to similar conditions for *Populus nigra* and *Populus tremula*, while *Populus alba* has a slightly worse ranking.
- Regarding the genus *Prunus*, *Prunus padus* switches from the highest rates in the reference period to the last ranked *Prunus* species in the far future period of SSP5-8.5 and is associated with the five worst deciduous species. *Prunus avium* and *Prunus spinosa* show decreases related to average values within the deciduous. The latter even shows minor increases over all socio-economic pathways
- Both observed *Quercus* species show similar and only slightly differing changes starting from scenario SSP2-4.5. *Quercus robur* had a small advantage in the reference period, while *Quercus petraea* has higher increases under the smallest climatic changes. Observing the area of potential natural conditions in SSP5-8.5, *Quercus robur* can maintain the lead.
- The genus *Salix* is represented by *Salix alba* and *Salix caprea*. The latter had significantly bigger areas of potential natural conditions in the past, while *Salix alba* shows increasingly growing areas under climate change impacts. Accompanied by widely equal decreases for both species, this leads to similar performances for both species in the far future period of scenario SSP5-8.5.
- Both *Tilia* species show similar conditions with a slight advantage for *Tilia cordata* in the reference period. *Tilia platyphyllos* can constantly achieve minor increases across all scenarios. While decreasing frequencies are identical over many pathways, *Tilia cordata* has the lead in SSP5-8.5. This refers to a nearly equal

distribution of potential natural conditions for the second period of SSP5-8.5.

- Within the *Sorbus* species, *Sorbus aucuparia* has the best references in the past. Under climate change impacts, *Sorbus torminalis* can spread its potential natural stands, resulting in a nearly equal performance of the three observed *Sorbus* species for scenario SSP5-8.5.
- *Ulmus glabra* is assigned to have 95–100% potential natural conditions over all observation units in the reference period but has to face some decreases for future predictions. While *Ulmus minor*, with a worse starting point, can achieve increases under minor climate change impacts in scenario SSP1-2.6. Under proceeding climatic changes decreases also accompany the gains and lead to shifts in the spatial distribution of potential natural conditions. This results in only slightly better performing *Ulmus glabra* for SSP5-8.5 in the far future period.
- The genus of *Pinus* shows various aspects: *Pinus cembra* and *Pinus mugo unc*. and *rot*. Are related to higher altitude and almost not represented by their potential natural conditions in the observed railway corridor. Compared to *Pinus sylvestris*, *Pinus nigra* starts with lower frequencies in operational units assigned to a high percentage of potential natural conditions in the past reference period, but shows fewer decreases accompanied by minor increases under climate change impacts. Through its higher frequency of decreases, *Pinus sylvestris* is ranked after *Pinus nigra* for the most heavily impacted scenario SSP5-8.5 in the far future period.

4 Discussion

Many studies point out that, especially in alpine regions, climatic changes are complex and include nonlinear processes (Gobiet et al., 2014; Ohmura, 2012; Schär et al., 2004). The literature indicates that extreme weather events will increase under the influence of climate change (Glade et al., 2020; IPCC, 2021; IPCC, 2019, p. 20; Stott, 2016). This will significantly impact the management of protective forests and challenges in protecting the railway network from natural hazards. Even if through our study no exact distribution scenarios can be derived due to the limitation of input parameters to annual values of precipitation and average temperature, the results allow the derivation of trends and tendencies on a regional basis.

Climate envelope models do describe the climatic conditions often linked to species persistence at broad scales (Hijmans and Graham, 2006). For our study we did not focus on the aspect of whether a species can persist or not. By filtering the input distribution data using species-specific attributes (e.g., altitude), we reduced the dataset, yielding a sample more representative of natural stand conditions. Beyond the meteorological and climatic inputs, our modelling approach is grounded in chorological data based on Caudullo et al. (2017). It is representing the contemporary distribution of tree species in their natural area. We treat these records as proxies for potential natural stands; however, we acknowledge that many of today's occurrences reflect long periods of managed forests systems and may already lie outside the species' natural habitat. Moreover, some populations are experiencing climatic stress resulting from historical and recent warming, further blurring the line between natural and anthropogenically maintained distributions. Consequently, the niches inferred from these data may be shifted toward conditions that overestimate a species' actual natural tolerance range. This likely leads to projections that derive more potential natural areas than those derived exclusively from pristine forest conditions.

The methodology of climate envelope models was critically reviewed in several papers (Araujo et al., 2005; Bolte et al., 2008; Elith et al., 2006; Hijmans and Graham, 2006; Kadmon et al., 2003; Pearson and Dawson, 2003; Soberon and Peterson, 2005; Thuiller, 2003). Non-climatic drivers of distributions are ignored (Araujo et al., 2005). Climate envelope models usually assume species are in equilibrium with current climate and that their climatic niche is stable over time, both assumptions are difficult to test and may be violated (Pearson and Dawson, 2003). If so, this is a critical aspect for forecasting. Failure in defining the envelope can also occur if the chosen climatic variables do not directly constrain the distribution of the species concerned (Araújo and Peterson, 2012). Nevertheless, other straightforward tools for predicting climate change impacts on natural vegetation in large scale are still missing. Soberon and Peterson (2005) state that different factors are relevant parameters for species dispersion, while it is recognized as a fact that species distribution is correlated to climatic and physical parameters at a specific scale. Furthermore, some positive aspects related to the climate envelope models were remarked in the literature. Hannah et al. (2002) state that these models can be a useful starting point for further research. There can be benefits from using this technique if put in the proper context (Thuiller, 2003).

Classical species distribution modelling focuses on a statistical relationship between species occurrence and characteristics from the environment (Elith, 2019; Pecchi et al., 2019). In contrast to the climate envelope reviews mentioned above, applying the climate envelope methodology was not used to predict or model future species distribution within this study. The presented model builds on the relationship of species to climatic parameters and thus relates to the concept of the basic ecological niche (Hutchinson, 1957). Natural sites, characterized by annual precipitation and average temperature, were defined by the extraction from given natural distribution data. The following comparison with modelled future climate data allows an extrapolation of potential natural site conditions under future scenarios. Therefore, the results must not be seen as predicting future species distribution but as localizing and quantifying potential natural conditions. This clearly distinguishes the application of the models from conventional and strongly criticized workflows.

Other studies used dynamic forest simulation models to predict climate change impacts on forest development. Changes in forest stands can be related to ecosystem services or protective functions via indices (Moos et al., 2023). With focus on natural hazards, dynamic forest simulations models have been coupled with hazard simulation models (Moos et al., 2021; Scheidl et al., 2020). While modelling approaches have been rolled out from site scale (Irauschek et al., 2017; Mina et al., 2017; Moos et al., 2021) to landscape scale (Suárez-Muñoz et al., 2021) recently, they still require detailed input information on site conditions, species composition, age classes, growth rates across the landscape and their current behavior (Käber et al., 2024; Suárez-Muñoz et al., 2021). Approaches to extrapolate information from plot level to polygon level exist and can be combined with geodata (Suárez-Muñoz et al., 2021). Nevertheless, the focus of dynamic forest models is on the simulation of growth, mortality, regeneration and disturbance of trees and forest stands over time and space (Dai et al., 2015).

In contrast, our study aims at very broad spectrum of species, including secondary or minor represented species. Species, that might not appear under current forest stand management but would find natural conditions under different management strategies or changed

climatic conditions, should be considered as well as currently widespread species. While using climate envelope models, we aimed at screening a wide range of species on regional scale. We cannot predict future forest composition, but we are able to detect potential natural conditions for additional species, that could be relevant for climate change adaptation of our protective forest stands. If we know about potentially interesting species, we can improve our data sources for species specific parameter, with regard to enable more detailed modelling also for these detected species.

Looking at the results on species level, they are in line with other climate change prognosis. As one of the novelties of this study lies in the broad spectrum of uniformly observed species, a holistic comparison of the whole species spectrum is not feasible. Most published studies refer to an European wide study site. Negative impacts on conifer stands are widely assigned (Dyderski et al., 2018; Illés and Móricz, 2022). The good prognosis for *Castanea sativa* was also found by Thurm et al. (2018). *Ulmus minor* and *Sorbus torminalis* were assigned good future conditions based on an European scale modelling approach (Dyderski et al., 2025), this is comparable to the prevailing results. The negative trends for the *Betula* genus may surprise, as it is known as pioneer species showing a broad ecological niche. Especially when looking on the alpine region, these results are in accordance with other models (Dyderski et al., 2025).

Downscaled climate data is in line with other recent studies (Haslinger et al., 2023; Kotlarski et al., 2023). When comparing downscaled climate data, the variation appears lower than for the measured Spartacus data. This is related to the big number of ensembles and the calculated mean values, that are compared to a single measured dataset. Rising temperature patterns are widely associated with anthropogenic driven climate change (IPCC, 2019). A rise of annual precipitation sum is a specific pattern related to Austrians topographical conditions. According to Haslinger et al. (2023) wetter annual conditions on average can be expected, they are accompanied by mainly stable summer means and higher evaporative demands, leading to a meteorological drought risk in summer. Due to the chosen methodical approach, seasonality is not considered in our study and can lead to an underrepresentation of water stress during summer months. Also, extreme weather events, that surely impact the development of forest stands, were not taken into account. For management measures it seems important to consider this seasonality on site scale.

The presented results can support the selection of vegetation types on a regional scale. Still, specific local conditions must be considered for an application as a protective forest management tool on site scale. The assumption that protective functions provided by ecosystem services are only present on potential natural stands may not represent all current processes appearing in nature. Observing and evaluating existing protective forests and their vegetation might conclude that specific individuals and stands can appear resilient and vital on sites categorized as non-natural in this study. Under selected circumstances, ecosystem services can also be provided on sites with non-natural conditions. However, the temporal duration of this stable status is not secured so far (Albrich et al., 2018; De Groot et al., 2012). Several aspects of climate change and biological factors will lead to changes significantly stronger than on natural stands. Vegetation communities on non-natural stands have less adaptive capacity regarding climate change and related impacts (Camarero et al., 2021). On the one hand, biological threats to stands as pests, diseases and calamities have more severe impacts on non-natural stands than on stands within the optimum of species-specific natural site conditions (Jandl et al., 2019). On the other hand, natural forest stands show higher diversity in species composition, which is closely linked to a higher resilience (Hurtado et al., 2025; Messier et al., 2019). As these factors are challenging to consider in a large-scale area-based analysis, we could not include them in this study. To not neglect these effects, we reduced and summed them up in the input criterion that only natural site conditions lead to stable and resilient ecosystem services in general.

Beside scaling effects and the definition of natural stands, we need to consider additional aspects for using this results in forest management strategies. This study defines the site conditions based on two parameters, annual average temperature and annual precipitation, representing a regional habitat (Pearson and Dawson, 2003). For the implementation of climate change mitigation measures in protective forest stands, a multitude of additional site parameters such as soil type, pH value, availability of nutrients, water logging, light conditions and exposition must be considered (Boisvenue and Running, 2006; Hopkins and Hüner, 2004; Schulze et al., 2019).

Beside additional site conditions, also characteristics of the observed species might play a role in their provision of protective functions. Even if a species finds a well-suited niche in an operational area, there might be species specific attributes that hinder it from building these vital and resilient stands, that we aim for in protective forest management. For example, low tolerance to snow pressure (e.g., *Cedrus libani*), late frosts, the ability to deal with saturated soil conditions after heavy rainfalls or the resistance to wind pressure are relevant exclusion criteria for several species at certain altitudes. When applying the prevailing results to a specific site, these species dependent characteristics must be considered. In forestry-related climate change research, often predictions of shifts in the altitude of species-specific distribution were made (Maharjan et al., 2023; Noce et al., 2023). Shifts in altitude were considered indirectly in this study, as temperature and precipitation are variables depending on altitude.

Taking into account 46 different species draw a wide picture. Nevertheless, it is not complete. We started from species being recorded on forest stands of the Austrian Federal Railways and supplemented them by species being discussed within the forest management. Further, we had to face limitations in terms of input data, namely current distribution data. This approach has to be seen as a starting point and should be further expanded. Especially to species, that were not considered due to missing input data (e.g., *Quercus pubescens*), but also to species that might find natural stands under future climate conditions. The adaptation of plant communities via migration is not considered in the prevailing modelling approach. This is a point criticized within reviews of species distribution models (Corlett and Westcott, 2013). Clark (2007) relativizes this aspect by human activities impacting species distributions over centuries. Accordingly, protective forest stands have been under the anthropogenic influence over centuries (Kleemayr et al., 2020).

Although there are large regional differences, apparent trends can be identified for various tree species. Furthermore, the study shows that the potential vegetation differs significantly between the climate change scenarios, making applications of concrete measures considerably more difficult.

The absence of natural conditions in the reference period for *Pinus cembra*, *Pinus mugo* and *Alnus viridis* is related to the altitudinal structure within the railway corridor and the related lack in high alpine areas. Natural conditions for these species were not part of the observation area and, therefore, not represented in the dataset of the

reference period. The best-ranked deciduous and conifer species (*Castanea sativa*, *Corylus avellana, Taxus baccata*) show good attributes regarding their resprouting capacity. Concerning the protective function against various types of hazards and the resilience of the stand, resprouting has significant advantages as it allows woody plants to regenerate more quickly, which is essential on slopes exposed to hazards. The period of limited protective function after an event, that led to damage within the protective forest, is estimated to be shorter, if species with good resprouting capacity were included in the stand structure. Moreover, coppice forest management becomes possible by implementing resprouting species. Particularly notable is the excellent prognosis of *Corylus avellana*. In commercially oriented forestry, the shrubby species receives little attention. *Corylus avellana* is of interest in protective forest management, especially on sites at risk of rockfall (Dorren et al., 2005; Jancke et al., 2009). The current species composition of protective forests must be rethought considering climate change effects to minimize the vulnerability of critical infrastructure. Our results suggest a potential loss of protective functionality especially for conifer dominated stands. A higher diversity of species can support the protective forest stands to resist climatic changes and show high resilience. Based on the results of this study, they should consist of a variety of deciduous species. If stands should be supported by conifers, *Taxus baccata* and *Cedrus Libani* show the best prognosis. The first is capable of resprouting, the second is limited in additional site-specific parameters (snow pressure). The species composition includes individuals with shrubby habitus and trees and mainly shows good resprouting capacities.

5 Conclusion

The regional results of the changing climatic conditions underline the urgency to climate change adaptations of the protective forest stands. In developing a two dimensional climatic envelop, natural stands for 46 species in all 26 operational units of the Austrian railway corridor were predicted. Several promising species were detected for future climate scenarios and European wide trends were confirmed on the regional scale. Especially *Castanea sativa*, *Ulmus minor* and *Sorbus torminalis* can help us to form vital stands that can deliver the protective functions we are aiming for.

As an initial step, the regional-scale approach offers full regional coverage and explicitly includes woody species that are often underrepresented in locally constrained studies. The results constitute a first step toward climate-change-adapted protective forest management in two respects: detecting changes in natural site conditions and predicting vulnerable areas along the Austrian railway corridor. It can be used as a management tool for operators of critical infrastructure, currently protected from natural hazards by forest stands, to actively choose future species and passively evaluate the risk of failing the requested protective functions. Beside all limitations discussed above, the combination of sophisticated downscaled climate data with defined niches for woody species appears as reasonable. It should be localized to site scale and implement additional vegetation specific parameters, that might constrain the vitalness of stands on specific sites.

As changes in forestry are related to long periods, the forestry management measures must be carefully considered. As one aspect, studies on a large spatial extent observing regional scale, such as this one, provide an understanding of general trends and tendencies. Although, detailed examinations on stand and site scale are indispensable and should be accelerated in future research with a strong focus on species providing ecosystem services in the form of protective functions.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: disaster risk reduction data OEBB. Requests to access these datasets should be directed to helene.mueller@boku.ac.at.

Author contributions

HM: Software, Writing – review & editing, Formal analysis, Writing – original draft, Methodology, Validation, Data curation, Visualization, Investigation, Conceptualization. HR: Supervision, Project administration, Validation, Conceptualization, Writing – review & editing, Funding acquisition. SL: Software, Writing – original draft, Conceptualization, Writing – review & editing, Investigation, Validation, Formal analysis, Visualization, Methodology, Data curation. CM: Funding acquisition, Conceptualization, Supervision, Writing – review & editing, Project administration. TF: Writing – review & editing, Conceptualization, Project administration. GH: Funding acquisition, Conceptualization, Writing – review & editing, Supervision, Project administration. CR: Resources, Writing – review & editing, Validation, Conceptualization. SH: Formal analysis, Validation, Data curation, Methodology, Conceptualization, Writing – review & editing, Investigation, Writing – original draft, Software, Visualization.

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