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**Title:** Ecosystem Services provision by Mediterranean forests will be compromised above 2°C warming

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## **Abstract**

Forests provide a wide range of provisioning, regulating and cultural services of great value to societies across the Mediterranean basin. In this study, we reviewed the scientific literature of the last 30 years to quantify the magnitude of projected changes in ecosystem services provision by Mediterranean forests under IPCC climate change scenarios. We classified the scenarios according to the temperature threshold of 2°C set by the Paris Agreement (below or above). The review of 78 studies shows that climate change will lead to a general reduction in the provision of regulating services (e.g. carbon storage, regulation of freshwater quantity and quality) and a general increase in the number of fires, burnt areas and generally, an increase in climate-related forest hazards (median +62% by 2100). Studies using scenarios above the 2°C threshold projected significantly more negative changes in regulating services than studies using scenarios below this threshold. Main projected trend changes on material services (e.g. wood products), were less clear and depended on (i) whether or not the studies considered the interaction between the rise in temperatures and other drivers (e.g. forest management, CO<sub>2</sub> fertilization) and (ii) differences in productivity responses across the tree species evaluated. Overall, the reviewed studies projected significant reductions in range extent and habitat suitability for the most drought-sensitive forest species (e.g. -88% *Fagus sylvatica*), while the amount of habitat available for more drought-tolerant species will remain stable or increase; however, the magnitude of projected change for these more xeric species was limited when high-end extreme climatic scenarios were considered (above Paris Agreement). Our review highlights the benefits that climate change mitigation (to keep global mean temperature increase < 2° C) can bring in terms of service provision and conservation of Mediterranean forests.

**Keywords:** Climate change; Ecological modelling; Ecosystem services; Hazards; Mediterranean forests; Fires; Forecasting; Scenarios

## INTRODUCTION

Forests in the Mediterranean basin are a good example of biodiversity-rich, complex socio-ecological systems that result from the coevolution of plants with millennia of human perturbations and management (Doblas-Miranda et al., 2015; Gauquelin et al., 2018; Nocentini and Coll, 2013). Mediterranean forests play a key role in the livelihoods of diverse communities by providing people with food (e.g. mushrooms, chestnuts) and other products for home consumption and income generation (e.g. cork), whose value often exceed the economic importance of wood products (Croitoru, 2007; FAO and Plan Blue, 2018; Merlo and Croitoru, 2005). They also hold many important non-marketed values, mostly regulating services. For example, forests regulate watershed hydrological regimes and protect against erosion and extreme flooding events, while filtering and purifying water for its local consumption (Guerra et al., 2016; Palahi et al., 2008). Mediterranean forests also play an important role in regulating micro-climatic conditions (Porté et al., 2004), the atmospheric composition, and the water and biochemical cycles (Peñuelas et al., 2017); they also represent a net carbon sink, contributing to mitigate climate change impacts (Wolfslehner et al., 2019). Their role as a carbon sink is especially relevant at the continental scale since they account for 30% of the total forest cover in Europe (Ding et al., 2016). Other societal values of Mediterranean forests include their cultural, spiritual and religious importance (especially that of the few remaining ancient forests; Mansourian et al., 2013) and their attractiveness (aesthetics) for recreational activities and tourism (Bernetti et al., 2019; FAO and Plan Blue, 2018; Raviv et al., 2020).

These ecosystems will be (and already are) subjected to the multiple impacts associated with climate change drivers (Doblas-Miranda et al., 2017). The Mediterranean basin warms at an average rate 20% faster than the global annual mean surface temperature, with summer warming projected to be 50% larger than global mean values (Lionello and Scarascia, 2018). Future temperature increases will concur with overall reduction of precipitation and the increase in frequency and intensity of extreme events (e.g. extended heatwaves and droughts, episodes of extreme rainfall) (Lionello and Scarascia, 2018; MEDECC, 2020). Increasingly warm and dry conditions can cause climate-driven declines in forest growth and die-off episodes from drought and heat stress (Gentilesca et al., 2017; Klein et al., 2019), increase crown defoliation responses (Carnicer et al., 2011), alter species phenology (leaf unfolding, flowering and fruiting; Peñuelas et al., 2004), limit forest growth and productivity (Peñuelas et al., 2018), increase fire risk (Bedia et al., 2014; Moriondo et al., 2006) and increase forest vulnerability to biotic disturbances (e.g. pests; Gauquelin et al., 2018; Lindner and Calama, 2013), among other impacts.

Fire activity and spread are also predicted to increase due to an increase in frequency of fire weather conditions linked to extremes (e.g., low humidity, high temperature, and strong winds) (Batllori et al., 2013; Turco et al., 2018) with consequent potential increase in burnt areas (Turco et al., 2018). These changes will ultimately lead to profound impacts in ecosystem function and associated services such as carbon uptake, timber or cork production, or water storage capacity (Felipe-Lucia et al., 2018; Oliveira et al., 2016; Peñuelas et al., 2017). However, while the impacts of climate change on the functioning of Mediterranean forests have been widely quantified, both on the basis of observational and experimental studies (see Doblas-Miranda et al., 2017; Peñuelas et al., 2018, 2017 for detailed reviews), information about the projected impacts on ecosystem services provision is scattered, biased and incomplete. For instance, projections of future provision or demand of non-material services of Mediterranean forests such as cultural values are almost absent in the literature (Morán-Ordóñez et al., 2019).

In this study, we reviewed the literature on the projected impacts of climate change on ecosystem service provision by forests across the Mediterranean basin. We focused on the main material, non-material and regulating services (including habitat creation and maintenance), but we also extracted projected trends for indicators related to wildfires and other climate-related hazards (e.g. heatwaves) because of their relevance at regulating ecological processes and forest persistence in Mediterranean habitats. We sought to answer the following questions: (1) how will the provision of ecosystem services linked to Mediterranean forests change over the course of the 21st century, based on future climate projections? What are the projections for fires and other related hazards? (2) how will the magnitude of projected changes vary between different climatic projections? and (3) how will it change over time horizons (mid-term vs long-term projections)? We focused on comparing projections of ecosystem services provision and fire and other climate-related hazards above and below the temperature threshold set in the Paris Agreement (Article 2, 2015). This agreement, adopted in 2015 during the 21st Conference of the Parties of the UNFCCC (United Nations Framework Convention on Climate Change), seeks to strengthen the global response to the threat of climate change by holding the global temperature rise well below 2 °C above pre-industrial levels (Article 2, Paris Agreement 2015). Given the importance of the services that forests provide to people across the Mediterranean basin, it is essential to quantify how their provision may change in the future under different climatic scenarios. This will allow current forest management to account for the uncertainty of future climate conditions in service provision and fire and other climate-related hazards and will open the possibility of adapting management to changes in service demands that may arise.

## **METHODS**

### **Literature review**

In December 2019, we conducted a systematic literature review of studies using modelling approaches to project future ecosystem service provision in Mediterranean forests under IPCC climate change scenarios. Our study builds on a previous review (Morán-Ordóñez et al., 2019) that focused on understanding the types of models - i.e. correlative, process-based or integrative - and drivers - single vs multi- driver approaches - considered when making future projections of the condition of Mediterranean forests, as well as on assessing the types ecosystem services indicators evaluated. Here, we go a step further to assess what the projected trends for those indicators are and whether these depend on the climate change scenario considered. Thus, we updated the bibliographic search in Morán-Ordóñez et al. (2019) – following the same search protocol (i.e. use of keywords and databases and criteria for manuscript inclusion) – to include peer-reviewed articles published between 2016 and 2019 (Appendix S1). Our search yielded 590 additional articles. After checking the abstracts to remove duplicates and articles clearly out of the scope of this study, we kept 84 articles that were added to the original 163 included in the database of Morán-Ordóñez et al. (2019) (Appendix S2). We read the full text of all the 247 selected studies, and retained those that met the following criteria: (a) they use IPCC scenarios to make future projections of ecosystems service provision (this criteria sought to ease comparison among case studies regardless their spatial scope), (b) they report either present and future values of the ecosystem service indicator/s evaluated, or its relative change under future climate conditions compared to current levels of service provision, and (c) they consider a time horizon between 2040 - 2100 (mid- to long-term future projections). This resulted in a final set of 78 articles (“studies”) to be considered for subsequent analyses (Appendix S3).

### **Extraction and organization of the information gathered**

For each study, we extracted information about the IPCC scenario used, the identity of the ecosystem service indicators evaluated, and the change between the current and future projected values reported for each indicator (in %). We decided to keep the percentage of change as a reference unit measure to be able to compare indicators with a different range of values and units. We also grouped the IPCC climate scenarios according to whether they predict a global mean temperature rise above or below the targets

set by the Paris Agreement: using the information provided by the fourth and fifth IPCC assessments (IPCC, 2014, 2007), we classified the IPCC scenarios RCP 2.6, RCP 4.5, and B1 as ‘very likely’ to lead to temperature rises below 2 °C (90% probability of occurrence; IPCC, 2005), whereas the scenarios A1B, A1FL, A2, B2, RCP 6, and RCP 8.5 were classified as ‘very likely’ to exceed this temperature target (Appendix S4). From here on, we refer to these as scenarios *below* or *above* the Paris Agreement, respectively. Finally, we considered the projections made for the periods 2040-2070 or 2071-2100 as mid-term or long-term projections, respectively. We also gathered additional information such as the geographic location of the study area, the focal species or habitat type, the time horizon investigated, and whether the scenario used to make future ecosystem service projections considered additional drivers besides climate change (e.g. management, land use changes). Since a given study can investigate different scenarios, time-horizons, species, and ecosystem service indicators, we generated a unique record (“observation”) for each combination of these four factors in our database. This led to a total of 1,767 observations in the database.

We categorized the ecosystem services indicators into 18 categories according to the Nature’s Contribution to People classification framework (NCP category from here on) developed by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2017). These categories were further grouped into three broad NCP groups: “Material”, “Non-material”, and “Regulating” (Table 1) (Appendix S5). The IPBES introduced the NCP framework as a supra-concept to Ecosystem Services, in an attempt to embrace a broader range of worldviews, knowledge systems and stakeholders’ perceptions of natural systems (beyond its potential role as commodities; Díaz et al., 2015). Despite the controversy over the adoption of this framework over previous classifications (e.g. the Common International Classification of Ecosystem Services- CICES) (see Kadykalo et al., 2019 for a review), we chose to follow the NCP framework for ease of results’ comparison with the most recent assessments on the status and trends of biodiversity at both the global (IPBES, 2019) and relevant regional levels (i.e. Europe and Central Asia IPBES, 2018a, Africa 2018b). In any case, in this study, we understand the terms “Nature Contributions to People” and “Ecosystem Services” as synonyms for identifying peoples’ dependencies on nature (sensu De Groot et al., 2018), and as such we use them interchangeably throughout the text. Besides extracting information on indicators within the NCP framework, we also extracted projected trends for indicators related to fire (e.g. fire intensity or severity, burnt area) and other climate-related hazards because of their relevance at regulating ecological

processes in Mediterranean forests. Table 1 provides a complete list of all the information extracted to the database, together with the criteria used for the classification of services into NCP categories.

### **Data analyses**

Using the information extracted into the database, we assessed for each NCP group and category of ecosystem service indicator - including “Fire and other hazards” - whether projected trends in service provision were significantly different from zero using Wilcoxon signed rank tests. We also assessed whether the projections of change in ecosystem service provision varied significantly between (i) scenarios above and below the Paris Agreement, and (ii) the time horizon assessed (mid-term vs long-term), using Wilcoxon rank sum tests. We used the same analyses to elucidate the effect of scenario type (above vs. below Paris agreement) and time horizon on the projected habitat distribution of the main Mediterranean tree species included in the reviewed literature. For the latter analysis, only those indicators classified as ‘Habitat creation and maintenance’ NPC category were retained. All the analyses were conducted using R version 3.6 (R Core Team, 2019).

**Table 1:** Information extracted from the selected articles. The right column describes in detail the type of information collected in each field for each study.

<b>Variable</b>	<b>Values</b>
<b>Country</b>	The country in which the projections are located, regardless of the scale of the study.
<b>IPCC Scenario</b>	Scenarios of the fourth (SRES A1B, A1FL, A2, B1, B2) and/or fifth (RCP 2.6, 4.5, 6, 8.5) IPCC assessment reports (IPCC 2007, 2014)
<b>Paris Agreement</b>	<p>Scenarios in the ‘IPCC scenario’ field were classified depending on whether they project an increase in mean global temperature by the end of the century below or above the 2°C target set by the Paris Agreement.</p> <ul style="list-style-type: none"> <li>● Below (low emission scenarios): RCP 2.6, RCP 4.5, B1</li> <li>● Above (high emission scenarios): A1B, A1FL, A2, B2, RCP 6, RCP 8.5</li> </ul> <p>See Appendix S4 for more details in scenario classification</p>
<b>Scenario drivers</b>	Other drivers included in the study besides climate, e.g. forest management, land use change, fire management, etc.
<b>Time horizon of the projection</b>	<p>The projection period gets classified in either:</p> <ul style="list-style-type: none"> <li>● Mid-term projection: 2040 – 2070</li> <li>● Long-term projection: 2071 – 2100</li> </ul> <p>If the time frame of the study did not fall exactly into these two periods (e.g. 2010 – 2070 or 2061 – 2080), we used the rounded mean of the study period to classify the projections made in that particular study either into the mid- or long- term projection horizons. Thus, the first example would fall into the mid-term category (mean = 2040) and the second example into the long-term category (mean = 2071).</p>
<b>Species/Habitat</b>	Target tree species at species/genus level (e.g. <i>Quercus ilex</i> or <i>Quercus</i> spp.) OR habitat type (e.g. Mediterranean forest or coniferous forest)
<b>Ecosystem service indicator</b>	Indicator measured (e.g. Net Primary Production, habitat extent, burnt area, etc.)
<b>NCP category</b>	Following the classification framework recently developed by the IPBES, indicators were classified into one of the 18 different Nature’s Contribution to People (NCP) categories (IPBES, 2017) (Appendix S5). These categories can be grouped in three broad groups of NCP’s: ‘Material services’, ‘Non-Material services’, and ‘Regulating services’. Besides NCP categories, we considered an additional category grouping indicators related to “Fire and other hazards”.
<b>Ecosystem service indicator change</b>	Projected % of change of the indicator value calculated as ((future indicator value – present value)/present value)*100 or directly extracted from the study (when the projected change was directly reported). We interpreted the projected trend in indicator values according to their impact on the service under consideration (e.g. an increase of habitat loss involves a decrease in the ‘habitat provision’ service). For articles projecting annual changes in service provision over the course of the century we extracted the mean projected change across all years within each of the time horizons evaluated (mid-term 2040-2070 and long-term 2071-2100).

## RESULTS

### *NCP categories, scenarios, time horizon and dominant species*

Most studies (49, 63% of the total number of studies) evaluated the provision of regulating services, whereas 27% (21 studies) focused on material services, and only two studies evaluated changes in non-material services. Also 25% of the studies evaluated projected changes in indicators related to fire and other hazards. Most studies (86%; 67 studies) focused on indicators within a single NCP group, and only nine of the 18 NCP categories were represented across the 78 articles reviewed. Almost half of them (30 studies) focused on the “Habitat creation and maintenance” NCP category, whereas one quarter assessed changes in the role of forests as “Regulators of climate”, focusing mostly on their carbon storage capacity, and another quarter (18 studies) made projections within the NCP category ‘Materials and assistance’, including measurements related to wood production, tree growth, cork weight or monetary income. The rest of the NCP categories represented in our database included four studies or less (see Appendix S6 for details in the indicators found within each of the NCP categories).

All but two studies considered climate change scenarios above the Paris Agreement threshold (2 °C), whereas a third of them (26 studies) included both scenarios below and above the Paris agreement. Regarding the time horizon, 86% and 54% of studies evaluated long-term and mid-term changes in the NCP indicators, respectively, and 40% considered both long-term and mid-term projections. Two thirds of the studies exclusively focused on climate as the only driver of forest change. The second most important drivers considered in projections were CO<sub>2</sub> fertilization and forest management (with 10 and 6 studies, respectively). The tree species most frequently studied were *Quercus ilex* (18 studies), followed by *Quercus suber* (14), *Pinus sylvestris* and *Pinus halepensis* (13), *Pinus pinaster* (12) and *Pinus nigra* (10). Overall, 52 different tree species were used to make ES indicator projections.

### *Predicted changes of ecosystem service indicators*

Future projected changes in ecosystem services indicators varied greatly between NCP groups (Figure 1a), but also exhibited some variability - albeit much smaller- among each of the categories within each group (Figure 1b). The median projected trend was slightly negative for “Material services” (Median change = -4.43%) and “Regulating services” (-8.6%), although only the latter was significantly different from zero (Wilcoxon Signed-rank test p-value < 2·10<sup>-16</sup>). The studies also predict a sharp increase in provision of “Non-material services” (+116%, p = 0.009; but note the small sample size) and in the risk derived from fire and other hazards (+62.2%, p < 2·10<sup>-16</sup>). Notably, all NCP categories within a group showed the same sign in response, although the magnitude of the predicted change did differ between categories (Figure 1b). The median projected change in service provision was negative for all the NCP categories within the “Regulating services” group, although it was only significantly different from zero for “Habitat creation and maintenance” (Median change = -44%; p < 2·10<sup>-16</sup>), and “Regulation of freshwater quantity, flow and timing” (-4.7%; p < 2·10<sup>-16</sup>). In the case of the “Material services” group, the projections forecast negative trends for both “Food and feed” (-16.1%), and “Materials and assistance” indicators (-3.9%), although estimations were not significantly different from zero. On the other hand, the median projected changes for the two NCP categories within the “Non-Material services” group were both clearly positive (+122% and +100%), although the small sample size (4 indicators evaluated, but all from the same study) prevented finding significant trends.

Studies using scenarios above the Paris Agreement projected more negative changes (or less positive) than those below the Paris Agreement for services within the “Regulating services” and “Non-material services”, although differences were only significant for the former group (Figure 2a). In contrast, studies predicted a lower decrease in “Material services” for scenarios above the Paris Agreement, which was mostly driven by the projected trend in indicators within the NCP category “Materials and assistance” (Figure 2b). We only observed significant differences between scenarios for two other NCP categories: “Regulation of Climate” (-0.021% vs. -0.81.1%; Wilcoxon rank sum test p-value = 0.019) and “Regulation of freshwater quantity, flow and timing” (-4.6% vs. -15.5%; p = 0.00172), whereas there were not noticeable differences between above and below Paris Agreement scenarios for the projections in ‘Fire and other hazards’.

The more negative effect on regulating services of scenarios above the Paris agreement was consistent regardless of the time horizon evaluated (mid-term 2040-2070 vs. long-term 2070-2100) (Figure 3). For the rest of NCP groups, long-term projections indeed projected more negative impacts on service provision, although the low sample size of some categories and the high variability across studies prevented finding statistical differences among temporal horizon or climatic scenarios. As an example, all indicators predicted positive changes in “Non-material services” at the mid-term, whereas the only study considering them at the long term forecasted negative changes. For all NCP categories, the variability in predicted trends was larger for studies considering long time horizons (Figure 3b).

Studies within the “Habitat creation and maintenance” NCP category projected species-specific responses to climate change in habitat suitability and extent (Figure 4). On average, studies forecast significant reductions in habitat for drought-sensitive species such as *Fagus sylvatica* (Median change = -88%;  $p = 0.0039$ ), *Castanea sativa* (-27%;  $p = 0.0038$ ), *Pinus sylvestris* (-86%;  $p < 0.001$ ) and *Pinus nigra* (-79.6%;  $p < 0.001$ ), whereas drought-tolerant species are projected to remain stable (e.g. *Quercus ilex*, 0.4%) or expand (e.g. *Pinus halepensis*, +52%;  $p = 0.0024$ ; Figure 4a) under climate change conditions. In fact, the specific rank in projected change in habitat suitability and extent matches species classifications of drought tolerance. The magnitude of the projected change greatly varied depending on the climate change scenarios considered. Scenarios above the Paris Agreement generally forecasted greater reductions (or lower increases) in habitat suitability and extent than those below the Paris Agreement, although for some species the low sample size did not allow proper statistical comparison across scenario types (e.g. *Pinus pinaster*; Figure 4b). The differences between scenarios were particularly noticeable for the two most drought-tolerant species (*Pinus halepensis* and *Quercus ilex*). Both species are predicted to sharply increase their habitat suitability under scenarios below the Paris agreement (+338% and +52%, respectively). However, studies including more severe climatic scenarios (above Paris Agreement) predict slight or null increases in their habitat (Figure 4b).

## **DISCUSSION**

The Mediterranean basin is one of the world's primary climate change hotspots (Diffenbaugh and Giorgi, 2012). Our review shows climate change will have an overall negative impact on the provision of "Regulating services" by Mediterranean forests both in the mid- and long-term. The impact is generally greater (i.e., more negative) when assuming changes in global mean temperature above the 2 °C threshold set by the Paris Agreement. The reviewed studies project negative impacts of climate change on most NCP categories within the "Regulating services" group, although the main forecasted impacts are a reduction of forest extent and loss of suitable habitat for many species (particularly drought-intolerants), and a reduction in the capacity of forests to regulate water cycle. The studies also project a significant increase (median change +62%) in indicators related to fire and other climate-related hazards (e.g. projected burnt area), with less clear trends in the provision of other services (either material and non-material). Overall, our results suggest climate change mitigation and forest management for reduction of forest vulnerability to future climate change risks will be key to warrant the persistence of Mediterranean forests, their biodiversity and societal values.

### ***The future of Mediterranean forests as providers of ecosystem services***

A warmer and dryer climate across the Mediterranean basin will increase plant evapotranspiration demands and therefore, decrease the movement of water from forest to downstream ecosystems (Peñuelas et al., 2018), compromising supporting services (e.g., water cycle), provision of habitat for aquatic species and water availability for consumptive uses (Biot et al., 2011). The studies included in this review project a generalized and statistically significant negative change in the regulation of freshwater quantity, flow and timing, both at the stand level (e.g. Ameztegui et al., 2017) or at the landscape scale (e.g. Serpa et al., 2015). Changes in water availability together with changes in carbon storage capacity are especially important, since they are the basis of the primary production that supports the provision of material services (e.g., timber) and play a fundamental role on climate change mitigation (Peñuelas et al., 2017; Ruiz-Peinado et al., 2017). For example, Palma et al. (2015) projected a decrease of up to 30% in carbon storage capacity and 20% in productivity of cork oak stands in central Portugal if current management was maintained under a severe climate change scenario (A1 - above the Paris Agreement). Whereas increasing atmospheric CO<sub>2</sub> concentrations might directly promote forest

productivity and growth (e.g. Keenan et al., 2011), this effect will be strongly modulated by increasing temperatures and drought conditions (Bussotti et al., 2014; Doblas-Miranda et al., 2017; Lo et al., 2019; Penuelas et al., 2011). This might partly explain why median projected trends for the “materials and assistance” category were more negative for scenarios below the Paris Agreement (Figure 2b), under which CO<sub>2</sub> forcing is smaller. Nevertheless, other factors can also explain the variation of results across indicators in this group, such as differences in productivity across the evaluated tree species or whether the studies considered the interaction between the CO<sub>2</sub> fertilization effect and the rise in temperatures.

The response of other forest ecosystem services to climate change drivers was more variable. This variability can be explained by different factors for each NCP category, including low sampling size. For example, our literature search only found four studies evaluating indicators within the category “Food and feed” and, although the overall median projected trend across all indicators and studies was negative (Figure 1), the three studies focusing on mushroom production projected contrasting trends of future provision values. There is ongoing debate about how mushroom productivity will change under climate change: some studies have highlighted that it may be experiencing a sharp drought-induced decrease (e.g. Ágreda et al., 2015; but see also Boddy et al., 2014; Thomas and Büntgen, 2019 in the review ) due to delayed phenology in the autumn season under warmer and drier conditions (Büntgen et al., 2015; Kausarud et al., 2012); on the contrary, simulations by Karavani et al. (2018b; also included in this review) pointed towards an increase in production of edible and marketable species under climate change scenarios as a consequence of an elongation of the mushroom fruiting season. Likewise, the little coverage of cultural services in the literature reviewed (2 studies) also evidences the difficulty to quantify, model, and predict changes in social values over time (Morán-Ordóñez et al., 2019). Anyhow, these studies projected a potential increase in both passive use (maintenance of options: e.g. changes in the number of distinct populations within a species; Temunović et al., 2013) and recreational values of Mediterranean forests (Ding et al., 2016). The latter might relate to the increasing attraction of forest for tourists, which has been suggested to be potentially detrimental to other forest services (García-Nieto et al., 2013) or to the forest itself if not well regulated (Kuvan, 2010).

### ***Projected changes in habitat suitability for forest species and fire and other risks***

Overall, the future extent of suitable habitat for Mediterranean forests was projected to significantly decrease under climate change (“Habitat creation and maintenance category”; Fig. 1b), although sharp species-specific differences arose. Drought-intolerant species, that find the rear edge of their distribution in the Mediterranean (e.g., deciduous temperate species like *Fagus sylvatica* or *Castanea sativa*) and mountain species (e.g., *Pinus sylvestris*) will be the most threatened by climate change, with ranges and climatic suitability predicted to shrink in future projections (Fig. 4). On the other hand, the most xeric Mediterranean species, which are better adapted to drought (e.g. *Quercus ilex*, *Pinus halepensis*) are expected to entail fewer problems for survival and/or even range expansion under future climate change (Bussotti et al., 2014; Linder and Calama, 2013; Ruiz-Labourdette et al., 2012). Tree species with wide distribution ranges seem to display contrasting responses to climate change across their entire range. For example, Benito-Garzón et al. (2008) and Attorre et al. (2008) projected opposite trends for *Quercus ilex* future area coverage in the Iberian Peninsula - decreasing - and the Italian region of Lazio - increasing-, despite both considered long-term climatic projections above the Paris Agreement. These divergent trends might relate to the intraspecific plasticity and genetic differentiation among tree populations as a result of differences in the intensity of the environmental stresses over their distribution ranges (Benito-Garzón et al., 2013).

However, even drought-adapted species are sensitive to extended drought events, especially in dense, unmanaged forests (Linder and Calama, 2013) or in sites with superficial soils (Lloret et al., 2004). Projections of increasing habitat suitability and forest extent for *P. halepensis* and *Q. ilex* were much smaller or even negligible for scenarios above the Paris Agreement, highlighting the importance of keeping the increase in average global mean temperature below 2 °C. Moreover, the actual response of species to climate change can be linked to other factors such as migration capacity, habitat fragmentation and response to extreme events (Margalef-Marrase et al., 2020), which are usually not included in the modelling process (Lindner et al., 2014) (case of all studies forecasting future habitat suitability included in this review).

Our results also suggest that forest loss due to fire or other climate associated risks will be very high both under scenarios below and above the Paris Agreement, highlighting the need to urgently put in place climate change mitigation policies. In particular, climate change mitigation,

along with fire management (e.g. fuel reduction, creation of landscape mosaics) will both prove key to minimize the impacts of wildfires and other climate-related hazards on Mediterranean forests values and human wellbeing (Moreira et al., 2020; Moreira and Pe'er, 2018). On the one hand, fuel reduction through forest management at stand level (e.g. thinning) can reduce fire risk while increasing the growth and value of the remaining trees (i.e. the value of material services) and also improving their resistance to drought events (Sohn et al., 2016b, 2016a). This will also minimize potential vegetation transitions from forest to shrublands or steppe vegetation as a result of both increasing drought conditions (Hickler et al., 2012) and the interactive effect between drought and fire (Batllori et al., 2019; Karavani et al., 2018a). On the other hand, fuel reduction through creation and maintenance of mosaics of low-flammability crops, orchards and oak trees can also reduce fire risks (Moreira and Pe'er, 2018; Moriondo et al., 2006) and fire suppression costs (increasingly expensive and challenging in the era of megafires; Stephens et al., 2013), while promoting biodiversity values and ecosystem services flows (Otero et al., 2015).

### ***Sources of uncertainty, limitations and future research needs***

The projected rates of change for NCP groups and categories evaluated in this review summarize values across a diversity of non-standardized indicators that differ on many aspects, including the data available for service quantification, their spatial and temporal scale, and their units. This lack of standardization (common in ecosystem service assessment approaches; Burkhard and Maes, 2017) meant that the rate of change in the indicator was the only comparable measure across studies available to us and impeded a formal meta-analysis. Uncertainty about climate change projections was also unevenly treated across the 78 studies evaluated: some studies reported trends under a single global or regional circulation model, while others made projections using multiple regional circulation models or ensemble forecasting approaches across models. Also, only ~6% of studies reported downscaled projected temperature changes for the study area under evaluation, so we decided to use the average global temperature increase to classify each scenario. Therefore, we could not directly test the effect of temperature increase on ecosystem service provision, and we used non-parametric tests to classify and compare projected indicator trends across scenarios.

Although IPCC scenarios are rather holistic and integrate the effects of many drivers (emissions, economic change, environmental attitude/protection, etc.), we observed substantial variation in

responses when additional drivers of change were included. For instance, studies explicitly including a CO<sub>2</sub> fertilization effect projected lower impacts of climate change on the services linked to forest growth (Dury et al., 2011; Gaucherel et al., 2008; Keenan et al., 2011), and forest management can also have a larger impact on ecosystem service provision than climate (Morán-Ordóñez et al., 2020; Palma et al., 2015). Similarly, studies projecting burnt areas rarely account for the potential of mitigating impacts through fire or landscape management (but see for example Duane et al., 2019). Moreover, many of the studies evaluating the joint impact of climate change and other drivers in future provision of a given service lacked a full factorial experimental design of the drivers involved, making it hard to disentangle the individual impacts of each driver in the indicator.

Finally, despite our best efforts, our study might not be representative enough of plausible future changes in ecosystem service provision in South- and East- Mediterranean countries where bigger changes in average climate and extreme events are projected, but where scientific expertise in ecosystem services mapping and forecasting is often limited (IPBES 2018b) (Appendix S8; Morán-Ordóñez et al. 2019). A careful assessment of non-scientific reports or the so-called “grey literature” might help to correct the geographic bias, but the diversity of languages spoken in the Mediterranean makes it less accessible and more difficult to evaluate systematically.

Even with limitations, the large volume of studies and indicators gathered suggest our results were robust at identifying the main general projected trends in service provision by forests under climate change scenarios. Despite some imbalance in sample size - with a few studies contributing many entries to the database (Appendix S9)- our results are in line with the recent Pan-Mediterranean assessment on the projected impacts of climate and environmental change in ecosystems (MEDECC, 2020). This is especially true for some of the NCP groups and categories such as “Fire and other Hazards” and “Habitat creation and maintenance”, that were evaluated across many studies (19 and 30, respectively). To get a more complete picture of how climate change will affect service provision, future studies should focus on some of the less studied NCP categories (e.g. physical and psychological experiences, maintenance of options), but also on better addressing the uncertainty around climate projections, and on better integrating the effect of additional drivers other than climate on future projections (IPBES, 2016; Morán-Ordóñez et al., 2019). Additionally, investigating multiple indicators from different NCP categories within

the same study would allow to understand the trade-offs and synergies among future service provision, enabling informed forest management and decision making under uncertain future scenarios.

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**The data that support the findings of this study are openly available in figshare at <https://doi.org/10.6084/m9.figshare.14737446.v1>**

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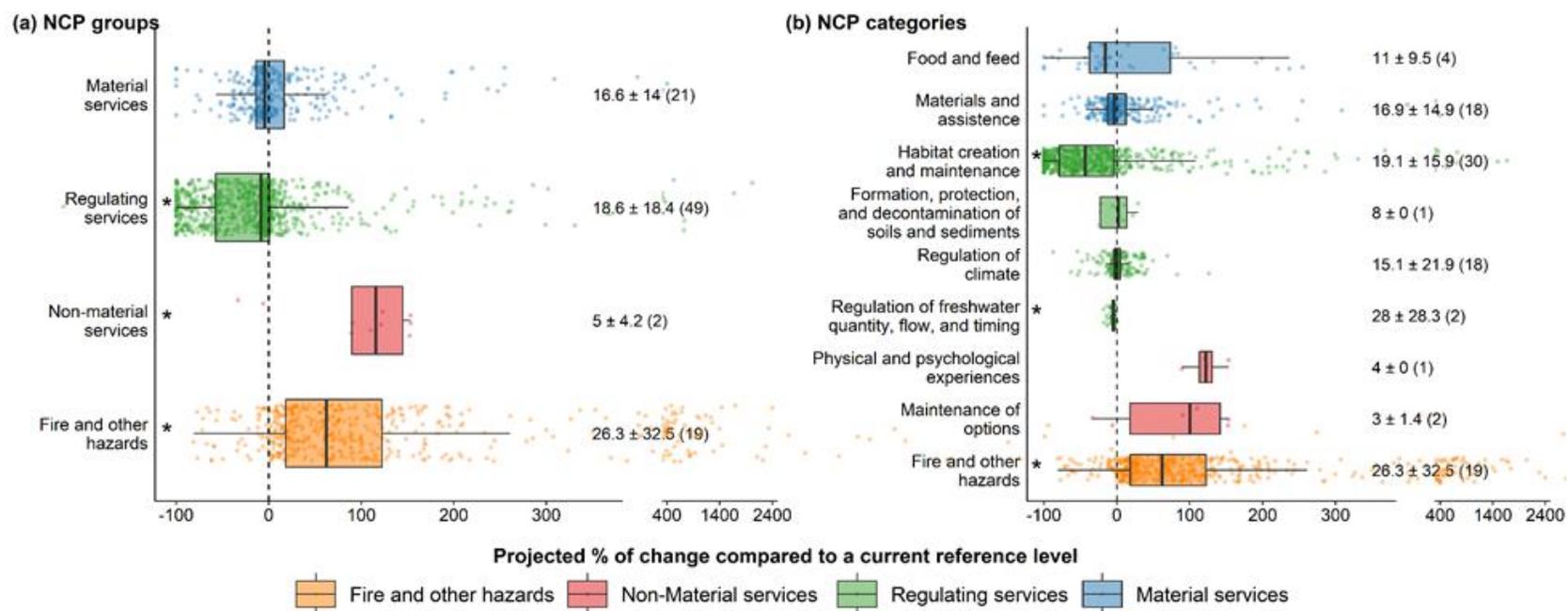
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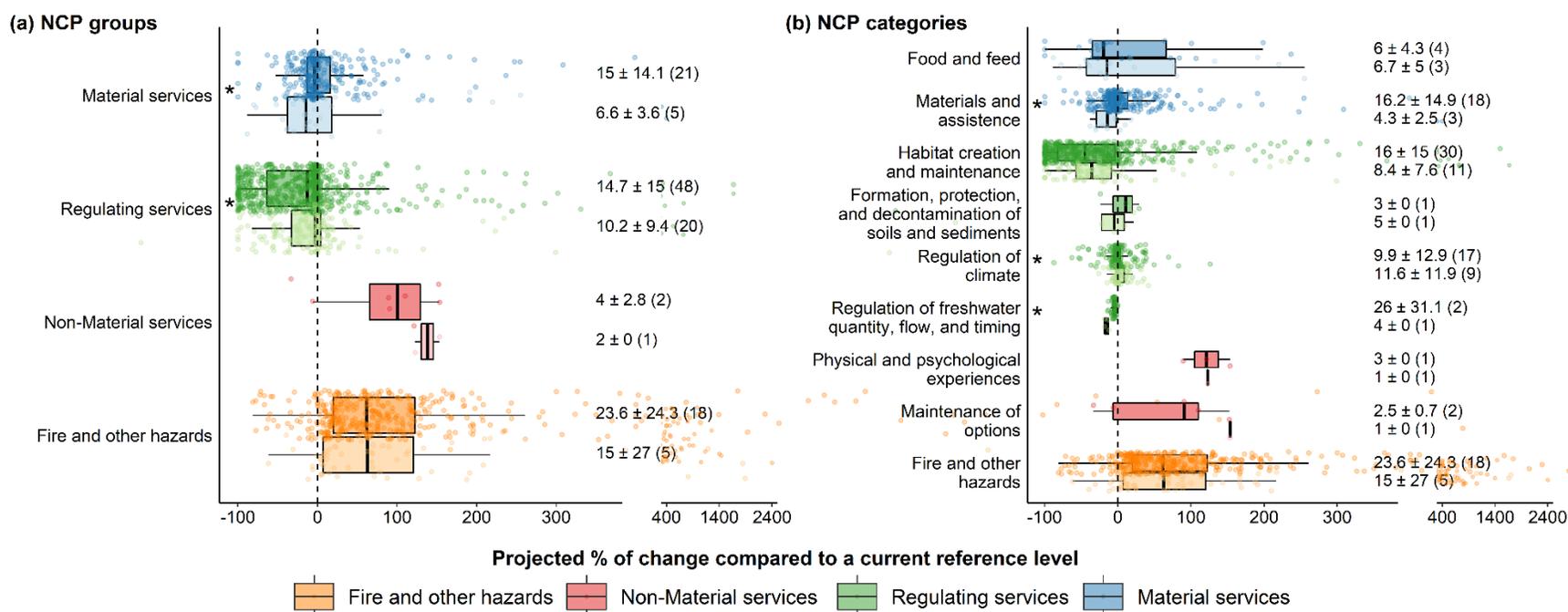
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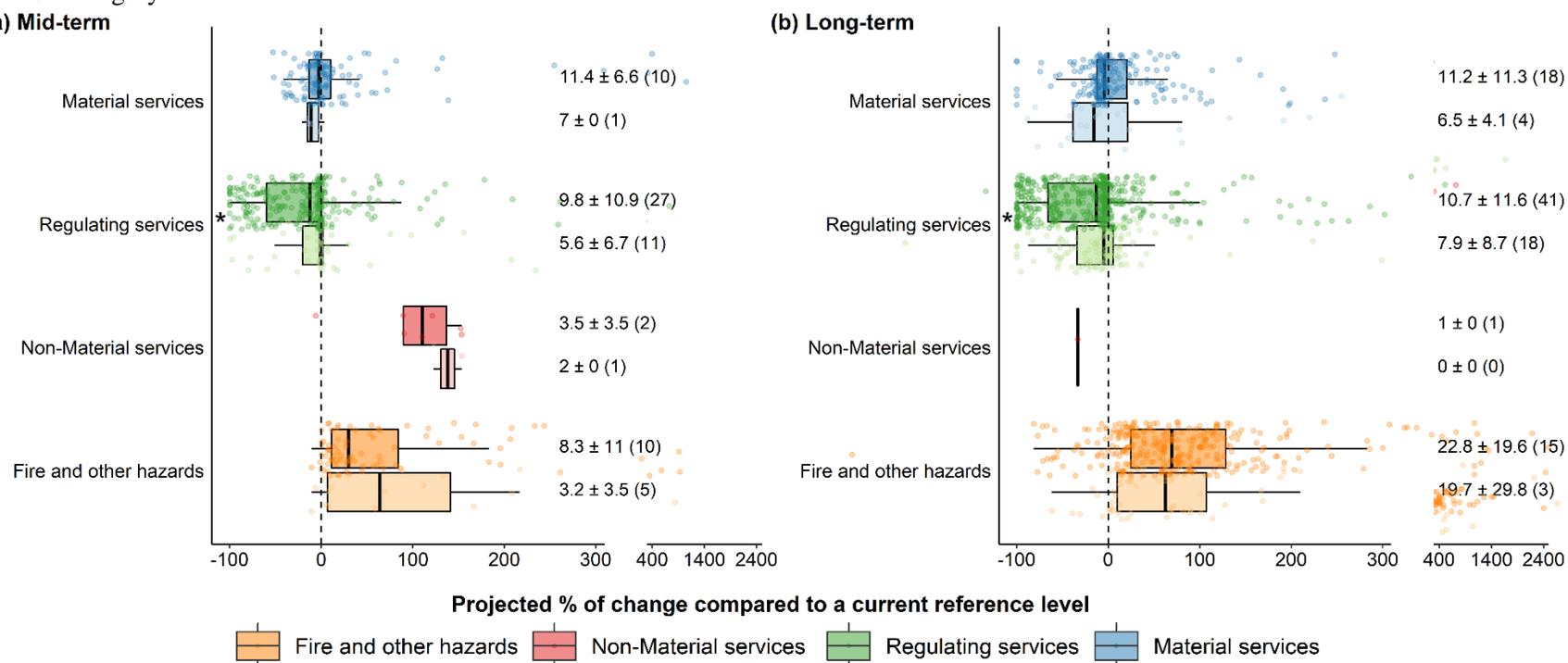
**Figure 1:** Projected percentage of ecosystem service change over the course of the century for (a) the main NCP groups; and (b) detailed for each NCP category. In each boxplot, boxes delimit interquartile ranges (IQR, 25th and 75th percentiles), whiskers extend to 1.5x IQR, and the solid vertical black line indicates the median value. The numbers in the upper end of the whiskers of each box indicate [mean number of observations per study  $\pm$  standard deviation (number of studies in the NCP group or category)], as a measure of the distribution of the number of observations among studies. An asterisk in front of the box indicates the median projected trend is significantly different from zero ( $\alpha=0.05$ ) following Wilcoxon signed-rank test. Note that in both panels the X-axis is truncated to improve visualization of the indicators for which smaller changes were projected.



**Figure 2.** Projected percentage of ecosystem service change over the course of the century as a function of climate change scenario for (a) the main NCP groups; and (b) detailed for each NCP category. Boxplots in light and dark colors show projected trends under scenarios below or above the Paris Agreement, respectively. In each boxplot, boxes delimit interquartile ranges (IQR, 25th and 75th percentiles), whiskers extend to 1.5x IQR, and the solid vertical black line indicates the median value. The numbers in the upper end of the whiskers of each box indicate [mean number of observations per study  $\pm$  standard deviation (number of studies in the NCP group or category)], as a measure of the distribution of the number of indicators among studies. An asterisk in one of the NCP groups or categories indicates projected trends in service provision in that category were significantly different between scenarios above and below the Paris Agreement (Wilcoxon rank-sum test;  $\alpha=0.05$ ). Note that in both panels the X-axis is truncated to improve visualization of the indicators for which smaller changes were projected.



**Figure 3.** Projected percentage of ecosystem service change for the main NCP groups for (a) predictions at the mid-term time horizon (2040-2070) and (b) predictions at the long-term horizon (2071-2100). Boxplots in light and dark colors show projected trends under scenarios below and above the Paris Agreement, respectively. In each boxplot, boxes delimit interquartile ranges (IQR, 25th and 75th percentiles), whiskers extend to 1.5x IQR, and the solid vertical black line indicates the median value. The numbers in the upper end of the whiskers of each box indicate [mean number of observations per study  $\pm$  standard deviation (number of studies in the NCP group)], as a measure of the distribution of the number of indicators among studies. An asterisk in one of the NCP groups indicates projected trends in service provision in that group were significantly different between scenarios above and below the Paris Agreement (Wilcoxon rank-sum test;  $\alpha=0.05$ ). Note that in both panels the X-axis is truncated to improve visualization of the indicators for which smaller changes were projected. See Appendix S7 for corresponding results detailed by NCP category.



**Figure 4:** Projected percentage change in habitat suitability/extent/coverage over the course of the century for the most studied tree species **(a)** overall trend across the 78 studies evaluated and **(b)** separating projected trends above and below the Paris Agreement, as indicated by boxplots in dark and light colors, respectively. In each boxplot, boxes delimit interquartile ranges (IQR, 25th and 75th percentiles), whiskers extend to 1.5x IQR, and the solid vertical black line indicates the median value. The numbers in the upper end of the whiskers of each box indicate [mean number of observations per studies  $\pm$  standard deviation (number of studies for a particular species)], as a measure of the distribution of the number of indicators among studies. An asterisk in front of the box indicates in (a) that the median projected trend is significantly different from zero ( $\alpha=0.05$ ) following Wilcoxon signed rank test, whereas in (b) it indicates significant differences between scenarios above and below the Paris Agreement (Wilcoxon rank-sum test;  $\alpha=0.05$ ).

