



Forecasting the circum-Mediterranean firs (*Abies* spp., Pinaceae) distribution: an assessment of a threatened conifers' group facing climate change in the twenty-first century

Javier López-Tirado¹ · Manuel Moreno-García² · Daniel Romera-Romera¹ · Virginia Zarco³ · Pablo J. Hidalgo³

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Abstract

This study examines 10 different taxa within the genus *Abies* identified in the circum-Mediterranean area: *A. alba*, *A. borisii-regis*, *A. cephalonica*, *A. cilicica*, *A. nebrodensis*, *A. nordmanniana* subsp. *equi-trojani*, *A. nordmanniana* subsp. *nordmanniana*, *A. numidica*, *A. pinsapo* var. *marocana* and *A. pinsapo* var. *pinsapo*. We assess the potential distribution of these species in the Mediterranean Basin, most of Central-Northern Europe and Asia Minor through analysis of 8 bioclimatic variables. First, the potential distribution (suitability area) was calculated with Biomod2 package for R using 10 algorithms. Models were ensemble for the present period and then projected into two climate change scenarios (an intermediate and the most extreme) within two time slices (2041–2060 and 2081–2100) and two Global Circulation Models (GCMs). The analysis showed an increase in total suitable area under both forecasted scenarios. *Abies* spp. appeared to be resilient against climate change, showing a latitudinal and longitudinal migration trend in response to the loss of current habitats. A proposal of assisted migration (managed relocation) is suggested as an interesting alternative to guarantee the preservation of the most endangered species by promoting the establishment of new populations outside of their historical distribution area.

Keywords Circum-Mediterranean *Abies* · Forecasting · Climate change · Potential distribution · Climate relicts

✉ Javier López-Tirado
b92lotij@uco.es

¹ Department of Botany, Ecology and Plant Physiology, University of Córdoba, Campus of Rabanales, Córdoba 14071, Spain

² IFAPA, Centro “Alameda del Obispo”, Av. Menéndez Pidal s/n, Apdo. 3092, Córdoba 14080, Spain

³ Center for Natural Resources, Health and Environment (RENSMA), University of Huelva, Avda. Tres de Marzo s/n, Huelva 21071, Spain

Introduction

In the first two decades of the twenty-first century, climate change has had different environmental effects on flora, such as extinction of species and habitat loss. Species which have suffered a contraction of their original geographic distribution, through the years due to climate change are known as climate relicts. In order to avoid extinction, these organisms modify their geographical distribution or their affinity to the new conditions brought about by environmental changes (González-Hernández et al. 2021). The former trait is related to the migration speed, i.e., the relocation of the plant in response to the effects of climate change. Hence, migration speed might drive the survival of plant populations, particularly in species with restricted distribution (Corlett and Westcott 2013). Today, many species still have some relict populations in areas they widely inhabited during the cold stages of the Quaternary (Hampe and Petit 2005). Due to the variation in environmental conditions over time, these species have little or no opportunity for genetic interchange between distant populations (Hampe and Jump 2011). The circum-Mediterranean is one of the hotspots of biodiversity in the world (Médail and Quézel 1997), with many relict tree species remaining in the mountain ranges. Forecasting the behavior or the presence of a species, taking into consideration the medium- and long-term effects of climate change, can lead to the development of specific programs directed at the conservation of threatened species (Guisan and Thuiller 2005).

Firs are evergreen conifers with regularly whorled branches belonging to gymnosperms (Tutin et al. 1993). The *Abies* genus is composed of 33 species around the world (Costa Tenorio et al. 2005), hosting the Mediterranean Basin some *Abies* endemic taxa (Dering et al. 2014; Sánchez-Robles et al. 2014; Gutiérrez Hernández et al. 2016; Alba-Sánchez et al. 2018), with two main significant spots comprising the Iberian Peninsula and North Africa (Morocco and Algeria) on the one hand, and Turkey and Greece on the other (López-Tirado and Hidalgo 2014). The most widely distributed species of *Abies* in Europe is the silver fir (*A. alba* Mill.). At lower latitudes it is less frequent and restricted to mountain ranges, where circum-Mediterranean firs occur (Aussenac 2002). Today, these relict firs are represented by fragmented populations, playing a key ecological role in Mediterranean mountain forests (Aussenac 1980). These plants are well adapted to climatic stress from cold, wet winters and extremely hot, dry summers, with periods of drought due to the irregular rainfall patterns of the Mediterranean bioclimate.

In the circum-Mediterranean area, as in many other areas of the world, forests of the genus *Abies* underwent a decrease in their distribution as a result of glaciation. Consequently, the genus has diversified, leaving isolated populations and their current ranges are therefore usually smaller than the original natural distribution, while overexploitation and improper forest management in recent centuries have also had a negative impact (Alba-Sánchez et al. 2019, 2021). Future distributions could be smaller than nowadays (Felicísimo et al. 2002) due to drastic climate change.

In the Iberian Peninsula there are only two species of *Abies*, *A. alba* and *A. pinsapo* Boiss. The former grows in the Pyrenees, and is frequently associated with beeches (*Fagus sylvatica* L.) in the form of beech-fir woods (mixed forests). It is found at higher altitudes ranging from 1200 to 2000 m a.s.l., with lower environmental humidity and poor soils. The latter is a Mediterranean fir occurring in southern Spain and North Africa, and was used as a source of wood as well as fuel until the beginning of the 20th century (Soto García 2006).

According to Alba-Sánchez et al. (2010) both taxa remained isolated throughout the Quaternary. The Iberian stands of *A. pinsapo* are located in the southernmost provinces (Cádiz and Málaga), being its optimal in the supra-Mediterranean belt (Valle 2004). The two species exhibit different hydrological traits and anatomical differences that could partly explain their wide geographical separation (Peguero-Pina et al. 2011). The current distribution of *A. pinsapo* is the result of biogeographical isolation since the last glaciation, as a result of which some stands are found in areas of highest annual rainfall in the Iberian Peninsula – at least 1000 mm (Fernández-Cancio et al. 2007; López González 2001), and, exceptionally, 4000 mm in the Sierra de Grazalema mountain range in the Province of Cádiz (Costa Tenorio et al. 2005). In north Africa there are two firs, possibly derived from a common ancestor with *A. pinsapo*. The first of these, *A. pinsapo* var. *marocana* (Trab.) Ceballos & Martín Bol. is located in the Rif mountain range (Morocco), while the second, *A. numidica* de Lannoy ex Carrière, named after the ancient kingdom of Numidia, is found in Algeria. Another fir species was initially described, named *A. tazaotana* Côzar ex Villar, but recent research suggests that this species is not consistent (Sánchez-Robles et al. 2014). *Abies nebrodensis* (Lojac.) Mattei is the most endangered circum-Mediterranean fir. There are approximately only 30 individuals in the Nebrodes mountain range (northern Sicily, Italy) (Ducci et al. 2000; Parducci et al. 2001; Thomas 2017), although its distribution was wider in the past (Pasta et al. 2020). This ‘critically endangered’ species has been studied from seed viability (Mirabile et al. 2022) and has been included in Annex II of the Habitat Directive as the only tree on this list of species requiring the designation of Special Areas of Conservation.

A further two circum-Mediterranean firs can be found on the Greek Peninsula. In the north, there are scattered populations of *A. borisii-regis* Mattf., named in honor of King Regis of Bulgaria, while in the south *A. cephalonica* Loudon is present, including on Kefalonia, the island from which it takes its name. Some additional circum-Mediterranean firs are located in Turkey and other areas around the Black Sea, such as the *A. nordmanniana* (Steven) Spach complex. Some of these populations have been difficult to classify, such as *A. bornmuelleriana* Mattf., analyzed under *A. nordmanniana* subsp. *nordmanniana* and considered a hybrid between *A. cephalonica* and *A. nordmanniana* (Farjon and Rushforth 1989; Ben-Said 2022; Liepelt et al. 2010). *Abies nordmanniana* subsp. *equi-trojani* (Asch. & Sint. ex Boiss.) Coode & Cullen is located and restricted to western Turkey (Nikolić et al. 2021). This complex may have evolved from the same ancestral fir (Kaya et al. 2008). A third fir in the oriental Mediterranean mountains is *A. cilicica* Carr., located in northern Turkey and eastern fringes of the Black Sea.

In biogeographical terms, *A. alba* is more characteristic of the Eurosiberian region than the Mediterranean one. Nonetheless, its distribution reaches southern Italy and Greece, overlapping with other Mediterranean firs. For this reason it has been included in this work even if it is not considered a circum-Mediterranean fir (Aussenac 2002). Moreover, *Abies* species may hybridize easily either in a spontaneous or in an artificial way (Vooková and Kormuták 2003; Hansen and Nielsen 2008; Kobliha et al. 2014; Krajmerová et al. 2015). In fact, it has been found that *A. nebrodensis* shows close relationships with the current surrounding *Abies* species (Ducci et al. 2000).

This study analyzes the potential distribution of 10 different *Abies* taxa: *A. alba*, *A. borisii-regis*, *A. cephalonica*, *A. cilicica*, *A. nebrodensis*, *A. nordmanniana* subsp. *equi-trojani*, *A. nordmanniana* subsp. *nordmanniana*, *A. numidica*, *A. pinsapo* var. *marocana* and *A. pinsapo* var. *pinsapo* according to two different scenarios and two periods (2041–2060 and

2081–2100). The main goal of the study was to analyze the potential distribution of these species in the present period and to then project this distribution forwards in two climate change scenarios. The ultimate goal was to understand the dynamics of these singular tree species and to suggest a proposal for assisted migration for conservation programs.

Materials and methods

Study area

The study area encompasses the Mediterranean Basin, most of Central-Northern Europe and Western Asia. Orography is complex, considering the wide variety from the sea level to the highest mountain ranges such as the Alps, Mount Elbrus (the highest European summit at 5642 m a.s.l.), and Mount Ararat in Turkey (5137 m a.s.l.), among others. As shown in Fig. 1, some of the target taxa were restricted to few populations or specimens; the most extreme case was *A. nebrodensis* in Sicily (Italy) with only several mature individuals. Other *Abies* were mainly scattered across Greece like *A. borisii-regis* and *A. cephalonica* (Christopoulou et al. 2018). Finally, species such as *A. alba*, *A. nordmanniana* and *A. cilicica* were the most widely distributed over the study area. Occurrence data was retrieved from the European Forest Genetic Resources Programme (euforgen.org, last accessed in December 2020). *Abies cilicica* was considered *sensu lato* in this work due to lack of information in the data of origin, although at least two subspecies can be recognized (Boratyńska et al. 2015).

Most of the circum-Mediterranean *Abies* species are usually found at altitudes above 400 m a.s.l. with a wide range reaching above 2000 m a.s.l. in the majority of species. *Abies nordmanniana* is the only one species that can be found at sea level in some areas (Aus-

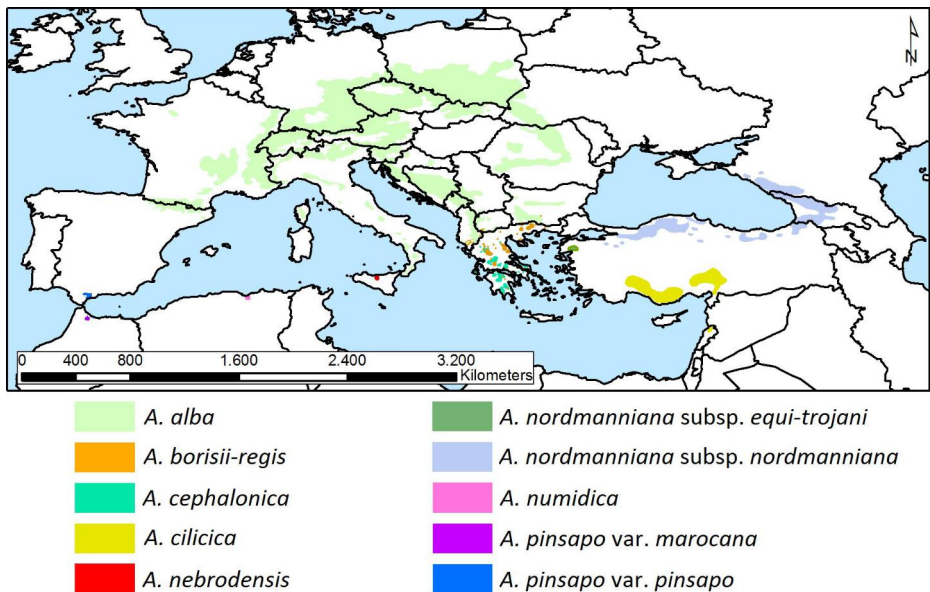


Fig. 1 Current distribution of the ten taxa studied

senac 2002). In addition to the mountainous habitats, *Abies* species are found in areas with annual precipitation of around 800 mm and high humidity, but also show tolerance to long droughts during summer (Tinner et al. 2013). The species form pure stands in optimal conditions, although they can grow mixed with junipers (*Juniperus* spp.), pines (*Pinus* spp.), cedars (*Cedrus* spp.) and oaks (*Quercus* spp.), among others. Different protected reserves and conservation programs have been developed to protect populations of the species from fires, livestock grazing and genetic drift (Caudullo and Tinner 2016).

Explanatory variables and processing

Data was taken from the WorldClim 2.1 project. This information was downscaled from the Coupled Model Intercomparison Project Phase 6 [CMIP6] (Eyring et al. 2016), the most recent projection for forecasting currently available. Of the 19 bioclimatic variables, 8 were considered in our modelling after a correlation analysis performed by the software SPSS statistics 20 (see Supplementary Material 0). Annual mean temperature (Bio1) was included because of its significance (Moles et al. 2014) (Table 1).

Modelling was carried out at 2.5 min spatial resolution (the highest one available until now). The first step was to calculate the potential distribution or suitability area in the present period for each taxon. These were then projected for two scenarios in two different time periods (2041–2060 and 2081–2100) in the MIROC6 and CMCC-ESM2 Global Circulation Models (GCMs). Data processing was carried out using ArcGIS 10 (ESRI, 2010). In terms of severity, we selected an intermediate (ssp245) and the most extreme (ssp585) scenarios (Steven et al. 2020).

Performance and validation of the models

Modelling of the present period was carried out using the Biomod2 (3.5.1) package for R. Ten algorithms were considered as follows: Artificial Neural Networks (ANN), Surface Range Envelope (SRE), Flexible Discriminant Analysis (FDA), General Linear Models (GLM), General Additive Models (GAM), General Boosted Models (GBM), Classification Tree Analysis (CTA), Multiple Adaptive Regression Splines (MARS), Random Forests (RF) and Maximum Entropy model (MaxEnt). Pseudo absence points were generated by the software itself. Training and testing data percentages were set to 75% and 25% respectively, in accordance with the default options. Models for each species were ensemble in the present period. Then, future projections were also processed by the Biomod2 (3.5.1) package for R to obtain the final forecasted map for each scenario and time period.

Table 1 Variables used for modelling

Variable	Label	Source
Annual Mean Temperature (°C)	Bio1	WorldClim 2.1
Mean Diurnal Range (°C)	Bio2	WorldClim 2.1
Isothermality (Bio2/Bio7) x 100	Bio3	WorldClim 2.1
Temperature Seasonality (SDx100) (°C)	Bio4	WorldClim 2.1
Mean Temperature of Wettest Quarter (°C)	Bio8	WorldClim 2.1
Annual Precipitation (mm)	Bio12	WorldClim 2.1
Precipitation Seasonality (Coeff. of variation)	Bio15	WorldClim 2.1
Precipitation of Warmest Quarter (mm)	Bio18	WorldClim 2.1

Models were validated by three metrics: the Receiver Operating Characteristic (ROC) curve, calculating the Area Under the Curve (AUC) (Ben-David 2008; Fawcett 2006; Fielding and Bell 1997; Vuk and Curk 2006), the True Skill Statistic (TSS) and Kappa, in order to assess the robustness of the model.

Results

The results of the model for the present potential distribution indicated an increase in suitability area with respect to the current distribution for all the taxa. Regarding GCMs, both CMCC-ESM2 and MIROC6 showed similar trends in the forecast. In general terms, the 2041–2060 and 2081–2100 periods showed similar distribution areas, although the latter indicated that an upward migration in latitude could be possible for most of the species. Focusing on *Abies* spp. with a small current distribution, the projected range of *A. nordmanniana* subsp. *equi-trojani* and both varieties of *A. pinsapo* showed a marked contrast in comparison with other restricted firs such as *A. numidica* and *A. nebrodensis*. According to our results, these latter firs could spread in the future (especially *A. numidica*), whereas the former group is predicted to undergo a smooth reduction of suitability area outside its current distribution.

Figure SM1 (Supplementary Material) shows the results of the model for *A. alba*. Present and future scenarios display a similar potential area, except for ssp585 (2081–2100) for both GCMs. The main range of this fir is distributed across Central Europe, where, over the successive time periods and scenarios, the areas it occupies could be reduced to the higher reaches of the Alps and the Carpathian Mountains. New areas of suitability were identified in the Cantabrian Range (western Spain) and the Caucasus Mountains. The harshest scenario indicated a loss of *A. alba* in the Pyrenees and the Apennines, ranges where it grows today, while the Caucasus arose as a suitable territory to maintain potential afforested stands throughout the current century. *Abies borisii-regis* (figure SM2) could find suitable areas along an East-West belt—from Azerbaijan and Iran to the Iberian Peninsula—in similar latitudes to where it occurs nowadays in the Balkans. In the case of the ssp585 (2081–2100) scenario, its current distribution would not be sustained for MIROC6. Suitable areas would include the northernmost mountains of the Balkans, a northern belt in Turkey facing the Black Sea and other areas in France and north-western Spain. In figure SM3, a similar result can be seen for *A. cephalonica*, with both *A. borisii-regis* and *A. cephalonica* sharing scattered spots of occurrence in the Balkan Peninsula and Greece. Thus, again an East-West belt of suitability can be found in all the studied scenarios. The main differences between the two species in the harshest scenario (ssp585, 2081–2100) were: (i) fewer suitable areas were projected for *A. cephalonica* than for *A. borisii-regis*; and (ii) while some pixels in the current distribution of *A. cephalonica* remained suitable, the areas where *A. borisii-regis* currently grows were totally unsuitable in the MIROC6 GCM. The present potential distribution of the eastern-Mediterranean *A. cilicica* in Turkey and Lebanon (figure SM4) was very similar to the actual distribution, with some enlargement into patches in Central Anatolia and the Armenian Plateau in Turkey, and some spots in North Africa. In the forecasted scenarios, a wider suitable area was found, where a migration into eastern Turkey was detected. North Africa (Algeria and Morocco), Cyprus and the Iberian Peninsula could also harbour stands of this fir even in the most extreme and temporally distant scenario. The isolated Lebanese

stand could be also preserved in this scenario. Figure SM5 shows the potential distribution of *A. nebrodensis*. This species, endemic to Sicily, could find new suitable areas inland and close to the sea, such that the island could sustain more stands than it does today. Other potential areas in mainland Italy included Calabria and the Central Apennines. More distant zones found to be suitable in the study encompassed coastal areas on Sardinia and Corsica. The forecasted scenarios indicated a retraction of suitability in the study area. The two subspecies of *A. nordmanniana* followed different trends. The scarce *A. nordmanniana* subsp. *equi-trojani* (figure SM6) could experience a reduction in its current distribution. New potential areas could be found over the coming decades (2041–2060 period) in the Iberian Peninsula, Sardinia, Greece and western Turkey. In the most severe scenario, only a small number of suitable patches were found close to its current distribution. By contrast, *A. nordmanniana* subsp. *nordmanniana* (figure SM7), whose current distribution is found across northern Turkey and the Caucasus, could benefit from the expected environmental changes. The present potential distribution was wider than its actual current range, incorporating new suitable areas in the Balkan Peninsula. The forecasted scenarios predicted an enlargement to the western study area. High ranges like the Carpathian Mountains, the Alps, the Pyrenees and the Cantabrian Range could sustain this taxon even in the ssp585 (2081–2100) scenario. In any case, this subspecies would never colonize either the current or potential areas of *A. nordmanniana* subsp. *equi-trojani*. With respect to *A. numidica* (figure SM8), the North African coast (Tunisia, Algeria and Morocco) and western Iberian Peninsula should be highlighted. On both continents, a potential distribution of this species was found where both varieties of *A. pinsapo* grow today, i.e. the Moroccan Rif for *A. pinsapo* var. *marocana*, and the Baetic Range for *A. pinsapo* var. *pinsapo*. The Eastern Mediterranean was also suitable for *A. numidica*, including Albania, Greece, Crete, Lebanon, Syria and Turkey, among others. The forecast for *A. numidica* showed it to be the fir that potentially undergoes the largest expansion of suitable area, especially around the Mediterranean Basin. The models for both *A. pinsapo* varieties indicated that the surroundings of the Strait of Gibraltar are suitable in the present and in the future. *Abies pinsapo* var. *marocana* (figure SM9) could also thrive especially in northern Portugal. *Abies pinsapo* var. *pinsapo* (figure SM10) could also find suitable areas in Portugal, although showed a decrease in the ssp585 (2081–2100) scenario.

Regarding validation of the models, Table 2 shows high accuracy of three metrics to validate the models.

Table 2 AUC, TSS and Kappa values to each studied taxon

	AUC	TSS	Kappa
<i>A. alba</i>	0.986	0.876	0.973
<i>A. borisii-regis</i>	0.996	0.962	0.938
<i>A. cephalonica</i>	0.998	0.977	0.968
<i>A. cilicica</i>	0.999	0.981	0.971
<i>A. nebrodensis</i>	1.000	1.000	1.000
<i>A. nordmanniana</i> subsp. <i>equi-trojani</i>	1.000	1.000	1.000
<i>A. nordmanniana</i> subsp. <i>nordmanniana</i>	0.993	0.922	0.898
<i>A. numidica</i>	1.000	1.000	1.000
<i>A. pinsapo</i> var. <i>marocana</i>	1.000	1.000	1.000
<i>A. pinsapo</i> var. <i>pinsapo</i>	1.000	1.000	1.000

Discussion

Ecological Niche Modelling (ENM) and Species Distribution Models (SDMs) are being used to understand modifications in the distribution of species in the context of climate change. A constant and exhaustive study of Global Climate Models (GCMs) generates updated and more accurate data regarding species distribution. The World Climate Research Programme (WCRP) in its Coupled Model Intercomparison Project Phase 6 [CMIP6] (Eyring et al. 2016) was the basis for the WorldClim 2.1 project, from which the explanatory variables were retrieved. The performance of the algorithms were excellent, as the metrics indicate. According to Swets (1988), AUC values between 0.5 and 0.7 indicate low accuracy; between 0.7 and 0.9 suggest that the results are potentially useful; and >0.9 is a signal of high accuracy.

Most of the Mediterranean firs had to cope with severe climatic fluctuations during the Pleistocene. The distribution patterns of each species are thus the result of expansions and contractions in their dynamic range (Liepelt et al. 2010). The circum-Mediterranean might be an especially vulnerable region to global change Giorgi and Lionello (2008). However, the response to these changes depends on the resilience of each species. On the other hand, the increasing CO₂ in the atmosphere could benefit *A. cephalonica* growth (Koutavas 2008), whilst raising temperatures and a reduction in rainfall during summer could harm *A. borisii-regis* radial growth (Pasho et al. 2014).

Abies alba is one of the most common trees in Central Europe (Ficko et al. 2011). It suffered clear-cutting in past centuries for use in salt mines, promoting *Picea abies* (L.) H.Karst. (Mellert et al. 2011). This fir is of special interest as it is the species with the widest current distribution. The ssp245 scenario shows a higher distribution in the period 2041–2060, but this decreases in the period 2081–2100. A similar behaviour occurs under ssp585, where the distribution shows a slight reduction in 2041–2060, but is then followed by a drastic decrease. This species would be able to adapt to the climatic conditions in the first period, but would suffer a decrease under the effects of more severe climate change. The results obtained show the same behaviour that was reported in Tinner et al. (2013), i.e. *Abies alba* could not contract its potential distribution even if the climate becomes warmer than today, because the species is able to move around the circum-Mediterranean looking to find suitable areas with high altitudes (altitudinal migration) and mostly humid (latitudinal migration), and is able to regenerate well in stands mixed with other evergreen species (e.g., *Quercus ilex* L.) (Walder et al. 2021). Our results show that, *A. alba* is one of the dominant Mediterranean species and the only species from the European representatives of the *Abies* that has a wide distribution (Muller et al. 2007). In contrast to other typical circum-Mediterranean species, *A. alba* shows a continuous range of distribution. It is able to withstand Mediterranean summer droughts, and to regenerate naturally and regularly in these environments. It has been estimated that *A. alba* migrates less than 250 m per year (Cheddadi et al. 2014).

As demonstrated, the secondary forest of *A. nordmanniana* subsp. *equi-trojani* and *A. pinsapo* var. *marocana* have the smallest current distribution, often found as a mosaic of patches of various development stages showing different stand structures and successional stages (Navarro et al. 2020). This leads to a limited capacity for resilience in the face of abrupt changes in the environment. Thus, they are the most vulnerable species in that both could experience a drastic reduction in range. According to the results, *A. pinsapo* tends to

migrate latitudinally to the west, looking for a favourable climate. *Abies pinsapo* var. *pinsapo* grows on its own phytoclimatic Mediterranean forest, which would make it difficult to spread to other places, and hence assisted migration seems to be the only alternative. Fortunately, there are suitable areas to preserve it *ex situ* (Cardalliaquet et al. 2019) and its current distribution seems to be also suitable across this century. Due to the projected climate change, some species with limited dispersal may be unable to migrate at the pace necessary in case of losing their current distribution (Wang et al. 2019). One strategy for conservation and protection could be assisted migration, also known as managed relocation (Richardson et al. 2009; Schwartz et al. 2012) or assisted colonization (Hällfors et al. 2014; Ferrarini et al. 2016), regarded as the strongest method for testing the relationship of range and niche limits (Gaston 2003). Assisted migration aims to move these species into locations that have been predicted to be more suitable under future climate conditions (Loss et al. 2011; McLachlan et al. 2007). This method has been used for decades in attempts to revegetate marginal or highly impacted areas, or in response to large disturbances such as wildfire, where species are translocated and reintroduced for the recovery of vulnerable sites (Vitt et al. 2010). Accordingly, the current distribution and the sites where the species were located previously, can be interesting places to induce assisted migration, considering that they have the altitude and climatic variations tolerable for each species. In any case, it is a controversial technique as we are introducing species outside of their historical range and the new assisted population should be confined, to avoid conflicts with native populations or undesirable hybridizations. In this context, botanical gardens located in protected sites could play a significant role.

Other species could benefit under the forecasted scenarios by greatly gaining suitable areas. The species standing to gain the most could be *A. numidica*. The current large potential distribution of *A. nordmanniana* subsp. *nordmanniana* could be originated because of the dynamic range expansions and contractions during the intense Quaternary climatic fluctuations (Liepelt et al. 2010). The current distribution can also show an increase under both forecasted scenarios, although it could lose suitability in its current distribution and find new potential areas in central-western Europe. Taking this into consideration, the better adaptation forecasted for *A. nordmanniana* subsp. *nordmanniana* in comparison with *A. nordmanniana* subsp. *equi-trojani* could open a new line of investigation for the conservation of the species by establishing the factors underlying this difference. *Abies nebrodensis* is the species that could suffer a loss of suitability area in the harshest scenario. In any case, afforestation is therefore encouraged in its native territory. Regarding *A. numidica*, our results show that in the future will thrive, as the most resistant species for both scenarios and time slices, it could achieve its original distribution in Algeria (Sánchez-Robles et al. 2014). Considering that *Abies* spp. have played, and still play, a central environmental role in forested areas which extend over large parts of the northern hemisphere (Liepelt et al. 2010), *A. numidica* could be used for assisted migration from Iran to Portugal.

Eastern Mediterranean species, *A. cilicica*, *A. cephalonica* and *A. borisii-regis* show similar results. These indicate an increased distribution in the period 2041–2060 under both scenarios, followed by a decrease in the period 2081–2100, again under both scenarios, although it still remains higher than the current distribution. The current distribution of the population of *A. cilicica*, is endangered in areas of lower elevation due to arid conditions (Aussenac 2002; Gardner and Knees 2013). Nevertheless, the forecast shows an improvement in its distribution, given that the species is able to form pure or mixed stands with other

species (e.g. *Pinus nigra* subsp. *pallasiana* (Lamb.), *Cedrus libani* A. Rich. and *Juniperus excelsa* M. Bieb.) (Kavgaci et al. 2010). According to our results, the forecasted scenarios show a disjunctive geographic distribution divided into several areas isolated from each other, as was reported by Sękiewicz et al. (2015). They point out that this fragmentation has been happening since the glaciations as a result of the profound aridity caused by climatic variations, the same cause of the forecasted distribution.

Due to the extreme climatic episodes expected in the Mediterranean Basin, originating in the increase in the frequency and severity of drought events, as reported by Giorgi and Lionello (2008), an upward latitudinal migration could be expected in the Balkans, France and the Iberian Peninsula for *A. borisii-regis*, whereas *A. cephalonica* could maintain some areas of its original distribution, as well as extending its range from east to west, like in mountainous regions in the Iberian Peninsula and Africa (Awad et al. 2014).

Despite the effects of the forecast on the diversity of the species, both scenarios show that the overall distribution of *Abies* spp. in the circum-Mediterranean area could increase, but for *A. nebrodensis*, according to the harshest scenario. Even so, however, the range of suitable locations could remain larger than the current distribution.

Conclusions

The forecasted scenarios delivered different results, according to the taxa. Most showed an increased potential distribution with respect to the present. Nonetheless, other taxa showed a decrease, and even a complete loss in the case of *A. nebrodensis* in the harshest scenario. In the case of *A. alba*, despite encompassing the largest current distribution, the forecasted scenarios do not ensure an extensive potential distribution, taking into consideration climate change. On the other hand, the *Abies* genus seemed to be resilient to climate change, showing that a latitudinal and an altitudinal upward migration could be feasible as a response to the changing bioclimatic conditions expected over the next few decades (González-Hernández et al. 2021). According to our results, the general potential distribution of genus *Abies* could increase in the circum-Mediterranean. This study confirms that in the coming years, *Abies* genus could undergo variations in its current distribution as an effect of climate change. Finally, anthropogenic alterations are causing loss of biodiversity (Nieto-Lugilde et al. 2021). The results presented here could help to carry out afforestation programs, in which human-induced disturbances are developed, especially in species not adapted to fires (Ganatsas et al. 2012). Applied strategies of conservation by assisted migration could be an effective method for conserving the *Abies* genus in the circum-Mediterranean in the face of climate change.

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Declarations

Competing interests The corresponding author on behalf of all the authors of this manuscript, declare that there are no competing interests.

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