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# Reviewing climatic traits for the main forest tree species in Italy

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**The future dynamics of forest species and ecosystems depend on the effects of climate change and are related to forest management strategies. The expected impacts of climate change are linked to forest growth and productivity. An increase in the length of the growing season and greater productivity are likely as well as shifts in average climatic values and more variable frequencies, intensities, durations and timings of extreme events. The main aim of this work is to assess and describe the climatic requirements for Italian forest tree species. We used 7,272 field observations from Italian National Forest Inventory plots and average annual temperatures and precipitation as interpolated from raster maps with 1 km spatial resolution. On this basis we evaluated the current observed distributions of the 19 most important tree species in Italy with respect to potential climatic limits based on expert knowledge and the available literature. We found that only 46% of the observations fall within the potential joint temperature and precipitation limits as defined by expert knowledge. For precipitation alone, 70% of observations were within the potential limits, and for temperature alone, 80% of observations were within the potential limits. Similarity between current observed and potential limits differ from species-to-species with broadleaves in general more frequently distributed within the potential climatic limits than conifers. We found that ecological requirements and potential information should be revised for some species, particularly for the *Pinus* genus and more frequently for precipitation. The results of the study are particularly relevant given the threat of climate change effects for Italian forests which are broadly acknowledged to be a biodiversity hotspot. Further investigations should be aimed at modelling the effects of climate changes on Italian forests as a basis for development of mitigation and adaptation forest management strategies.**

**Keywords: National Forest Inventory, Sustainable Forest Management, Spatial Analysis, Forest Monitoring, Climatic Drivers**

## Introduction

The sustainable management of forest resources is acknowledged as one of the main issues for human well-being (Wagner et al. 2014). Forests are fundamental for economic and productive aspects, as indicated by the growing interest in the bioeconomy (Corona 2015) and strategies for mitigating the effects of future climate. The Intergovernmental Panel on Climate Change (IPCC) defines climate change as "any change in climate over time, whether due to natural variability or because of human activity"(IPCC 2001). For most scenarios, the expected increase in average annual temperature ranges between +2 and +4 °C for this century. The precipitation regime is predicted to be more discontinuous with precipitation concentrated in fewer and potentially dangerous extreme events (Ummenhofer & Meehl 2017). The combined temperature and precipitation interactions may threaten forest ecological processes leading to modifications of growth rates and delivery of ecosystem services (Ray et al. 2017). Moreover, changes in the frequency, intensity, duration and timing of "exogenous disturbances" such as wildfires, pests and diseases are expected.

Climate change effects have already been observed for tree species and ecological systems (Lindner et al. 2010). For example, Boisvert-Marsh et al. (2014) reported a latitudinal shift of the distribution of forest species in North America; similar studies have been conducted in Europe and specifically in the Mediterranean region (Marchi et al. 2016). Chirici et al. (2017) reported the effects of recent, unprecedented wind storms in Italy, and Allen et al. (2010) conducted a global review of tree mortality following heat waves and water stresses.

Forest planning oriented on implementing strategies that adapt to climate change are central across all of Europe (Petr et al. 2014). The growth rate and resilience of forest systems to disturbances are directly connected to ecological requirements and adaptation capacity (Williams & Dumroese 2013). Changes in species composition, reduction in biodiversity and smaller wood increments with reduced carbon sequestration are just few examples of the possible effects of climate change on forest ecosystems. In this sense, future provisioning of forest ecosystem services will be strongly

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influenced by the soil type, climatic drivers and forest management (Lindner et al. 2010, Ray et al. 2017).

The worldwide relevance of forests in climate change scenarios is acknowledged in international agreements, particularly by the IPCC (2014), thanks to their ecosystem services such as Volatile Organic Compounds absorption and $CO_2$ sequestration (Canadell & Raupach 2008). Knowledge of the ecological plasticity of a given species is essential to support selection of suitable forest planning and management choices for mitigating the adverse effects of climate change (Nocentini et al. 2017). As a consequence, adequate and current information on forest tree species auto-ecology can be useful for adaptive forest management and for genetic selection (Williams & Dumroese 2013, Marchetti et al. 2015).

Recently, the Joint Research Centre (JRC) of the European Commission proposed a broad study on all forest tree species found in Europe: the European Atlas of Forest Species (San-Miguel-Ayanz et al. 2016). This publication describes the main forest European tree species and their ecological and genetic characteristics. Predictive models have been applied to construct land suitability maps for each species. The spatial data were obtained starting from the European Forest Data Center – Forest Information Service for Europe (EFDAC-FISE – http://forest.jrc.ec.europa.eu/) data sets, while local bioclimatic variables were retrieved from publicly available datasets at the global scale. Using these data, a series of three bi-dimensional auto-ecology diagrams or climate space diagrams were drawn for each species. These graphs describe the distribution of species relative to pairs of bioclimatic factors: annual average temperature and total annual precipitation which are investigated for this study, potential solar irradiation during spring and summer season with the average temperature of the coldest month and the seasonal variation of the monthly precipitation. However, no numeric values have been publicly shared. Another extensive study regarding forest tree species is represented by the Climate Change Tree Atlas proposed by the USDA Forest Service (Iverson et al. 2008). This Atlas is based on plot data acquired by the Forest Inventory and Analysis program of the USDA Forest Service and forms a spatial database for the 134 most common forest tree species in the eastern USA. The main aim of this database is to evaluate the current distribution of forest species and to forecast the possible impacts of climate change using regression tree analysis, Bagging Trees (BT) and Random Forest (RF) as predictive algorithms (Iverson et al. 2008).

NFIs are the most extensive and comprehensive source of forest information suitable for spatial analysis, ecological modelling and statistical mapping of forest attributes (Johnson et al. 2014, Di Biase et al. 2018, Marchi & Ducci 2018). Raw georeferenced data for sampling units obtained in the field are fundamental for many research activities in the forestry field and are becoming publicly available in most countries (Borghetti & Chirici 2016, Mauri et al. 2017). At the same time, several large research projects in the last decade have made spatially interpolated climate variables available at different scales (Maselli et al. 2012, Fick & Hijmans 2017). All the above-mentioned spatial sources of information are now available for the entire Italian territory, although no extensive analysis of the relationships between tree species distributions and current climate conditions have yet been conducted. Despite Italy being one of the most climate change prone countries in Europe and in the Mediterranean region, auto-ecological characterization of vegetation in Italy still relies on expert-based literature (Bernetti 1995) and empirical observations based on the bioclimatic classification proposed early in the last century by Pavari (1916), and later implemented by De Philippis (1937).

The primary scientific literature consulted to assess auto-ecological characteristics of forest tree species consists of a recent series of textbooks by Del Favero (2004, 2008, 2010) and Pedrotti (2013). However, no additional quantitative information about the auto-ecology of species beyond Bernetti (1995) could be identified.

Climate is acknowledged to be one of the main factors accounting for the spatial distribution of forest tree species and represent one of the most important aspect to be carefully evaluated in forest monitoring efforts (Del Favero 2010, Ferrara et al. 2017). Thus, a detailed and current analysis of the relationship between vegetation and climate is essential for any investigation of the possible climate change effects on forest species distributions. The main aim of this study is to update knowledge on the climatic drivers related to the most important forest tree species in Italy. We used 7,272 field plots from the most recent Italian NFI (INFC2005) for which data are currently available, and the 1 km resolution climatic temperature and precipitation data from downscaled E-OBS gridded data (version 17.0) from the EU-FP6 project ENSEMBLES (Haylock et al. 2008). We compared our findings with ecological niche information available in the literature. This analysis is intended as a starting point for further studies on future spatial distributions of tree species and growth models under climate change scenarios. In fact, adequate and current knowledge of ecological requirements for forest tree species represents the main source of information for future projections and forest ecosystem assessments.

## Materials and methods

### Materials

The spatial distributions of tree species in Italy were determined from the raw INFC2005 data freely available at https://www.inventarioforestale.org/ (Borghetti & Chirici 2016). INFC2005 was based on a three-phase sampling procedure with 13m-radius plots located at the intersections of a 1 × 1 km grid. Such scheme gave a statistical robustness to this dataset and can be used for further analysis. Here we used data for all 7,272 plots from the INFC2005 third phase that were visited in the field between 2006 and 2007. For each plot, data for the callipered trees are in the form of 230,874 tree records which served as a key source of information for species distribution analysis.

We considered 19 forest tree species selected as the most representative based on economic, ecological and landscape factors: European beech (*Fagus sylvatica* L.), silver fir (*Abies alba* Mill.), Norway spruce (*Picea abies* Karst.), downy oak (*Quercus pubescens* Willd), Turkey oak (*Quercus cerris* L.), common chestnut (*Castanea sativa* Mill.), holm oak (*Quercus ilex* L.), European larch (*Larix decidua* Mill.), black pine (*Pinus nigra* Arnold), cork oak (*Quercus suber* L.), sessile oak (*Quercus petraea* Liebl.), Aleppo pine (*Pinus halepensis* Mill.), maritime pine (*Pinus pinaster* Ait.), Corsican pine (*Pinus nigra* Arnold subsp. *laricio* Palib. ex Maire – synon. *Pinus laricio* Poir.), stone pine (*Pinus pinea* L.), pedunculate oak *(Quercus robur* L.), arolla pine (*Pinus cembra* L.), Mediterranean cypress (*Cupressus sempervirens* L.) and Douglas fir *(Pseudotsuga menziesii* [Mirb.] Franco). The number of forest inventory plots by species is reported in Tab. 1. For this study, Bernetti (1995) was considered the sole reference regarding the climatic limits of Italian forest tree species. Bernetti (1995) describes 81 species with respect to botanical, geographic and ecological factors and includes potential climatic ranges based on mean annual temperature (MAT) and total annual precipitation (TAP – Tab. 1).

Climatic temperature and precipitation data were derived from a 1-km downscaled climatological maps for Italy for the 1981-2010 period developed from the E-OBS database. Specifically, these climatic data were derived using a downscaled procedure *via* a spatially-weighted regression model fully described by Maselli et al. (2012). The significant underestimation of mapped rainfall reported by Maselli et al. (2012) was corrected using ground measurements reported by Fibbi et al. (2016).

### Methods

Because INFC2005 plots may include multiple tree species (Bravo-Oviedo et al. 2014), we omitted species representing less than 15% of the plot basal area (Giannetti et al. 2018). The dataset included a total of 7,272 tree species observations. For each georeferenced INFC2005 plot we further extracted the total rainfall and average annual temperatures from the downscaled E-OBS 1-km resolution maps.

All spatial analysis were done in the R sta-

**Tab. 1** - List of the studied tree species and their ecological ranges for temperature and precipitation as reported in the literature (Bernetti 1995). (n): number of plots of the INFC2005 where the species was detected; (%): percentage of the total number of observations; (MinTmean, MaxTmean): minimum and maximum average annual temperatures, respectively; (MinPrec, MaxPrec): minimum and maximum total annual precipitation, respectively.

| Code | Species | Observations | | Ecological range from literature | | | |
|---|---|---|---|---|---|---|---|
| | | n | % | MinTmean | MaxTmean | MinPrec | MaxPrec |
| 10 | *Abies alba* | 210 | 2.8 | 6 | 12 | 1200 | 1500 |
| 280 | *Castanea sativa* | 865 | 11.4 | 10 | 14 | 700 | 2400 |
| 60 | *Cupressus sempervirens* | 42 | 0.6 | 12 | 17 | 800 | 1200 |
| 330 | *Fagus sylvatica* | 1003 | 13.2 | 6 | 12 | 1200 | 1500 |
| 80 | *Larix decidua* | 465 | 6.1 | 1 | 5 | 400 | 700 |
| 20 | *Picea abies* | 715 | 9.4 | 3 | 7 | 400 | 2000 |
| 40 | *Pinus cembra* | 58 | 0.8 | 1 | 5 | 400 | 2000 |
| 42 | *Pinus halepensis* | 155 | 2.0 | 15 | 23 | 300 | 400 |
| 45 | *Pinus laricio* | 104 | 1.4 | 7 | 12 | 1400 | 1800 |
| 49 | *Pinus nigra* | 329 | 4.3 | 7 | 12 | 1400 | 2900 |
| 47 | *Pinus pinaster* | 113 | 1.5 | 14 | 30 | 800 | 1200 |
| 43 | *Pinus pinea* | 93 | 1.2 | 14 | 18 | 350 | 600 |
| 90 | *Pseudotsuga menziesii* | 33 | 0.4 | 8 | 13 | 700 | 1500 |
| 300 | *Quercus cerris* | 1078 | 14.2 | 10 | 14 | 700 | 2400 |
| 311 | *Quercus ilex* | 494 | 6.5 | 12 | 17 | 800 | 1200 |
| 307 | *Quercus petraea* | 155 | 2.0 | 10 | 15 | 700 | 2400 |
| 308 | *Quercus pubescens* | 1392 | 18.4 | 10 | 14 | 700 | 2400 |
| 302 | *Quercus robur* | 89 | 1.2 | 10 | 15 | 700 | 2400 |
| 313 | *Quercus suber* | 179 | 2.4 | 14 | 18 | 600 | 800 |

tistical language (R Development Core Team 2018).

## Results

The distributions of 19 tree species from INFC2005 plots relative to TAP and MAT are graphically reported in Tab. 2 and Fig. 1 along with the comparisons to the potential limits for these variables reported by Bernetti (1995). In Fig. 1 a bi-dimensional graph for each species is presented, with MAT values as the *x*-axis and TAP as the *y*-axis. On the side opposite to the axes, density distribution graphs have been added to characterize the frequency of records across the analyzed ecological ranges. Asymmetric distributions were often observed, mainly for rainfall. This is confirmed by the skewness and smaller ranges for the histograms, *i.e.*, the distribution tails were often outside literature limits or were poorly characterized. The current observed MAT and TAP distribution limits for the 19 Italian forest tree species are reported in Fig. 2.

The spatial analysis shows that the climatic ranges proposed by Bernetti (1995)

**Tab. 2** - Results of the spatial overlay between INFC2005 plots and interpolated climatic data used in this study. (MinTmean, Tmean, MaxTmean): minimum, mean and maximum average annual temperatures, respectively; (MinPmean, Pmean, MaxPmean): minimum, mean and maximum average annual precipitation, respectively.

| Species | Temperature Range | | | Precipitation Range | | |
|---|---|---|---|---|---|---|
| | MinTmean | Tmean | MaxTmean | MinPmean | Pmean | MaxPmean |
| *Abies alba* | 2.10 | 8.03 | 15.78 | 676 | 1310 | 2002 |
| *Castanea sativa* | 3.80 | 11.76 | 17.20 | 669 | 1238 | 2257 |
| *Cupressus sempervirens* | 10.78 | 14.00 | 17.95 | 487 | 865 | 1359 |
| *Fagus sylvatica* | 3.07 | 9.15 | 15.78 | 742 | 1361 | 2708 |
| *Larix decidua* | -0.91 | 5.40 | 11.56 | 589 | 1067 | 1914 |
| *Picea abies* | -0.88 | 6.32 | 12.86 | 570 | 1170 | 2446 |
| *Pinus cembra* | 0.85 | 3.27 | 6.86 | 642 | 942 | 1213 |
| *Pinus halepensis* | 11.53 | 14.92 | 17.60 | 447 | 772 | 1310 |
| *Pinus laricio* | 9.46 | 11.81 | 15.20 | 752 | 1116 | 1543 |
| *Pinus nigra* | 5.44 | 11.31 | 16.11 | 663 | 1172 | 2441 |
| *Pinus pinaster* | 9.81 | 13.19 | 16.38 | 614 | 1039 | 1789 |
| *Pinus pinea* | 11.75 | 14.99 | 17.97 | 480 | 831 | 1345 |
| *Pseudotsuga menziesii* | 6.99 | 11.26 | 14.80 | 802 | 1261 | 1929 |
| *Quercus cerris* | 7.51 | 12.54 | 17.07 | 607 | 1011 | 1847 |
| *Quercus ilex* | 8.60 | 14.07 | 17.53 | 507 | 883 | 1529 |
| *Quercus petraea* | 5.78 | 11.73 | 16.18 | 546 | 1188 | 1999 |
| *Quercus pubescens* | 5.16 | 12.82 | 17.66 | 527 | 965 | 2098 |
| *Quercus robur* | 9.13 | 13.16 | 16.87 | 649 | 1002 | 1810 |
| *Quercus suber* | 12.37 | 15.00 | 18.01 | 473 | 751 | 1347 |

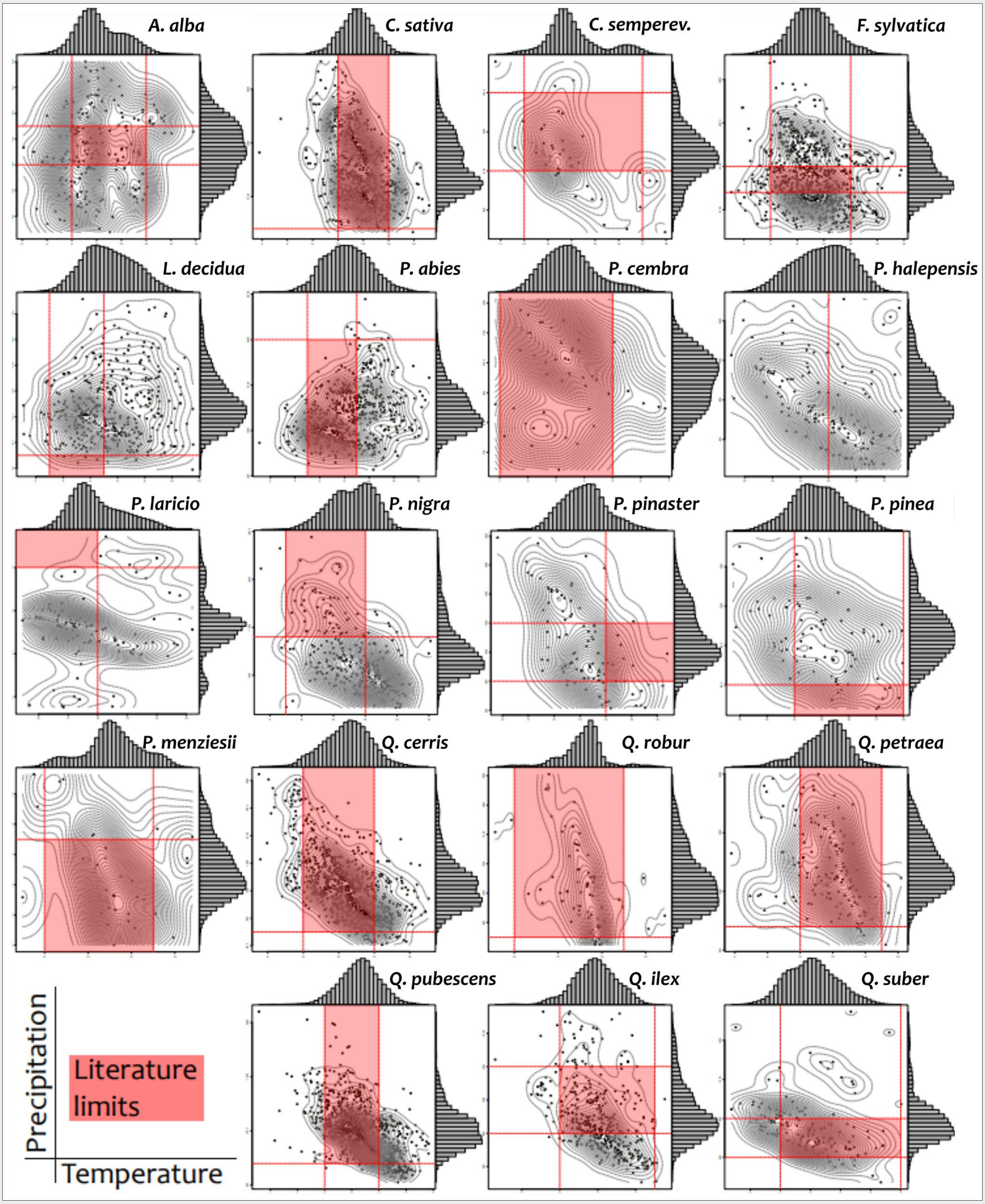

**Fig. 1** - Distribution of the 19 tree species in terms of average annual temperature (*x*-axis) and total annual precipitation (*y*-axis). The limits of the species' ecological range from the literature are highlighted as a red square. Marginal histograms represent the frequency distribution of records.

are generally appropriate. Of the total number of observations for the 19 species, 46% fall within the joint temperature and precipitation ranges, 70% fell within the ranges for TAP alone, and 80% fell within the ranges for MAT alone. Similarities between current observed and Bernetti (1995) potential ranges differed by species (Fig. 3). For the species of the *Fagaceae* family which represent almost the 70% of the observations, the limits of our current observed distributions are similar to the potential limits reported by Bernetti (1995): for all species of this family the current observed limits fell within the Bernetti

(1995) limits (Fig. 2). For the genus *Quercus*, at least 60% of the observations (with the exception of the most Mediterranean species, *Quercus ilex* and *Quercus suber*) were usually within the potential limits for both MAT and TAP. *Q. ilex* tends to grow in drier conditions than those described by Bernetti (1995) with current observed TAP of 883 mm *versus* a potential minimum of 800 mm, while *Q. suber* tends to be distributed in cooler and more humid areas than the potential limits of Bernetti (1995).

The current observed distribution of *Castanea sativa* is similar to the potential distribution, with 70% of the observations falling within both the temperature and precipitation potential limits. Also, for *Fagus sylvatica* the temperature limits are similar, while for precipitation the observations show that beech forests are also present in extremely rainy sites. From this perspective, the maximum potential TAP limit of 1500 mm reported by Bernetti (1995) is too low.

For the Pinaceae family the situation is different. For the genus *Pinus*, except for *Pinus cembra* where current observed and potential limits were similar, our results demonstrated that these species tend to grow in conditions that differ from the potential limits reported by Bernetti (1995). The limits of the current observed distribution of *Pinus pinea, Pinus nigra* and *Pinus laricio* are similar to the potential limits for temperature but not for precipitation. *Pinus pinea* tends to grow in conditions that are rainier than those predicted by Bernetti (1995) who report a maximum potential of 600 mm versus the current observed average of 831 mm. On the contrary, *Pinus nigra* and *Pinus laricio* are currently distributed in drier conditions than those reported by Bernetti (1995) with current observed TAP of 1172 and 1116 mm respectively for *P. nigra* and *P. laricio versus* a minimum potential of 1400 mm for both species.

The limits of the current observed distributions of *Pinus pinaster* and *Pinus halepensis* are generally similar to the potential precipitation limits but not the potential temperature limits. In fact, both these species tend to grow in warmer conditions than those reported by Bernetti (1995) with 14 °C and 15 °C as minimum MAT value reported by Bernetti (1995). *Abies alba* tends to be more plastic than reported by Bernetti (1995) in that it can be found in conditions with both more or less rainfall than the potentials. Bernetti (1995) reported a potential minimum TAP value of 1200 mm and a potential maximum of 1500 mm, while the observation averages are 1310 mm with minimum of 676 mm and maximum of 2002 mm. The current observed limits of the distributions for *Picea abies* are similar to the potential limits with almost all precipitation observations within the potential limits and almost 70% of the temperature observations within the potential limits. *P. abies* also tends to grow in slightly warmer conditions than the potential with observed MAT of 6.3 °C which is very close to the maximum limit of 7 °C reported by Bernetti (1995).

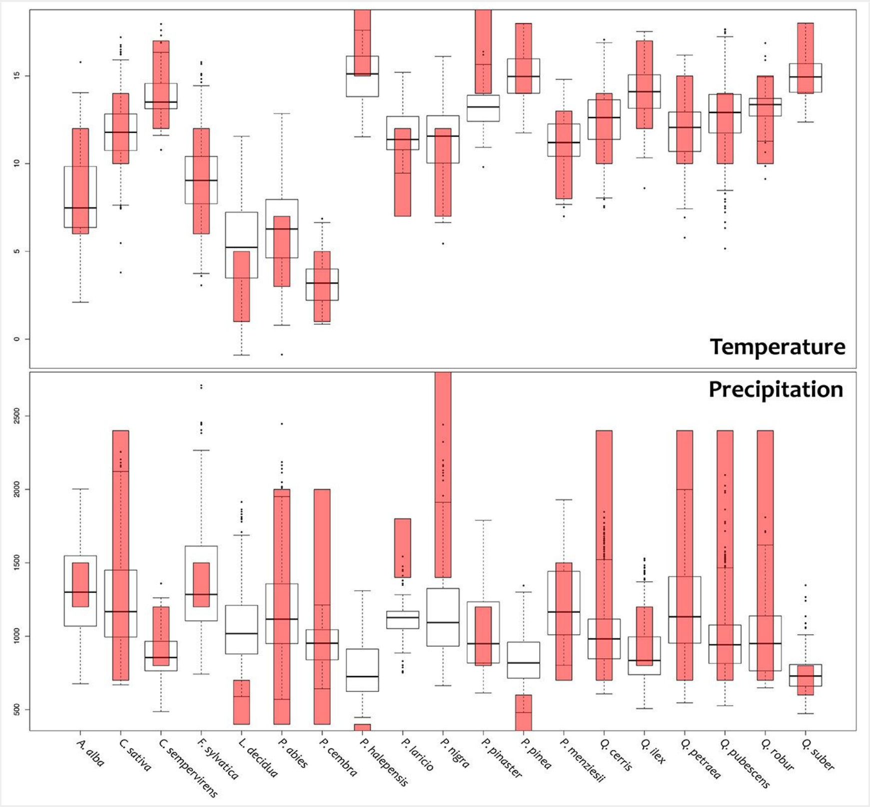

**Fig. 2** - Box-plots for temperature (above) and precipitation (below) values retrieved from INFC data for the 19 different forest tree species. The limits of the species' ecological range retrieved from the literature are reported as red rectangles.

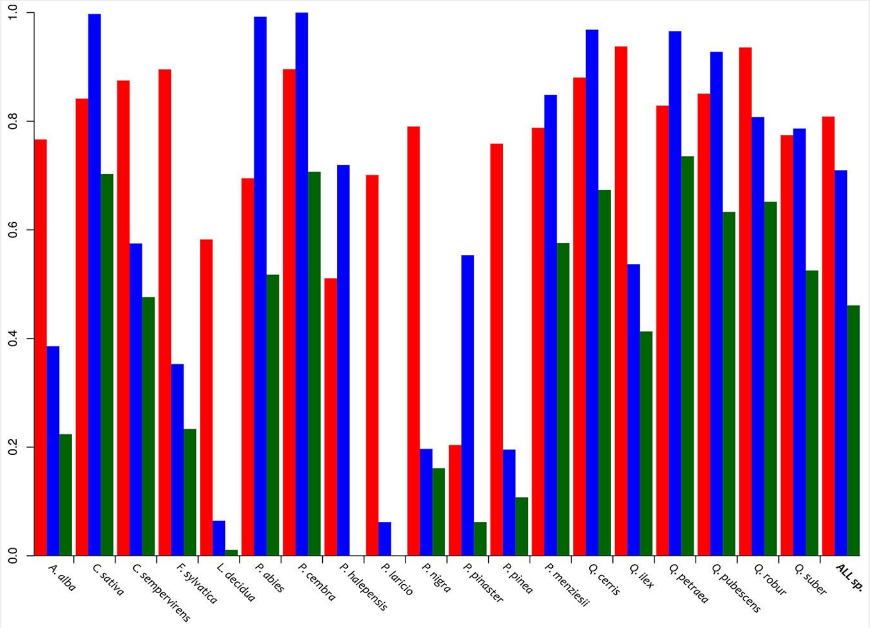

**Fig. 3** - Proportion of observations falling within the ecological range from the literature for each species and the whole dataset ("All sp.") concerning temperature (red), precipitation (blue) and both (green).

*Larix decidua* tends to grow in warmer and more humid conditions than those reported by Bernetti (1995). For precipitation the current observed average was 1067 mm *versus* a potential maximum of 700 mm, while for temperature the current observed average was 5.4 °C *versus* 5 °C as the potential maximum.

Finally, for *Cupressus sempervirens* current observed and potential distributions were generally similar, especially for temperature for which almost 90% of the observations were within the potential limits.

## Discussion

Traditional knowledge about potential climatic limits for Italian forest tree species was found to be only partially consistent with the data we derived from the current observed spatial distributions, particularly for some species of the *Pinaceae* family. Unfortunately, it is difficult to determine if these inconsistencies are due to inadequate characterisations of species potential limits or to the results of forest management and reforestation programmes (Cantiani & Marchi 2017, Del Perugia et al. 2017). Actually, foresters often distributed forest tree species beyond their geographical limits (*i.e.*, the expected ecological domain), especially after the First and the Second World Wars. In addition, it is important to note that such particular are represented, in our analysis, by a relatively limited number of observations from the NFI database and that some uncertainties may arise from the mappings of the climatic data. In particular, temperature is generally easier to map than rainfall whose distribution is more irregular and has a more complex dependence on altitude (Maselli et al. 2012). This problem was partly addressed for this study using the correction proposed by Fibbi et al. (2016), thereby reducing the inaccuracy of the rainfall estimates where the density of the original E-OBS stations was small.

To frame our results in a European context, a simple graphical comparison has been conducted using graphs provided in the JRC European Atlas of forest tree species (San-Miguel-Ayanz et al. 2016). However, as already mentioned, no tables neither numerical supplementary data were delivered in addition to the full text file and the comparison was possible for all the species with some exceptions. This has been performed in order to include the "Italian forests" in a broader context. *Pinus laricio* is absent from the European Atlas, while *Quercus petraea* and *Quercus robur* are grouped therein as well as *Pinus halepensis* and *Pinus brutia*. The comparison is, therefore, only indicative and is reported here simply to provide hints about the comparison of Italian population relative to Europe populations. Indeed, sensible differences are possible between different meteorological data used. Nonetheless, italian tree species populations are generally within European Atlas limits, with some exceptions. Moreover, the climatic ranges that we observed in Italy are narrower than the Europe ranges for some species (as expected given the smaller study area), particularly for temperature. Concerning rainfall, a restricted range is clearly detectable for Italian populations of stone pine, Douglas fir and peduncolate oak for which Italian minima are greater than European minima, while the Italian maxima are less than the European maxima. Italian populations of arolla pine, Mediterranean cypress, cork oak and Norway spruce grow in conditions that are drier than the European range limit. The Italian populations of common chestnut, European beech, Turkey oak, black pine, maritime pine and Downy oak seem to be slightly shifted to more humid conditions, with Italian minima and maxima greater than the European limits. Finally, the observed precipitation ranges for Italian Silver fir populations were greater than the ranges reported in the European Atlas. For the other species differences relative to the European Atlas were less relevant.

Regarding temperature, the ecological range of Italian populations of the genus *Quercus* was shifted to slightly warmer conditions relative to European populations, with Italian climatic minima for these species greater than the European minima. Climatic maxima for Italian and European populations were similar, except for sessile and pedunculate oaks for which the Italian climatic maxima were greater than the European maxima. A similar situation was observed for species of the genus *Pinus* (black pine, maritime pine and stone pine), Mediterranean cypress and Douglas Fir.

As for European larch, Norway spruce and Arolla pine, European populations are located in slightly colder areas than Italian populations, with European climatic minima greater than Italian minima. Finally, Italian populations of common chestnut are shifted to slightly colder conditions relative to European populations with the current observed Italian temperature minimum smaller than the corresponding European minimum.

In recent years, marginal and peripheral forest populations have gained unique importance with respect to information they provide regarding the potential of forest tree species to adapt to ecological stresses (Hampe & Petit 2005). The new quantitative data provided by this study can be used to identify stands that may be adversely affected by the effects of climate change effects earlier than those located in the core of the geographic distribution. This information can be fundamental in Italy and more generally in the Mediterranean region, both of which are considered important European biodiversity hotspots featuring unique species richness (Médail & Quézel 1997, Hampe & Petit 2005, Marchi & Ducci 2018). Moreover, the Mediterranean region is also considered to be seriously threatened by future climate change effects (Resco De Dios et al. 2007, Lelieveld et al. 2012). Mediterranean trees species are classified among many different taxa with a large biodiversity levels that, in part, originated as adaptive responses to previous climate changes ( Benito Garzón et al. 2007). Indeed, many recent research efforts have focused on populations living at marginal ecological domains in the Mediterranean region (Hampe & Petit 2005, Marchi et al. 2016). Both biodiversity conservation and sustainable forest management issues may be supported by the results of this study. Besides conservation, inaccurate characterization of environmental conditions characteristic of current growing zones may produce inaccurate future projections of ecosystem services and timber from productive forests, and consequently a loss of economic return (Ray et al. 2017). In such a context, the recently released georeferenced raw data from the last Italian NFI (Borghetti & Chirici 2016) represent a new source of consistent, empirical big-data in the form of real information regarding climatic and growth conditions for the most important Italian forest trees species that circumvents the traditional reliance on expert opinion and out-dated observations. In addition to climatic conditions, soil attributes, which are also a fundamental for describing forest species distributions, can mitigate or amplify climatic drivers (Bréda et al. 2006, Van Der Maaten-Theunissen et al. 2016). Future analyses should also consider features such as soils, but a consistent source of quantitative soil information at the national level is still not publicly available in Italy.

## Conclusions

For 7,272 plots of the Italian National Forest Inventory, we calculated average annual temperatures and precipitation from 1 km resolution climatic data. Using these data, we compared the current observed ecological distribution of the 19 most important tree species in Italy to the expert knowledge potential limits reported by Bernetti (1995). We found that climatic limits and potential information should be probably revised for some of the species, particularly for some conifers and more frequently for precipitation data.

The public availability of georeferenced, national forest inventory (NFI), plot-level data is fundamental for ecological forest studies (Corona et al. 2011). Further evidence concerning growth trends provided by the next inventory cycle, INFC 2015 which is still in progress, will increase the knowledge about existing adaptive traits across Italy and will allow comparison among and within the plots. On the other side, new interpolation techniques and methodological research on climate may increase accuracy and precision with respect to climatic information. Knowledge of the actual distribution of forest species and ecological niches is fundamental for both spatial and process-based simulation models used to deal with future scenarios. Thus, this study should motivate more detailed analyses on species distribution which could be used to identify country-level, future forest management strategies.

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## References

Allen CD, Macalady AK, Chenchouni H, Bachelet D, McDowell N, Vennetier M, Kitzberger T, Rigling A, Breshears DD, Hogg EHT, Gonzalez P, Fensham R, Zhang Z, Castro J, Demidova N, Lim JH, Allard G, Running SW, Semerci A, Cobb N (2010). A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. Forest Ecology and Management 259: 660-684. - doi: 10.1016/j.foreco.2009.09.001

Benito Garzón M, Sánchez De Dios R, Sáinz Ollero H (2007). Predictive modelling of tree species distributions on the Iberian Peninsula during the Last Glacial Maximum and Mid-Holocene. Ecography 30: 120-134. - doi: 10.1111/j.2006.0906-7590.04813.x

Bernetti G (1995). Selvicoltura speciale [Special silviculture]. UTET, Torino, Italy, pp. 415. [in Italian]

Boisvert-Marsh L, Périé C, De Blois S (2014). Shifting with climate? Evidence for recent changes in tree species distribution at high latitudes. Ecosphere 5: art83. - doi: 10.1890/ES14-00111.1

Borghetti M, Chirici G (2016). Raw data from the Italian National Forest Inventory are on-line and publicly available. Forest@ 13: 33-34. [in Italian with English summary] - doi: 10.3832/efor0083-013

Bravo-Oviedo A, Pretzsch H, Ammer C (2014). European mixed forests: definition and research perspectives. Forest Systems 23: 518-533. - doi: 10.5424/fs/2014233-06256

Bréda N, Huc R, Granier A, Dreyer E (2006). Temperate forest trees and stands under severe drought: a review of ecophysiological responses, adaptation processes and long-term consequences. Annals of Forest Science 63: 625-644. - doi: 10.1051/forest:2006042

Canadell JG, Raupach MR (2008). Managing forests for climate change mitigation. Science 320: 1456-1457. - doi: 10.1126/science.1155458

Cantiani P, Marchi M (2017). A spatial dataset of forest mensuration collected in black pine plantations in central Italy. Annals of Forest Science 74: 50. - doi: 10.1007/s13595-017-0648-8

Chirici G, Bottalico F, Giannetti F, Del Perugia B, Travaglini D, Nocentini S, Kutchartt E, Marchi E, Foderi C, Fioravanti M, Fattorini L, Bottai L, McRoberts RE, Corona P, Gozzini B (2017). Assessing forest windthrow damage using single-date, post-event airborne laser scanning data. Forestry 1-11. - doi: 10.1093/forestry/cpx029

Corona P (2015). Forestry research to support the transition towards a bio-based economy. Annals of Silvicultural Research 38: 37-38. - doi: 10.12899/asr-1015

Corona P, Chirici G, McRoberts RE, Winter S, Barbati A (2011). Contribution of large-scale forest inventories to biodiversity assessment and monitoring. Forest Ecology and Management 262: 2061-2069. - doi: 10.1016/j.foreco.2011.08.044

De Philippis A (1937). Classificazioni ed indici del clima in rapporto alla vegetazione forestale italiana [Classifications and indices of the climate in relation to the Italian forest vegetation]. Nuovo Giornale Botanico Italiano 44: 1-169. [in Italian]

Del Favero R (2004). I boschi delle regioni alpine italiane: tipologia, funzionamento, selvicoltura [The woods of Italian Alpine regions: typology, functioning, silviculture]. CLEUP, Padua, Italy, pp. 600. [in Italian]

Del Favero R (2008). I boschi delle regioni meridionali e insulari d'Italia: tipologia, funzionamento, selvicoltura [The woods of southern and insular regions of Italy: typology, functioning, silviculture]. CLEUP, Padua, Italy, pp. 472.

Del Favero R (2010). I boschi delle regioni dell'Italia centrale: tipologia, funzionamento, selvicoltura [The wood of central regions of Italy: typology, functioning, silviculture]. CLEUP, Padua, Italy, pp. 426. [in Italian]

Del Perugia B, Travaglini D, Bottalico F, Nocentini S, Rossi P, Salbitano F, Sanesi G (2017). Are Italian stone pine forests (*Pinus pinea* L.) an endangered coastal landscape? A case study in Tuscany (central Italy). Italian Journal of Forest and Mountain Environments 72: 103-121. - doi: 10.4129/ifm.2017.2.01

Di Biase RM, Fattorini L, Marchi M (2018). Statistical inferential techniques for approaching forest mapping. A review of methods. Annals of Silvicultural Research 42 (2): 46-58. - doi: 10.12899/asr-1738

Ferrara C, Marchi M, Fares S, Salvati L (2017). Sampling strategies for high quality time-series of climatic variables in forest resource assessment. iForest - Biogeosciences and Forestry 10: 739-745. - doi: 10.3832/ifor2427-010

Fibbi L, Chiesi M, Moriondo M, Bindi M, Chirici G, Papale D, Gozzini B, Maselli F (2016). Correction of a 1 km daily rainfall dataset for modelling forest ecosystem processes in Italy. Meteorological Applications 23: 294-303. - doi: 10.1002/met.1554

Fick SE, Hijmans RJ (2017). WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. International Journal of Climatology 37: 4302-4315. - doi: 10.1002/joc.5086,

Giannetti F, Barbati A, Mancini L, Travaglini D, Bastrup-Birk A, Canullo R, Nocentini S, Chirici G (2018). European Forest types: toward an automated classification. Annals of Forest Science 75: 6. - doi: 10.1007/s13595-017-0674-6

Hampe A, Petit RJ (2005). Conserving biodiversity under climate change: the rear edge matters. Ecology Letters 8: 461-467. - doi: 10.1111/j.1461-0248.2005.00739.x

Haylock MR, Hofstra N, Klein Tank AM, Klok EJ, Jones PD, New M (2008). A European daily high-resolution gridded data set of surface temperature and precipitation for 1950-2006. Journal of Geophysical Research 113 (D20): 1691. - doi: 10.1029/2008JD010201

IPCC (2001). climate change 2001: the scientific basis. Contribution of Working Group I to the Third Assessment Report of the Interngovernmental Panel on Climate Change (Houghton, JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA eds). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 881.

IPCC (2014). Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Field CB, Barros VR, Dokken DJ, Mach KI, Manstrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL eds). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1132.

Iverson LR, Prasad AM, Matthews SN, Peters M (2008). Estimating potential habitat for 134 eastern US tree species under six climate scenarios. Forest Ecology and Management 254: 390-406. - doi: 10.1016/j.foreco.2007.07.023

Johnson KD, Birdsey R, Finley AO, Swantaran A, Dubayah R, Wayson C, Riemann R (2014). Integrating forest inventory and analysis data into a LIDAR-based carbon monitoring system. Carbon Balance and Management 9: 1-11. - doi: 10.1186/1750-0680-9-3

Lelieveld J, Hadjinicolaou P, Kostopoulou E, Chenoweth J, El Maayar M, Giannakopoulos C, Hannides C, Lange MA, Tanarhte M, Tyrlis E, Xoplaki E (2012). Climate change and impacts in the Eastern Mediterranean and the Middle East. Climatic Change 114: 667-687. - doi: 10.1007/s10584-012-0418-4

Lindner M, Maroschek M, Netherer S, Kremer A, Barbati A, Garcia-Gonzalo J, Seidl R, Delzon S, Corona P, Kolström M, Lexer MJ, Marchetti M (2010). Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. Forest Ecology and Management 259: 698-709. - doi: 10.1016/j.foreco.2009.09.023

Marchetti M, Vizzarri M, Lasserre B, Sallustio L, Tavone A (2015). Natural capital and bioeconomy: challenges and opportunities for forestry. Annals of Silvicultural Research 38: 62-73. - doi: 10.12899/asr-1013

Marchi M, Ducci F (2018). Some refinements on species distribution modelling using tree-level National Forest Inventories for supporting forest management and marginal forest population detection. iForest - Biogeosciences and Forestry 11: 291-299. - doi: 10.3832/ifor2441-011

Marchi M, Nocentini S, Ducci F (2016). Future scenarios and conservation strategies for a rear-edge marginal population of *Pinus nigra* Arnold in Italian central Apennines. Forest Systems 25: e072. - doi: 10.5424/fs/2016253-09476

Maselli F, Pasqui M, Chirici G, Chiesi M, Fibbi L, Salvati R, Corona P (2012). Modeling primary production using a 1 km daily meteorological data set. Climate Research 54: 271-285. - doi: 10.3354/cr01121

Mauri A, Strona G, San-Miguel-Ayanz J (2017). EU-Forest, a high-resolution tree occurrence dataset for Europe. Scientific Data 4: 160123. - doi: 10.1038/sdata.2016.123

Médail F, Quézel P (1997). Hot-spots for conservation of plant diversity in the Mediterranean Basin. Annals of the Missouri Botanical Garden

84: 122-127.

Nocentini S, Buttoud G, Ciancio O, Corona P (2017). Managing forests in a changing world: the need for a systemic approach. A review. Forest Systems 26 (1): eR01. - doi: 10.5424/fs/2017261-09443

Pavari A (1916). Studio preliminare sulla coltura di specie forestali esotiche in Italia. Prima parte generale [Preliminary study on the cultivation of exotic forest species in Italy. First general part]. Annali del Regio Istituto Superiore Nazionale Forestale vol. I - 191, pp. 221. [in Italian]

Pedrotti F (2013). Geobotanical mapping and its levels of study. In: “Plant and Vegetation Mapping. Geobotany Studies (Basics, Methods and Case Studies)”. Springer- Verlag Berlin Heidelberg, Germany, pp. 1-6. - doi: 10.1007/978-3-642-30235-0_1

Petr M, Boerboom L, Ray D, Van Der Veen A (2014). An uncertainty assessment framework for forest planning adaptation to climate change. Forest Policy and Economics 41: 1-11. - doi: 10.1016/j.forpol.2013.12.002

R Development Core Team (2018). R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. [online] URL: http://www.r-project.org

Ray D, Petr M, Mullett M, Bathgate S, Marchi M, Beauchamp K (2017). A simulation-based approach to assess forest policy options under biotic and abiotic climate change impacts: a case study on Scotland’s National Forest Estate. Forest Policy and Economics [in press]. - doi: 10.1016/j.forpol.2017.10.010

Resco De Dios V, Fischer C, Colinas C (2007). Climate change effects on mediterranean forests and preventive measures. New Forests 33: 29-40. - doi: 10.1007/s11056-006-9011-x

San-Miguel-Ayanz J, De Rigo D, Caudullo G, Durrant HT, Mauri A (2016). European atlas of forest tree species. Publication Office of the European Union, Luxembourg, pp. 202. - doi: 10.2788/4251

Ummenhofer CC, Meehl GA (2017). Extreme weather and climate events with ecological relevance: a review. Philosophical Transactions of the Royal Society B: Biological Sciences 372: 20160135. - doi: 10.1098/rstb.2016.0135

Van Der Maaten-Theunissen M, Bümmerstede H, Iwanowski J, Scharnweber T, Wilmking M, Van Der Maaten E (2016). Drought sensitivity of beech on a shallow chalk soil in northeastern Germany - a comparative study. Forest Ecosystems 3: 24. - doi: 10.1186/s40663-016-0083-6

Wagner S, Nocentini S, Huth F, Hoogstra-Klein M (2014). Forest Management Approaches for Coping with the Uncertainty of Climate Change: Trade-Offs in Service Provisioning and Adaptability. Ecology and Society 19: 397-412. - doi: 10.5751/ES-06213-190132

Williams MI, Dumroese RK (2013). Preparing for climate change: forestry and assisted migration. Journal of Forestry 111: 287-297. - doi: 10.5849/jof.13-016