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The high climate vulnerability of western Mediterranean forests

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HIGHLIGHTS

- We provide an *in-situ* climate risk analysis of Mediterranean forest types.
- The sensitivity and adaptive capacity complement the climate risk analysis.
- Under RCP8.5-MRI-CGCM3, 82.82 % of the Mediterranean forests face climate risk.
- Under RCP8.5-MIROC-ESM, 98.38 % of the Mediterranean forests face high climate risk.
- Most vegetation types are highly vulnerable to climate change.

GRAPHICAL ABSTRACT
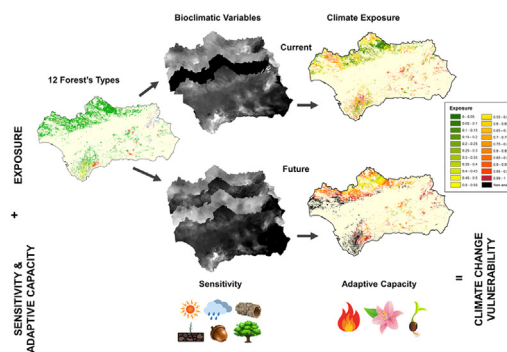
ABSTRACT

Understanding the effects of climate change is one of the most challenging goals for biodiversity conservation. The forests of Andalusia, in Southern Spain, are part of an important Mediterranean Basin biodiversity hotspot. However, great changes in climate are expected to occur in this region, and there is an increasing need to assess the vulnerability of its vegetation.

We assess the vulnerability of twelve forest types in the region that are included in the European Directive 92/43/EEC as Habitats of Community Interest (HCI). HCI are natural habitat types which are in danger, have a small natural range, or present an outstanding example of a biogeographical regions in the European Union. We assessed vulnerability by analyzing the climate exposure level of each forest type under two global climate models (MRI-CGCM3, which predicts warmer and wetter conditions, and MIROC-ESM which predicts hotter and drier conditions), two emission scenarios (RCP4.5, a representative concentration pathway that predicts stable emissions of CO_2, and RCP8.5, that predicts the highest CO_2 emissions) by the mid- and end-century time periods. The vulnerability analysis also includes the sensitivity and adaptive capacity of the dominant tree species which compose each forest type. An overall vulnerability score was calculated for each forest type, model, scenario and time period.

High-elevation forest types and those with high moisture requirements were more vulnerable to climate change, while forest types dominated by more thermophilic species were less vulnerable and more resilient. The worst climate impacts were predicted in the MIROC-ESM model and RCP8.5 scenario by the end of the century (2070–2100), while the least climatic stress was obtained in the MRI-CGCM3 model and RCP4.5 scenario by the mid-century (2040–2070), which still shows high potential stress for most forest types. By the end of the century, the climate exposure of the entire forest domain will range between 32 % in the least stressful situation (MRI-CGCM3 and RCP4.5), and 98 % in the most climatically stressful situation (MIROC-ESM and RCP8.5). However, the effects of climate change will be perceptible by the mid-century, with most of the HCI forest types suffering climate stress.

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The "Andalusian oak forest" and the "*Corylus* wet forest" types were the most vulnerable to climate change, while the "Mediterranean pine forest", the "*Olea* and *Ceratonia* forests" and the "oak forests" were the least vulnerable.

This assessment identifies the vulnerable forest types to climate change in the south of the Iberian Peninsula, and provides context for natural resource managers in making decisions about how to adapt forests to the impacts of climate change.

1. Introduction

There is a pressing need to assess the climate risks for vegetation types and their dominant species, especially in biodiversity hotspot areas, where climate change threatens high numbers of species (Anaya-Romero et al., 2015; Benito et al., 2011; Diffenbaugh and Giorgi, 2012). In Europe, the loss of suitable climatic conditions in forests by the end of this century is expected to result in shifts in geographic range, abundance, and species composition of vegetation types (Araújo et al., 2011). The decrease of water availability and stress caused by increasing temperatures could induce changes in species' functional responses, their persistence and mortality rates, and changes in demography (Ruiz-Benito et al., 2020). The forests of southwestern Europe are projected to face increased stress due to climate change, such as increasing fire risk, severe drought, and a decrease in the prevalence of their dominant tree species (European Environment Agency, 2010; Field et al., 2014; Schröter et al., 2005). This is particularly true for the Iberian Peninsula, an important biodiversity hotspot in Europe, (Médail and Quézel, 1999; Myers et al., 2000). Studies in this territory have predicted a reduction of suitable climatic conditions and the area of some forest species due to the predicted changes in bioclimatic conditions (Benito et al., 2011; Giorgi, 2006; Sousa et al., 2007). Forests and woodlands in the south of the Iberian Peninsula developed as a consequence of changes in the environment and geology at the end of the Tertiary (Blanca, 1993; Médail and Quézel, 1997; Peñas et al., 2005). They are associated with the region's Alpine orogeny and present diverse types in the surroundings of the Baetic range (Maldonado et al., 1999; Peñas et al., 2005). These forest types vary from low-altitude, meso-Mediterranean distribution, including *Quercus rotundifolia* Lam. and *Quercus suber* L. perennial forests and relict forests of *Quercus canariensis* Willd., to forests restricted to higher altitudes (supra and/or oro-Mediterranean), such as relict forests of *Abies pinsapo* Boiss., forests of *Pinus nigra* subsp. *salzmanii* and deciduous *Quercus pyrenaica* Willd. (Rivas-Martínez, 1988; Rivas-Martínez et al., 1997). Regarding conservation, these forest types are defined as Habitats of Community Interest (HCI) in the group "Forests of temperate Europe" (Group 9) (CEC, 2013), and their floristic composition, based mainly on diagnostic, constant and dominant species, is known (Chytrý et al., 2020). The HCI are natural habitat types whose distribution is principally located in the European Union. The HCI designation refers to habitats that are in danger, have a small natural range, present an outstanding example of a biogeographical region, or present distinguished vegetation (Evans, 2006). These habitats are included in the Annex I of the Habitats Directive, the legislative instrument used to establish a framework for the conservation of wild plant and animal species, and natural habitats of Community interest (CEC, 2013). The conservation requirements for vegetation types with HCI designation are to establish special conservation areas based on outstanding examples of vegetation (Directive 92/43/EEC). These areas have had considerable use in conservation planning, monitoring, and assessment.

Biogeographic estimates of climate change effects can be calculated using species distribution models (SDMs; Miller, 2010), and ecological niche modeling (ENM; Warren, 2012). However, for managing extant vegetation, place-based models of climate change vulnerability can be used to evaluate the relative susceptibility of vegetation types or ecosystems. This approach often uses a climate change vulnerability index (CCVI; Williams et al., 2008; Young et al., 2012), and has been applied extensively for climate-adaptive conservation as well as in other fields (Foden et al., 2013; Oppenheimer et al., 2014). A climate change vulnerability index (CCVI) approach to climate vulnerability assessments can be defined as the combination of the climate exposure, and the sensitivity and adaptive capacity of a species or vegetation type to changing climate conditions (Field et al., 2014; Glick et al., 2011). Exposure is the magnitude and rate of change that a type is likely to experience due to climate change and associated problems. The use of climate change projections can provide context for where and how much stress a habitat may experience (Glick et al., 2011). Sensitivity refers to the degree to which changes in climate are thought to directly impact different species, while adaptive capacity refers to estimates of the degree to which different species' life history characteristics may moderate climatic impacts (Adger, 2006; Comer et al., 2012; Glick et al., 2011; Millar et al., 2007). Vulnerability is the combination of the sensitivity, adaptive capacity and exposure (Williams et al., 2008) which represent the biological attributes of the dominant species in each forest group. The CCVI variation used in this assessment was implemented by Thorne et al. (2016) and (2018), which is a trait-based vulnerability approach (Moyle et al., 2013; Pacifici et al., 2015). The methodology involves the selection of functional traits related to sensitivity (e.g. Gardali et al., 2012) and adaptive capacity (e.g. Foden et al., 2013) combining them with estimates of exposure (Lawler et al., 2010; Muñoz-Sáez et al., 2021; Williams et al., 2008).

CCVI usage is growing among conservation organizations and management agencies because they enable a relatively swift evaluation for vegetation types and species, which can be utilized to prioritize conservation planning and the execution of adaptation strategies (Pacifici et al., 2015). As climate adaptation and mitigation actions are implemented, regional and more localized assessments are needed to inform management plans for these specific areas. In response to this need, we assessed the climate vulnerability of twelve HCI forest types, by using a place-based spatial analysis of their exposure to the climatic change and an evaluation of their sensitivity (or resistance) and adaptive capacity (Thorne et al., 2016) according to functional traits of the dominant tree species composing each HCI.

This study differs from recent work on the climate risks of the forest in the south of the Iberian Peninsula by using a place-based climate exposure, rather than species distribution (movement) model-based estimate of the impact of climate change; and the incorporation of plant species functional traits as attributes of sensitivity and adaptive capacity. Recent studies (Hidalgo et al., 2008; López-Tirado and Hidalgo, 2014, 2015, 2016, 2018; Galacho-Jiménez et al., 2023) had examined where species are likely to move. To our knowledge, there have been no studies that also include species functional traits in a CCVI framework.

Our objectives were: (1) to assess the climatic exposure of the forests in the south of the Iberian Peninsula using maps of 12 HCI types from the "Habitats Directive" as defined and mapped by the Andalusian Environmental Information Network (REDIAM, 2022) (climatic exposure was modeled for the future climate conditions for every grid cell of each forest type); (2) to compare the vulnerability results depending on two different Representative Concentration Pathways (RCP4.5 and RCP8.5); (3) to obtain biological evidence of each forest type's sensitivity and adaptive capacity to the future projections by assessing their dominant species; and (4) to develop an overall score for vulnerability based on the combination of results in exposure, sensitivity and adaptive capacity for each forest type, and identify their relative and highest areas of vulnerability.

2. Material and methods

2.1. Study area

We studied the forests in the south of the Iberian Peninsula, which cover an area of 87,600 km^2 (Fig. 1). The study area has a hot-summer
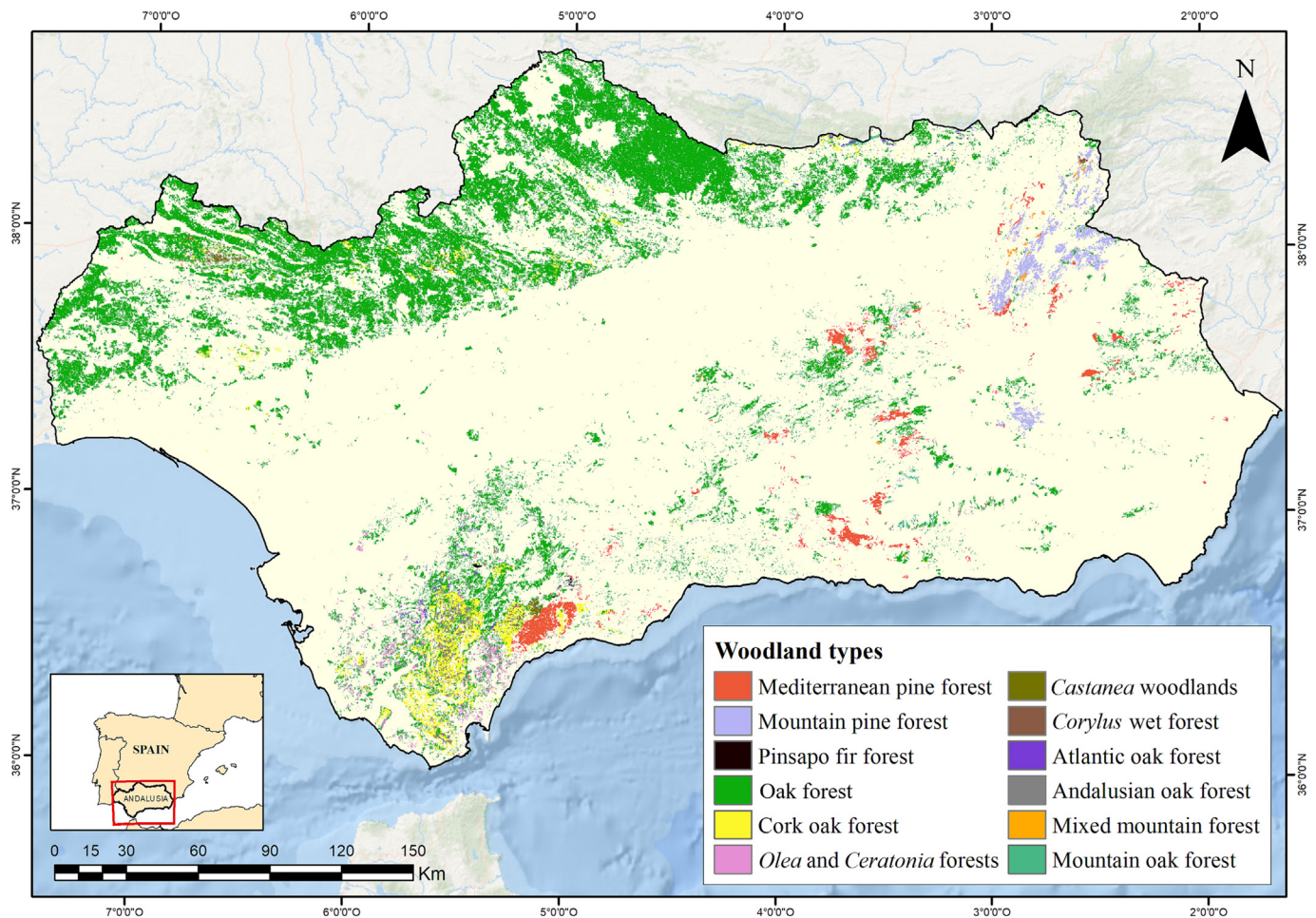
Fig. 1. Map of forest types in the south of Iberian Peninsula with the classification created for this study derived from the different Habitats of Community Interest. For more information see Table 1 and Supplementary Information Appendix 1, Table S1.

Mediterranean climate (Csa) according to the Köppen-Geiger classification, and also presents some cold semi-arid (steppe) climate (BSk) in the region of Almeria (Kottek et al., 2006; Peel et al., 2007). The region spans a broad gradient of environmental conditions that encompass a diverse array of forest types, including cool and moist coastal, high-elevation, and termophilic forests (Costa Pérez et al., 2004; López-Tirado and Hidalgo, 2018). Elevations in this area range from 0 to 3479 m.a.s.l., and annual average temperatures range from 8.74 to 25.71 °C. It is the hottest region of the Iberian Peninsula, and contains both the driest site and one of wettest areas in the Peninsula (REDIAM, Junta de Andalucía, 2022; Rivas-Martínez et al., 1997; Rodrigo et al., 1999). The South of Iberian Peninsula is separated from the African continent by 14.4 km. The collision between the African and European tectonic plates in the Tertiary formed the Baetic range, one of the most important ranges together with Sierra Morena in this area (Maldonado et al., 1999; Rosenbaum et al., 2002). Biogeographically, the south of the Iberian Peninsula is located in the Western-Mediterranean subregion, and shows connections between Iberian and Moroccan Atlantic territories through the Strait of Gibraltar (Galán de Mera et al., 2003).

2.2. Vegetation map and species composition

We used the original map of forests of HCI compiled from REDIAM, which identified 11 different types (REDIAM, 2020). We resampled the original map using the majority sample rule in ARCGIS (ESRI 10.1) from a shapefile to a raster at a spatial resolution of 200 m per pixel. This was necessary to match the resolution of the vegetation map to the current and future climate data used, and served as the operational grid scale for

the analysis. We defined a new classification for the forests starting from the HCI classes in REDIAM, based on ecological, biogeographical distribution and species composition, obtaining 12 different forest types (Table 1). The recombination of the forest types attended to their ecological and chorological coincidences (Molero and Marfil, 2017). For the new combination, we reclassified meadows "dehesas" as oak forests. In addition, forests dominated by *Quercus faginea* s.s. were combined with forests dominated by *Acer*, forming a "mixed mountain forest" class (Supplementary data Appendix S1, Table S1). Riparian forests were excluded in this assessment because of their close dependency of the hydrological courses, groundwater and inundations (González et al., 2012), which have not been measured for this assessment. The new map of forests covers 16.2 % of the whole studied extension and occupies 13,984.12 km^2.

For each forest type, the composition of dominant tree species was identified according to REDIAM (2020), to VV.AA (2009) and to the "Interpretation Manual of European Union Habitats" produced by the European Commission (CEC, 2013). The dominant tree species lists were further reviewed and finalized based on our field work experience. These species can be considered as a combination of diagnostic species and species with higher constancy that together define a vegetation unit (Braun-Blanquet, 1979). Here, we included three types of trees as dominant species: diagnostic species (species with occurrences concentrated in a particular habitat, being absent or rare in other habitats), constant species (species that occur frequently but not necessarily exclusively in a particular habitat), and majority cover species (species that often reach high cover in a particular habitat, thus determining the habitat physiognomy) (Chytrý and Tichý, 2003). The dominant tree species list analyzed for each studied forest type is indicated in Table 1.

Table 1

The forest types analyzed and their dominant species (CEC, 2013; REDIAM, 2020). The correspondence with the EU Directive 92/43/EEC (EUNIS) is also shown. (*) Priority natural habitats, which are threatened in the European Union territory.

Forest type	Characteristics species	Number of grid cells	Km^2	Description	Correspondence in EUNIS
Mountain oak forest	- *Quercus pyrenaica*	728	29.12	*Quercus pyrenaica* forests of siliceous supra-Mediterranean areas with sub-humid climate of the western Sierra Nevada, the Sierra de Alfacar, the northern flanks of the Sierra de Cazulas and the Sierra Tejeda.	(9230) Galicio-Portuguese oak woods with *Quercus robur* and *Quercus pyrenaica*
Mixed mountain forest	- *Quercus faginea* subsp. *faginea* - *Quercus alpestris* - *Acer monspessulanum* - *Acer opalus* subsp. *granatense*	953	38.12	Combination of two forests sharing ecological and chorological characteristics - Xero-mesophile *Quercus faginea* forests of slopes and plateau of middle elevations of the Spanish Meseta and associated ranges. - Deciduous forests dominated by maples with enough arboreous cover (>25 %).	(9240) *Quercus faginea* and *Quercus canariensis* Iberian woods
Andalusian oak forest	- *Quercus canariensis*	2598	103.92	Humid and hyper-humid, luxuriant *Quercus canariensis* forests of the ranges of extreme southern Spain, limited to the Aljibe and a very few localities in the Serrania de Ronda.	(9240) *Quercus faginea* and *Quercus canariensis* Iberian woods
Atlantic oak forest	- *Quercus faginea* subsp. *broteroi*	1252	50.08	*Quercus faginea* subsp. *broteroi* forests in middle elevations of the Spanish Meseta and associated ranges.	(9240) *Quercus faginea* and *Quercus canariensis* Iberian woods
Corylus wet forest	- *Corylus avellana*	143	5.72	Mediterranean forests of hazelnuts with mixed shrub and tree composition.	(9240) *Quercus faginea* and *Quercus canariensis* Iberian woods
Castanea woodlands	- *Castanea sativa*	2224	88.96	Forests with *dehesas*: - Supra-Mediterranean and sub-Mediterranean chestnut forests (>30 % arboreal cover) and old established plantations with semi-natural undergrowth. - Chestnut *dehesas*. Opened arboreous forests from anthropogenic origin (<30 % arboreal cover).	- (9260) *Castanea sativa* woods - (6310) *Dehesas* with evergreen *Quercus* spp.
Olea and *Ceratonia* forests	- *Olea europea* var. *sylvestris* - *Ceratonia siliqua*	5480	219.2	Combination of two Mediterranean forests: - Thermo-Mediterranean forests dominated by arborescent *O. europaea* var. *sylvestris* in vertisols. - Forests of *C. siliqua* and *O. europea* var. *sylvestris* in limestones substrate with high temperatures.	(9320) *Olea* and *Ceratonia* forests
Cork oak forest	- *Quercus suber*	22,062	882.48	West-Mediterranean silicicolous forests dominated by *Quercus suber*.	(9330) *Quercus suber* forests
Oak forests	- *Quercus rotundifolia* - *Quercus suber*	288,361	11,534.44	Sclerophyllous grazed forests (*dehesas*) with *Quercus suber* and/or *Quercus rotundifolia* Crops, pasture land or meso-Mediterranean arborescent shrubland, in juxtaposition or rotation shaded by a fairly closed to very open canopy of native evergreen oaks.	- (6310) *Dehesas* with evergreen *Quercus* spp. - (9340) *Quercus ilex* and *Quercus rotundifolia* forests
Pinsapo fir forest	- *Abies pinsapo*	337	13.48	Forests and stands of the endemic *Abies pinsapo* of the supra-meso-Mediterranean level.	(9520) *Abies pinsapo* forests
Mountain pine forest	- *Pinus nigra* subsp. *salzmannii*	10,493	419.72	Forests of the montane-Mediterranean level, on dolomitic substrate (high tolerance to magnesium), dominated by endemic pines of the *Pinus nigra* group, often with a dense structure.	(9530*) (Sub-) Mediterranean pine forests with endemic black pines
Mediterranean pine forests	- *Pinus halepensis* - *Pinus pinaster* subsp. *aquatisquama*	14,972	598.88	Mediterranean and thermo-Atlantic forests of thermophilous pines, mostly appearing as substitution or paraclimactic stages of forests of the *Quercetalia ilicis*.	(9540) Mediterranean pine forests with endemic Mesogean Pines

2.3. Climate data selection

Baseline climate data for years 1960–2000 was obtained from the State Meteorological Agency (AEMET), and future climate data for mid-century (2040–2070) and end-century (2070–2100) was available on Spain's REDIAM website (REDIAM, 2022) with a spatial resolution of 200 m-grid. REDIAM (2022) uses the climate projections of the 5th IPCC report (Intergovernmental Panel on Climate Change, 2014). We obtained nine general circulation models (GCMs) for both the 4.5 and 8.5 Representative Concentration Pathways (RCP4.5 and RCP8.5) that represent future conditions in the south of the Iberian Peninsula. We used GIS analysis to select two GCMs that bracket nearly the entire range of the GCM projected futures for annual minimum temperature (Tmin) and annual precipitation (PPT) (Supplementary data Appendix S2, Table S2). These variables were used to select the GCMs because they represent the general changes in future climate predictions, and vegetation types are strongly associated with these climatic variables (Chapin et al., 2011; Choe and Thorne, 2019). We determined which two GCMs to use by examining the predicted change by 2070–2100 in Tmin and PPT (Thorne et al., 2016), from the baseline time period (1960–2000). Two GCMs that were the furthest away from the baseline conditions due to the highest increase of Tmin and the highest increase/decrease in precipitations were selected (Supplementary data Appendix S2, Fig. S1, and S2). To examine a broad range of potential future conditions, both the "hotter and drier" GCM and the "wetter and warmer"

GCM were selected due to these models predicted the most variation. The MIROC-ESM model (Watanabe et al., 2011) was chosen as the "hotter and drier" prediction (+5.64 °C and −18.25 % PPT by 2070–2100) compared with the other GCMs, while the MRI-CGCM3 model (Yukimoto et al., 2012) was chosen as the "warmer and wetter" prediction (+3.13 °C and +5.2 % PPT by 2070–2100) (Supplementary data Appendix S2, Table S2, Figs. S1 and S2).

2.4. Climate exposure analysis

We used 100,000 randomly selected points across the study area to extract current and projected future climate conditions. For each point, we examined 23 bioclimatic variables from the current time period provided by Spain's REDIAM (Supplementary data Appendix S2, Table S3; available in website Portal REDIAM, 2022), and under the four future projections (2 GCMs × 2 RCPs). We analyzed variable collinearity in a principal component analysis (PCA) and the best proportion of variance to reduce the number of variables using the "prcomp" base function in R (R Core Team, 2021). The PCA helped to reduce the number of variables to nine: water deficit (mm), days of frost (T < 0 °C), winter precipitations (mm), autumn precipitations (mm), summer precipitations (mm), annual precipitations (mm), annual maximum temperatures (°C), annual mean temperatures (°C), and annual minimum temperatures (°C).

We then used a second round of PCAs to reduce the dimensionality of the climate variables to two dimensions and renter the current and future climate conditions to consistent climate units. Each of the four PCAs developed in the second round contained the baseline climate and one of the four climate futures which were used to assess climate exposure for each vegetation type (Williams et al., 2018). We used the resulting 2-dimensional point clouds to quantify the current vegetation climate space and to project future climate exposure of each forest type. We used the climate conditions described by the first two axes of the PCAs (Supplementary data Appendix S3, Fig. S3 and Table S4), which were defined from the combination of the baseline and two future time periods (2040–2070 and 2070–2100). This created four current/future climate projections with standardized unit values across the time periods (Thorne et al., 2017; Williams et al., 2018).

The climate exposure analysis was calculated using the frequency of climate conditions found in the sample grid cells of each forest type (Fig. 1; Table 1). The PCA of climate space explained between 83 and 86 % of the variance in PC1 and PC2 for the four exposure assessments. Bioclimatic loadings were very similar in the four cases, with temperature variables (maximum T, medium T and minimum T) strongly influencing on the PC1 and the precipitation variables (PPT during winter, PPT during autumn and annual PPT) with strongly influence on the PC2 (Supplementary data Appendix S3, Fig. S3 and Table S4).

The climate frequency distribution of PCA 1 & 2 from the current time was then used to classify commonly occurring climate conditions for each forest type. Climates extracted at the points in each forest type were disposed in a two-dimensional (2-d) surface of the first two principal components (PC1 and PC2) of the baseline climate conditions. We applied a kernel density estimator to quantify the frequency distribution of climates occupied by each vegetation type (Choe et al., 2017, Thorne et al., 2016). When we calculated the climate frequency distribution for each forest type, the results present a point density surface which indicates the frequency of climate conditions occurring across the range of the forest type (Supplementary Information Appendix S5, Figs. S4–S7). The point density surfaces were divided in contour lines of 5 % exposure increment intervals, with points closer to the core being the most frequently-occurring climates for a type, which we considered to be the least stressful conditions, and those towards the margins being the more climatically exposed and stressed conditions. The marginal areas are those climatic conditions most infrequently occupied by each forest type in the current conditions, therefore, we considered these marginal areas as critically exposed in the current time (Muñoz-Sáez et al., 2021; Thorne et al., 2017).

We created five exposure classes based on the frequency distribution of the baseline climate time period: (1) areas with "low" levels of climate exposure are those in the central 80 % of a forest type's climate distribution; (2) the areas with 80–95 % of exposure were considered as "medium" level of climate exposure; (3) the areas in the 95–99 % distribution range were considered to have "high" climate exposure; (4) the marginal areas in the last 1 % (>99 %) of exposure were considered as "critical" exposure (Thorne et al., 2017); and (5) Values falling outside the climate conditions that all forest types combined currently occupy were classified as "non-analog" (NA). NA indicates that the cells with these values experience such different conditions in the future that no samples were available in the current time with similar conditions to analyze them (Fitzpatrick et al., 2018). The results of these points present some uncertainty, however, we assumed that NA are already climatically stressed in some way as they had climatic conditions which differ the most from the baseline conditions, so they were classified into the highest exposed category (Choe and Thorne, 2019; Muñoz-Sáez et al., 2021; Thorne et al., 2018; Williams et al., 2018). For this study, we considered that NA conditions were likely to stress the vegetation, so we included NA cells also in the category of "critical" exposure, whose areas will experience changes in the dominant vegetation (Thorne et al., 2020).

Once the distribution of each forest type's climate exposure was quantified for each GCM, RCP and time period, an overall score for exposure was calculated based on the percentage of area falling in the "critical" exposure class. After calculating this score, it was later combined with the scores of

component species' sensitivity and adaptive capacity traits, needed to define climate vulnerability. The exposure scores were ranged from 1 to 5 in regular intervals: 1 or "low" exposure (1–20 % of its area with critical exposure); 2 or "moderate" exposure (>20–40 % of its area with critical exposure); 3 or "high" exposure (>40–60 % of its area with critical exposure); 4 or "very high" exposure (>60–80 % with critical exposure); 5 or "critical" exposure (>80–100 % of its area with critical exposure).

All analyses for the forest types were conducted on projections for the mid and end-century time periods (2040–2070 and 2070–2100).

2.5. Evaluation of sensitivity and adaptive capacity (S&A) to climate change

Sensitivity and adaptive capacity (S&A, respectively) represent the biological attributes of the dominant plant species in each type of forest. A total of 17 dominant tree species were studied for this forest assessment (Table 1). Sensitivity and adaptive capacity can be evaluated by a number of means (Glick et al., 2011; Friggens et al., 2013). We used species attributes identified by Thorne et al. (2016) to score S&A for the dominant species in our vegetation types. Each measured attribute was scored from 1 to 5 (for the sensitivity and adaptive capacity), where species with 1 were the least sensitive or have the most adaptive capacity according to their characteristics, and species with 5 were the most sensitive or with the least adaptive capacity. Finally, a single S&A score which ranged from 1 to 5, was obtained.

2.5.1. Sensitivity evaluation

Species sensitivity was assessed using six attributes that are important for dominant species response to disturbances. The reasoning and scoring rules are presented in the Supplementary data Appendix S4, Table S5: (a) "sensitivity to temperature" was calculated for each dominant species by overlapping their presence, based on GBIF records and according to their distribution across the temperature range, with the thermotypes map, calculated as a sum of the yearly average temperature, the average minimum temperature of the coldest month of the year, and the average maximum temperature of the coldest month of the year (map of Andalusia) (REDIAM, Junta de Andalucía, 2022); (b) the "sensitivity to precipitation" was calculated for each dominant species by overlapping their presence, based on GBIF records, according to their distribution across the precipitation range with the ombrotype map from REDIAM (2022), which is a measure of aridity calculated as the ratio between the yearly positive precipitation and the yearly positive temperature in degrees Celsius (Rivas-Martínez et al., 1997; Torregrosa et al., 2013). GBIF records are available on GBIF (2021); doi:10.15468/dl.qdy7em. These GBIF records were cleaned by the proximity to their associated HCI by overlapping the presence points with the HCI map of Andalusia (REDIAM, 2020), and also according to our judgement, given that the research team has a good knowledge of the vegetation of the study area since it has participated in the development of cartography and regional vegetation maps (Cabezudo et al., 2005; Junta de Andalucía, 2017; Pérez-Latorre, 1993; Pérez-Latorre et al., 1998, 2008, 2015; Pérez-Latorre and Cabezudo, 2002; REDIAM, 2020); (c) "fire sensitivity" was scored as a function of the presence or absence of characteristics (epidermis and canopy architecture susceptible) which provide fire protection or which are likely to be flammable and consulting Castroviejo (1986–2022), Valdés Castrillón et al. (1987) and Blanca et al. (2011); (d) the "sensitivity to germination agents" was scored on the conditions needed for the seeds of each species to germinate, such as inundation or moisture, winter cold or summer heat and fire. It was based on traits identified in the TRY database, and on estimates based on our field experience when data was not otherwise available in the TRY database (Kattge et al., 2020); (e) the "sensitivity to dispersal vectors" was based on the various modes of seed dispersal of the species and consulting Castroviejo (1986–2022), Valdés Castrillón et al. (1987), Blanca et al. (2011) and TRY (Kattge et al., 2020); (f) the "sensitivity to reproductive range or longevity" was scored by the species growth form, relating the growth form with the years of reproductive life of the dominant plant species (Cornelissen et al., 2003) and consulting Castroviejo (1986–2022), Valdés

Castrillón et al. (1987), Blanca et al. (2011) and the BIEN database (Maitner et al., 2018). For more information about the references and searches in databases see Supplementary data Appendix S4, Table S7.

2.5.2. Adaptive capacity evaluation

Species' adaptive capacity was scored for three attributes for dominant species, with the reasoning and scoring rules presented in Supplementary data Appendix S4, Table S6: (g) "adapted to fire" which was scored on the basis of the ability of the seeds to germinate after a fire and/or the resprouting ability of the species; (h) "adaptations related to fecundity or recruitment mode" were measured assessing the level of fecundity or capacity of reproduction; and (i) "adaptation related to seed longevity" was highly related to the quantity of the seeds generated by the plant species and/or the time of those seeds remaining viable. The attributes for g, h and i were consulted on TRY (Kattge et al., 2020), but when information was not available, the scores were based on estimates rather than from study results or substantial field observations. For more information about the references and searches in databases see Supplementary data Appendix S4, Table S7.

2.6. Vulnerability score

We summed the climate exposure (by GCM and RCP) and the sensitivity and the adaptive capacity scores (S&A) in order to create an overall vulnerability score for each forest type and by each future climate projection. In this sense, the contribution to vulnerability was equally weighted between exposure and S&A. The vulnerability scores comprised values between 2 and 10, with a maximum value of 5 in climate exposure and 5 in the S&A. Finally, regular intervals indicated the CCVI: scores ranking 2–3.59 indicated a "low" vulnerability, from 3.6 to 5.19 indicated a "moderate" vulnerability, from 5.2 up to 6.79 indicated a "high" vulnerability, from 6.8 to 8.39 indicated a "very high" vulnerability and >8.4 and up to 10 indicated a "critical" vulnerability for forests to climate change disturbances. Consequently, thanks to this CCVI, it was possible to assess the vulnerability to climate change among the different types of forests and in each GCM and RCP.

3. Results

3.1. Exposure

All models and scenarios show an increase in climate exposure for the forests (Fig. 2). For the total area of forests (13,984.12 km^2), in the "warmer and wetter" model (MRI-CGCM3) and RCP4.5, an area of 3851.11 km^2 becomes critically exposed (>95 % level of exposure and NA values) by the mid-century time period (2040–2070) (Fig. 2a), which increases by the end-century (2070–2100) to an area of 4517.97 km^2 (32.9 % of the forests; Fig. 2b). Under the RCP8.5, the critically exposed area is 5144.94 km^2 by the mid-century (Fig. 2c) and 11,581.7 km^2 (82.8 % of the forests) by end-century (Fig. 2d). Both critically exposed areas values are bigger in RCP8.5 than in the RCP4.5 scenario, regardless of the time period.

The "hotter and drier" model (MIROC-ESM) predicts considerably more exposure to climate change: in the RCP4.5 scenario an area of 7641.75 km^2 (more than half from the total area of forests) becomes critically exposed by mid-century (Fig. 2e), while by the end-century the model predicts an increase to 11,601.42 km^2 (82.9 % of the forests; Fig. 2f). For the RCP8.5, the critically exposed area is 12,295.83 km^2 by mid-century (Fig. 2g) and 13,758.05 km^2 (98.4 %) by the end-century period (Fig. 2h), very close to the total area of forests (Table 2). The MIROC-ESM model predicts an exposed area with a range between 17.9 and 60.4 % higher than results in MRI-CGCM3 by the mid-century and between 0.1 and 66.1 % higher by the end-century.

3.1.1. Exposure by forest type

The future climate models project a general increase of exposure (Table 2) relative to baseline conditions for all forest types ranging from 36.6 to 99.30 % (Supplementary data Appendix S5, Figs. S4–S7). The most-impacting predictions for the end of the century in terms of exposure are the ones in the MIROC-ESM and RCP8.5, where all forest types have practically the totality of their areas highly exposed (>98 % of exposed area). The more optimistic predictions are related to the MRI-CGCM3 model and/or the RCP4.5 scenario.

The "Mediterranean pine forests" are the least exposed to climatic change under the different models and scenarios, followed by the "mixed mountain forests" and the "oak forests". In contrast, the "Andalusian oak forests", the "*Corylus* wet forests", the "*Olea* and *Ceratonia* forests" and the "mountain pine forests" are the groups with higher exposure areas in all GCM and scenario combinations (Table 2; complete exposure scores by forest type in Supplementary data Appendix S5, Table S8).

3.2. Sensitivity and adaptive capacity

The total S&A score is the sum of sensitivity and adaptive capacity attributes, where the score has a 2–6 range (Supplementary data Appendix S6, Table S9).

Three forest types that were considered to have a lower sensitivity are "Mediterranean pine forests", "cork oak forests" and "oak forests". The rest of the forest types have a moderate sensitivity, with the "pinsapo fir forests" being the most sensitive, followed by the "Atlantic oak forest", the "Andalusian oak forest", the "*Corylus* wet forest", the "mountain oak forest" and the "mixed mountain forests". However, in the latter, it is important to clarify that dominant species such as *Q. alpestris*, *A. monspessulanum* and *A. opalus* subsp. *granatense* showed more sensitivity than *Q. faginea* despite being in the same forest type.

The forests with the highest adaptive capacity (A) were the "Mediterranean pine forests" followed by "mountain pine forests" and "*Olea* and *Ceratonia* forests". The rest of the forests have moderate adaptive capacity.

See Supplementary data Appendix S6, Table S9 for more S&A detailed results.

3.3. Overall vulnerability analysis

The results are given for each model and scenario combination for the mid-century and end-century time periods (Fig. 3; Supplementary data Appendix S7, Table S10). The overall vulnerability analysis for the forests showed critical vulnerability risk by mid-century (2040–2070) for the "Andalusian oak forest" and "*Corylus* wet forest" for all GCM and RCP combinations. "Atlantic oak forests", "*Castanea* woodlands" and "pinsapo fir forests" showed a high to critical vulnerability variation by mid-century depending on the GCM and scenario. In contrast, the least vulnerable forest types by mid-century were the "Mediterranean pine forests" and the "oak forests", presenting the lesser values of vulnerability in all cases with the exception of MIROC-ESM-RCP8.5, which reaches very high vulnerability. The rest of the forest types are highly and very highly-vulnerable, being more vulnerable under the MIROC-ESM GCM and RCP8.5 emission scenario. The exception is the "mountain oak forest" which presents a different vulnerability (from moderate to critical) depending on the GCM and RCP.

Predictions by 2100 are worse in terms of vulnerability (Fig. 3). The most vulnerable forest types by the end-century (2070–2100) are, again, the "Andalusian oak forests" and the "*Corylus* wet forests", which are in the critical vulnerability category in all models and scenarios. "Mountain oak forest", "Atlantic oak forests", "*Castanea* woodlands" and "pinsapo fir forest" are also in the critical vulnerability category in all cases, with the exception of MRI-CGCM3-RCP4.5, under which they are highly vulnerable. Under the RCP8.5 scenario the "mixed mountain forests" reach critical vulnerability, while in the RCP4.5 this type goes from high vulnerability under the MRI-CGCM3 to very high under MIROC-ESM. The least vulnerable forest type by 2100 is the "Mediterranean pine forest", ranging from low to high vulnerability, except under MIROC-ESM-RCP8.5, when it is in very high vulnerability. "Oak forests", "cork oak forests", "*Olea* and *Ceratonia* forests" and "mountain pine forests" are also less vulnerable than the rest of the forest types under all GCM and RCP combinations, with the exception
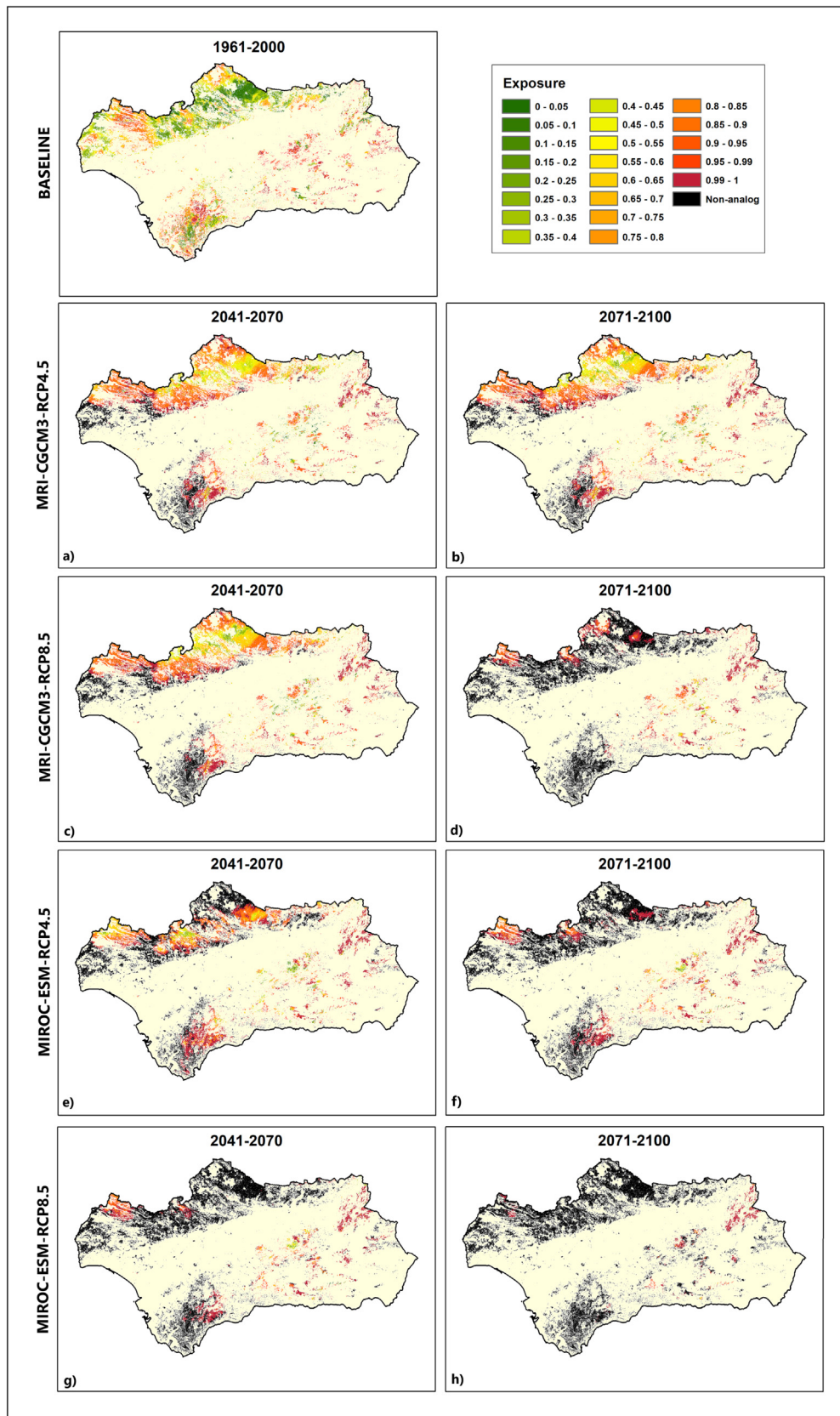
Fig. 2. Exposure maps of all forest types of the south of the Iberian Peninsula showing results for each GCM and RCP. Warmer colors indicate higher climatic exposure. The most marginal 1 % level of exposure is indicated in a darker red color. The "non-analog" conditions, being future climates that today do not exist in the study area and considered highly exposed, are colored in black.

Table 2

Critically exposed areas in the forest types by model, scenario and time period. Exposure is expressed in % and km² of the areas which are critically exposed from the initial total area of each forest type.

ID	Total area (Km²)	Time period	MRI-CGCM3				MIROC-ESM				GCM and RCP average
			RCP4.5		RCP8.5		RCP4.5		RCP8.5		
			%	Km²	%	Km²	%	Km²	%	Km²	%
		2040–2070	14.42	4.20	54.26	15.80	76.65	22.32	96.70	28.16	60.51
Mountain oak forest	29.12	2070–2100	39.15	11.40	84.07	24.48	92.31	26.88	99.18	28.88	78.67
		2040–2070	28.12	10.72	41.87	15.96	39.45	15.04	71.04	27.08	45.12
Mixed mountain forest	38.12	2070–2100	39.14	14.92	85.52	32.60	63.48	24.20	99.90	38.08	72.01
		2040–2070	93.07	96.72	100	103.92	82.02	85.24	100	103.92	93.77
Andalusian oak forest	103.92	2070–2100	92.69	96.32	100	103.92	99.69	103.60	100	103.92	98.09
		2040–2070	42.33	21.20	49.84	24.96	62.30	31.20	91.93	46.04	61.60
Atlantic oak forest	50.08	2070–2100	42.65	21.36	92.81	46.48	85.54	42.84	100	50.08	80.25
		2040–2070	97.20	5.56	99.30	5.68	100	5.72	100	5.72	99.13
Corylus wet forest	5.72	2070–2100	99.30	5.68	100	5.72	100	5.72	100	5.72	99.30
		2040–2070	53.73	47.80	73.02	64.96	70.01	62.28	92.27	82.08	72.26
Castanea woodlands	88.96	2070–2100	59.53	52.96	96.36	85.72	87.19	77.56	100	88.96	85.77
		2040–2070	75.02	164.44	92.70	203.20	92.21	202.12	99.74	218.64	89.92
Olea and *Ceratonia* forests	219.2	2070–2100	80.00	175.36	99.84	218.84	99.47	218.04	99.91	219.00	94.80
		2040–2070	51.04	450.44	66.56	587.36	52.58	464.04	93.48	824.92	65.92
Cork oak forest	882.48	2070–2100	55.57	490.36	96.64	852.84	87.28	770.20	99.76	880.36	84.81
		2040–2070	24.07	2775.86	31.62	3647.47	53.69	6192.47	87.73	10,119.53	49.28
Oak forest	11,534.44	2070–2100	28.22	3255.33	81.72	9425.55	83.08	9582.71	98.13	11,318.53	72.79
		2040–2070	38.87	5.24	71.22	9.60	63.20	8.52	89.32	12.04	65.65
Pinsapo fir forest	13.48	2070–2100	37.09	5.00	100	13.48	80.71	10.88	100	13.48	79.45
		2040–2070	42.37	177.85	64.22	269.54	88.01	369.38	99.91	419.36	73.63
Mountain pine forest	419.72	2070–2100	65.02	272.90	99.70	418.44	98.78	414.60	100	419.72	90.87
		2040–2070	15.21	91.07	32.81	196.47	30.62	183.39	68.18	408.33	36.70
Mediterranean pine forests	598.88	2070–2100	19.43	116.35	59.05	353.62	54.13	324.18	98.74	591.32	57.84
		2040–2070	27.54	3851.11	36.79	5144.94	54.65	7641.75	87.93	12,295.83	51.73
ALL	13,984.12	2070–2100	32.31	4517.97	82.82	11,581.70	82.96	11,601.42	98.38	13,758.05	74.12

of "mixed mountain forest", which is lesser in MIROC-ESM-RCP4.5, presenting high vulnerability in MRI-CGCM3-RCP4.5 and very high vulnerability in the rest of models and scenarios.

4. Discussion

This assessment shows that, on average, five of the twelve forest types will be critically vulnerable to climate change in the south of the Iberian Peninsula by the end of the century, and that these impacts will be perceptible by mid-century because of the very high and critical vulnerability (Supplementary data Appendix S7, Table S10). The MRI-CGCM3 model and RCP4.5 scenario contribute less to vulnerability than the MIROC-ESM model and RCP8.5 scenario. Although we cannot be sure which emission scenario or GCM is more likely to happen, all the predicted climate futures will induce high plant and vegetation stress.

The "Mediterranean pine forest" was found to be the least vulnerable forest type. This forest and its dominant species, *P. halepensis* and *P. pinaster*, could be resistant to the climatic change projected for temperature and precipitation in Southern Spain. These pines might be less vulnerable to increasing temperatures and drought episodes than the associated broadleaf tree species, due to the presence of traits like needle leaves or the presence of an efficient stomatal regulation system (isohydric adaptation behaviour) (Gracia et al., 2005; Helman et al., 2017). They may also be somewhat resistant to the increasing fires threats (Loustau et al., 2007). Nonetheless, if fire frequency goes further and occur too frequently, pine forests could be impacted and be replaced by scrublands (Mouillot et al., 2002). Fires in monospecific pine formations can also lead to an opportunity for colonization by more xerophilic species and consequently produce changes in the floristic composition (Piñar Fuentes et al., 2019). In addition, it is still not clear how increasing temperatures and decreasing precipitation might affect the survival of Mediterranean pine forests (Klein et al., 2013).

Our results for the oak forests were in accordance with Gracia et al. (2005) and López-Tirado and Hidalgo (2018), which predict an increase in the dominance of these species (*Q. rotundifolia* and *Q. suber*) as climate change becomes more pronounced. Our results indicate that "oak forests"

are one of the least exposed and least vulnerable forest types. This could lead to the transition of some forests to holm oak formations. Adaptive capacity is associated to the phenotypic plasticity, which tends to be higher in species with longer life span (*P. nigra* or *Q. rotundifolia*) and larger distribution (*Q. suber*, *P. halepensis* or *Q. rotundifolia*) (Gracia et al., 2005). In this case, compared to other types of forests, the "Mediterranean pine forest" and the "oak forests" present a lower vulnerability to climatic stress. This might provide them an opportunity to expand their areas and replace other forest types. Some studies have indicated that a replacement is already ongoing; *P. pinaster* by *P. halepensis*, and *Q. suber* and *Q. faginea* by *Q. rotundifolia* due to climate change in the Iberian Peninsula (Gracia et al., 2005; López-Tirado and Hidalgo, 2018; Ruiz-Labourdette et al., 2013). Nonetheless, some uncertainty remains with the predictions for holm oak formations, since there are no data on their mortality trends under climate change (Natalini et al., 2016; Acácio et al., 2021).

Our climate exposure projection for "*Olea* and *Ceratonia*" forests contrasts with the existing literature (Kassout et al., 2022). The high exposure projected in our analysis can be explained because this forest type is mostly concentrated in the southernmost part of the study area, which is likely to face major changes in the climate (a drastic reduction in precipitation). The exposure of this type of forest is in contrast with Kassout et al. (2022), who predict an increase for *O. europaea* var. *sylvestris* in north Morocco. However, we found that "*Olea* and *Ceratonia*" are one of the less sensitive forest types and have more adaptive capacity against climate change because of their dominant species' attributes (*O. europaea* var. *sylvestris* and *C. siliqua*). This finding is in agreement with Kassout et al. (2022). This shows that while our exposure analysis is purely a mathematical approach, the addition of S&A scores helped to reduce the vulnerability of this forest type, which puts our results in better alignment with Kassout et al. (2022). *C. siliqua* is acknowledged to have some resistance to climatic shifts such as drought, desertification or eroded soils, this resistance could help forests dominated by these species cope with a "hotter and drier" future (Ozturk et al., 2010). These are the second least-vulnerable forests by the end of the century, being moderate to high in overall. However, more attention must be paid to this type of forest, as other threats associated to climate change could endanger wild populations of olive trees such as

Fig. 3. Vulnerability scores for each GCM and RCP by the mid-century and end-century. Scores <3.6 indicated a "low" vulnerability, 3.6–5.19 indicated a "moderate" vulnerability, 5.2–6.79 indicated a "high" vulnerability, 6.8–8.39 indicated a "very high" vulnerability and >8.4 indicated a "critical" vulnerability for forests to climate change disturbances.

promoting the growth and development of pathogens (González et al., 2017) and changing conditions could favor the presence of *C. siliqua* in arid and semi-arid ecosystems (Zagoub et al., 2022).

Vessella et al. (2017) considered that the populations of *Quercus suber* in the Mediterranean Basin are expected to migrate to higher altitude and latitude areas by 2070, due to climate change. Their results showed migration to higher altitudes and bigger population changes in their "hotter and drier" model and worst scenario. Using the same models and scenarios as Vessella et al. (2017), we also found a higher level of exposure in our study (MIROC-ESM-RCP8.5). Duque-Lazo et al. (2018) also predicted a decrease in suitable area of *Q. suber* in Southwest Spain overtime. These results seem to be in accordance with our expected results for the "cork oak forest type", which is highly exposed to climatic change especially in MIROC-ESM-RCP8.5. Nonetheless, its dominant species *Q. suber* presents a low sensitivity which moderates the climate change vulnerability of this forest type. San-Eufrasio et al. (2020) studied the responses in tolerance to drought from *Quercus* spp. and Andalusian *Q. ilex* populations, they indicated that sclerophyllous species with small leaf sizes (*Q. suber* and *Q. ilex*) presented more adaptative capacity to drought conditions than deciduous species (*Q. pyrenaica* or *Q. faginea*) which we found to be more vulnerable.

The results for "mountain pine forest" showed critical exposure for almost the entire area by the end of the century. This agrees with another study which predicts a habitat loss near 70 % in Southwest Spain by 2100 (Navarro-Cerrillo et al., 2018). Nonetheless, the vulnerability score was moderate due to this type's adaptive capacity, which slightly reduces the

impact contribution in the vulnerability scores caused by its sensitivity and exposure results. On the other hand, the "pinsapo fir forest" shows very high and critical vulnerability to climate change in almost every GCM and RCP, and is, unsurprisingly, more exposed in the "hotter and drier" than in the "warmer and wetter" model, and more in the RCP8.5 than in the RCP4.5 scenario. This makes sense in the context of precipitation loss and increasing droughts, since the dominant species *Abies pinsapo* is very sensitive to moisture and water availability (Linares et al., 2011), and is vulnerable to increasing aridity (Alba-Sánchez et al., 2019; Gutiérrez-Hernández, 2018). *A. pinsapo* is an endangered species due to its relictual characteristics (Blanca et al., 2000). The "pinsapo fir forest" is a relictual ecosystem and unique in the world, only occurring in Andalusia (south of the Iberian Peninsula) and the north of Morocco (Linares and Carreira, 2006). Its vulnerability to climatic change could drive this forest to disappearance, considering its component tree species' specific climatic needs and their already reduced populations (Alba-Sánchez et al., 2019). Although the "mountain pine forest" was less vulnerable than "pinsapo fir forest", both forest types present an associated risk related to their low genetic variability, which could lead to a higher vulnerability against changes due to a possible lack of diversity in the adaptive capacity characteristics (Gracia et al., 2005). In addition, the "mountain pine forest" is classified as priority habitat type (indicated by an asterisk in the Directive 92/43/ EEC), which is a natural habitat type in danger of disappearance present in the European Union territory and for the conservation of which the Community has particular responsibility.

Although the "mixed mountain forest" shows high to very high vulnerability in the mid-century, its vulnerability becomes very high to critical by the end of the century. This forest type shows a higher exposure and vulnerability to climate change in the MIROC-ESM-RCP8.5 future case, which makes sense considering this model is drier than MRI-CGCM3 and its dominant species (*Q. faginea* subsp. *faginea*, *Q. alpestris*, *A. monspessulanum*, *A. opalus* subsp. *granatense*) present some moisture requirements in developed soils (Loidi, 2017). The "mountain oak forest" showed a considerable vulnerability at each future case, which agrees with Hernández-Santana et al. (2008) and Ruiz-Labourdette et al. (2013), who demonstrated that the presence of *Q. pyrenaica* is already decreasing in the center of the Iberian Peninsula as a result of the increased drought. Piñar Fuentes et al. (2019) found that deciduous forest in South-Central part of the Iberian Peninsula, with species such as *A. monspessulanum*, *A. opalus* subsp. *granatense*, *C. avellana* or *Q. pyrenaica*, are highly vulnerable due to predicted increases in potential evapotranspiration, aridity index and minimum temperatures, and decreases in humidity index and the ombrothermic index. In this sense, our results agree, since the forests composed of these species presented a high- to critical-vulnerability due to projected changes of temperature, precipitation and water deficit, being less exposed in the "warmer and wetter" model, but still highly exposed. It is important to note that, although a certain increase in precipitation is expected in MRI-CGCM3 model, this type of rainfall could be more associated to torrential rains, being more intense and making it difficult for vegetation to use this water efficiently (Alexander et al., 2006; Piñar Fuentes et al., 2019).

The "Atlantic oak forest" also showed vulnerability from high to critical. López-Tirado and Hidalgo (2016) showed that *Q. faginea* is vulnerable to climatic change in Andalusia (south of the Iberian Peninsula) and that its distribution area will decrease, with one component oak species, *Q. rotundifolia* (the holm oak), having an increase in its potential distribution. However, that study treated *Q. faginea* sensu *lato*, without considering the taxonomic distinction with *Q. faginea* subsp. *broteroi*. Our study is the first in assessing the climate change effects on this subspecies separately based on their geographical distribution.

The "*Castanea* woodlands", which are established plantations with semi-natural undergrowth in the study area, showed very high to critical exposure and their vulnerability ranges from high in mid-century to (mainly) critical in end-century. *C. sativa* is an important component species not just because of its ecology, but because of its economical and traditional cultivation importance in Europe (Conedera et al., 2004; Braga et al., 2015). A recent study demonstrated a more suitable area for cultivation of *C. sativa* in the northernmost sites of Portugal, while the southern half of Portugal showed a big loss in suitable area due to climate change (Freitas et al., 2022).

Our results for "Andalusian oak forest" were the worst prediction, in terms of exposure and vulnerability, together with the "*Corylus* wet forest" results. These forest types are critically exposed under all GCMs, RCPs and time periods. Some studies indicate that their dominant species will migrate upward in elevation and latitude (López-Tirado and Hidalgo, 2016; Piñar Fuentes et al., 2019; Ruiz-Labourdette et al., 2013). López-Tirado and Hidalgo (2016) indicate that *Q. ilex* and *Q. pyrenaica* can migrate upwards, replacing the conifer forests. However, this study indicates that the dominant species of the "Andalusian oak forest" (*Q. canariensis*) will drastically reduce its range because its distribution is mainly present in the southernmost areas of Andalusia, which is expected to suffer the biggest changes in climate exposure. This species also is expected to show reductions in growth, due to droughts and water stress caused by climate change, and it is expected that the low elevation populations of this species will be affected by climate change due to an observed lack of adaptation to the increase in temperatures in the last 30 years (Gea-Izquierdo et al., 2012). Piñar Fuentes et al. (2019) found that forests with *C. avellana* will face water stress and will suffer a replacement by xerophilic forests (e. g. *Quercetea ilicis*). Ruiz-Labourdette et al. (2013) found changes in tree species composition in the Iberian Peninsula, where cold-temperate species (*C. avellana* among them) will be replaced by species with less hydric requirements. Therefore, considering that our results showed such an

elevated vulnerability for these forests, changes could be expected to start by the mid-century.

Several climate assessments addressing tree species in the south of the Iberian Peninsula territory include predictions on the future distribution of vegetation types and species (e.g.: Hidalgo et al., 2008; López-Tirado and Hidalgo, 2014, 2015, 2016, 2018; Galacho-Jiménez et al., 2023). These studies found an expansion of thermophilic species with drought tolerance mechanisms, such as *Quercus ilex* L., *Pinus pinea* L., *Pinus pinaster* Aiton, and *Pinus halepensis* Mill. to the detriment of other tree species (Ferrio et al., 2003; Martinez-Ferri et al., 2000) such as *Q. suber*, *Pinus sylvestris* L., *Quercus faginea* Lam., or *Abies pinsapo* (Sánchez-Salguero et al., 2012; Gutiérrez-Hernández, 2018;). In addition, forests and ecosystem services, such as water availability, soil fertility, carbon fixation, food and feed production, wood production and other material services, are already threatened by other environmental stressors in the Mediterranean Basin, and are expected to be severely compromised in future climate scenarios (Morán-Ordóñez et al., 2021; Peñuelas and Sardans, 2021). Special attention is required for "Corylus wet forest", "Andalusian oak forest", "pinsapo fir forest" and "*Castanea* woodlands" because of their very high and critical vulnerability that is imminent by mid-century. This CCVI warns of the forest types that are most likely vulnerable to climate change (Fig. 3).

4.1. Caveats and future management

Several limitations to the CCVI framework imply caution for the interpretation of our results. These mostly have to do with the temporal and spatial scales of available data and the selected S&A traits. Because current knowledge about the tree species in each vegetation type and their physiological responses to climate varies, our assumptions of trait attributes introduce some uncertainty into the component scores used in the overall vulnerability scores. However, the introduction of these trait-rankings provides variation among the species, our assumptions are explicit, and the approach is designed to accommodate the addition of new information and future modifications. Additionally, we assume that the greater the diversity of species in an ecosystem, the greater its resilience to climate change due to functional redundancy, overlap, and connectivity (Peterson et al., 1998). For this reason, we also propose that improvements to the assessment could be to include other species present in each forest type. In addition, in future studies, it could be interesting to include leaf traits related with the response to climate change, such as specific leaf area, because of potential trade-offs between leaf functional traits under increasing climatic change stress (Dwyer et al., 2014; Yu et al., 2022). Other considerations of S&A are that while we assigned equal weight to each trait, certain characteristics could likely be more crucial than others in determining vulnerability to climate change (Pacifici et al., 2015).

Limitations could also appear in relation to the extent of the study area. By constraining the exposure analysis to the southern part of the Iberian Peninsula, we could be missing some of the range of climates that individual HCI may occupy, including range in northern parts of the Peninsula. Also, the northern areas of the Peninsula present markedly different future climate projections compared to the southern regions, since as the south of the Iberian Peninsula is expected to suffer a higher increase in temperature, a greater decrease of precipitation, and a higher increase of aridity (Amblar et al., 2017; Pereira et al., 2021).

Area-based studies may also have limitations related to the range of species, such as for *Olea*, mentioned above, or with regards to the full range of a forest type. While we based our climate exposure analysis on the current extent of each forest type in the study area, this is under the assumption that the current extent represents forest types in equilibrium with climate conditions. If actually, current forest types are not in equilibrium, then our estimates of climate exposure are potentially biased, likely towards lesser levels of climatic stress.

Other limitations may arise in relation to uncertainty about the future climate projections (Beaumont et al., 2019). This assessment considered only two of the many existing GCMs and RCPs available. Our study did

not aim to determine which scenario is most likely to occur, but we analyzed four futures that cover a wide range of the projected conditions. Nevertheless, we consider the RCP8.5 emission scenario the most relevant for natural resource conservation and climate risk assessment, because current emission rates most closely track this scenario (Schwalm et al., 2020).

Finally, other components and dynamics related to climate change that were not assessed in this study include the risk of increasing pests, pathogens which affect the forest's health, the risk of wildfires (Gullino et al., 2022), and the potential for key species to migrate, in order to track changing climate conditions.

Looking ahead, studies that combine this assessment with other tools like species distribution models or demographic dispersal models may increase our understanding of the effects of climate change for the forest types presented here. This study's framework can serve to create an updateable vulnerability ranking system for the rest of the Mediterranean areas of Europe and northwest Africa (Maghreb). As many other HCI types are present in the south of the Iberian Peninsula, including them in future climate change assessments would be interesting, in order to understand their potential risks and the impacts that climate change could produce.

5. Conclusions

Nearly half of the forest types assessed in this study are critically vulnerable to climate change. Forest types with less thermophilic dominant species such as "mixed mountain forest", "pinsapo fir forest", "mountain oak forest", and "*Castanea* woodlands", or with high moisture requirements, such as "*Corylus* wet forests" or the "Andalusian oak forest" are predicted to be more vulnerable to the projected climatic changes. The last two on the list, present the worst values for exposure, sensitivity and adaptive capacity. Both of these forest types are situated in the southernmost part of the study area, which is expected to experience the biggest changes in temperature and precipitation. Forest types dominated by more thermophilic species like "*Olea* and *Ceratonia* forests", "cork oak forest", "oak forests" and "Mediterranean pine forests" are less vulnerable and possibly more resistant to climatic shifts.

Management and conservation efforts will play an important role in adapting to or minimizing climate change impacts to forests in the south of the Iberian Peninsula. The timing of conservation efforts will be critical, given that some of the climate change effects predicted here by mid-century, have been found to be currently ongoing by other studies. This analysis can be of use for natural resource managers who require spatial tools to help management strategies and treatments to apply within the areas of each forest types extent, particularly to the zones with higher vulnerability. One policy strategy could be to include the types of forest with the greatest vulnerability to climate change as priority habitats at the national level, given the expected future impacts they will undergo. Further motivation for the rapid development of climate adaptation plans for these forests are the potential loss of their provisional ecosystem services and the potential for erosion and loss of forest cover.

CRediT authorship contribution statement

Noelia Hidalgo-Triana: Conceptualization, Investigation, Methodology, Visualization; Writing original draft; review & editing. **Andros Solakis**: Conceptualization, Formal analysis, Data curation, Formal analysis, Writing original draft & editing. **Federico Casimiro-Soriguer**: Data curation and Vegetation Mapping, review & editing. **Hyeyeong Choe**: Methodology, Software, Writing – review & editing. **Teresa Navarro**: S&A assessment; review & editing. **Andrés V. Pérez-Latorre**: review. **James H. Thorne**: Conceptualization, Methodology, Validation, Investigation, Writing – review & editing.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.164983.

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