Sweet chestnut (*Castanea sativa* Mill.) bioclimatic suitability in Central Italy: future potential scenarios under climate change

Journal:	*Annals of Silvicultural Research*
Manuscript ID	ASR-2023-0003.R2
Manuscript Type:	Research Paper
Date Submitted by the Author:	10-May-2023
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Keywords:	Species Distribution Modeling (SDMs), Bioclimatic predictors, Chestnut

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Abstract

The ecological and economic relevance of sweet chestnut (*Castanea sativa* Mill.) has long been related to its wide geographical distribution and multipurpose products potential. In Central Italy and especially in Latium, sweet chestnut finds optimal environmental conditions for growth, supported by the application of traditional silvicultural practices. Thus, its distribution has been radically modified and controlled by man in order to manage it in profitable and diversified ways (e.g., by coppices or orchards) to produce a wide range of ecosystem services, marketable (wood, fruits) and not marketable (landscape, water regulation, etc.) products. Over the years, due to climate change, some productivity changes have been observed and new challenges are expected to manage and cultivate this species. Based on this background, this work aims at investigating the possible impacts of climate change on sweet chestnut in Central Italy in medium (2041-2060) and long term (2081-2100). Adopting a standard protocol for reporting species distribution model (ODMAP - Overview, Data, Model, Assessment, Prediction), four Earth System Models have been combined into two Shared Socio-economic Paths and two Time Horizons, to produce potential chestnut bioclimatic suitability maps. The outlined scenarios represent valuable information for future chestnut policy and management for defining specific strategies, considering the adaptive capacity of the species in terms of resilience from pathogenic attacks and response to innovative silvicultural treatments.

Keywords: Species Distribution Modeling (SDMs), bioclimatic predictors, climate change, chestnut, silvicultural treatments.

Introduction

Forests are critically important for climate, biodiversity and human well-being, providing a vast amount of inter-related ecosystem services (e.g., carbon sequestration, recreation, biodiversity conservation, timber production, soil and natural hazard protection) which can define forest multifunctionality (Ammer 2018). Among European species, sweet chestnut (*Castanea sativa* Mill., here thereafter, chestnut) is an important species for the inland forests, and marginal (disadvantaged) areas in Italy, as well as a valuable food resource, which has accompanied the evolution of the human population over the centuries (Bounous 2005, Ministry of Agricultural Food and Forestry Policy 2008, 2010, Angelini et al. 2013). Therefore, its distribution has been radically modified and controlled by humans over the years, in order to manage it in profitable and diversified ways (e.g., by coppices or orchards) and produce a wide range of easily marketable (wood, fruits) and not marketable (landscape, water regulation, etc.) products (Mattioli et al. 2016, Carbone et al. 2020). Due to the increased worldwide demand for chestnut nuts in the last decade (FAOSTAT 2022) linked to their nutritional characteristics (Massantini et al. 2021) and the increasing interest in chestnut timber, both the planting of new chestnut stands and the recovery of suitable abandoned chestnut areas is advisable (Rossi et al. 2023).

Chestnut tree development and growth is largely influenced by several pedoclimatic factors, such as physical-chemical characteristics of the soil, orography, soil water distribution, and climatic conditions (Freitas et al. 2022). In Central Italy, chestnut finds optimal growth conditions, mainly on volcanic soils, and it is subject to the application of traditional silvicultural practice of coppicing. Forest management of chestnut coppices is based on short rotation (commonly, 14–16 years, with a single thinning – not always carried out – at half of the rotation age) in monospecific even-aged stands, clearcut on large areas, release of 30–80 standards per hectare, with the main purpose to profitably yield valuable wood assortments (poles and beams) (Mattioli et al. 2016). Concerning standards release, Manetti et al. (2022) demonstrate the uselessness of this practice in chestnut coppices devoted to quality wood production, except when other high value tree species are present and may be considered (Fabbio 2016, Manetti et al. 2016, Manetti et al. 2022) or when it is necessary to protect against shallow landslides located along steep slopes: in this case, also Dazio et al. (2018) suggest simple coppicing (no standards release) as the most suitable silvicultural system for chestnut.

The potential naturalness of chestnut stands has been recognized by the European Community Natura 2000 network (EU Council Directive 1992), which has declared both the chestnut-dominated forests and the long-established chestnut plantations with semi-natural undergrowth relevant habitats (9260: *Castanea sativa* woods) for biodiversity conservation (EC 2007). In addition, several studies have shown their high ecological importance in supporting biodiversity (e.g., Gondard and Romane 2005, Gondard et al. 2006, Mattioli et al. 2008, Pezzi et al. 2011, Guitian et al. 2012, Zlatanovet al. 2013, Mattioli et al. 2016, Corona et al. 2017, Manetti et al. 2017; 2020). Thus, a strong scientific debate persists on the trade-off between forest management for multifunctionality and biodiversity conservation (Ammer 2018), especially in recent years, where, due to climate change, some productivity changes have been observed and new challenges are expected. Distinctively, various stressors (both natural and anthropogenic) such as abandonment of traditional orchards, wildfire, and increased incidence of pests and diseases, are threatening chestnut stands (Bellat et al. 2019). Moreover, biodiversity is particularly affected by climate change in terms of species distribution, migration, and genetic variability (Borghetti et al. 2012). Accordingly, different scenarios on forest ecosystems were defined from regional (Ruiz-Labourdette et al. 2012, Jantsch et al. 2014, Hansen and Phillips 2015), to national (Woodall et al. 2010, García-López and Allué 2011, Garcia et al. 2013, Corda et al. 2014) and supranational scale (Iverson et al. 2008, Hickler et al. 2012, Meier et al. 2012, Tanaka et al. 2012, Casazza et al. 2014), including patterns of pests and diseases associated with chestnuts that may also shift with climate change (Dinis et al. 2011, Santos et al. 2017, Larue et al. 2021). As suggested by Fraga et al. (2020) and Freitas et al. (2022), where warmer temperatures accompanied by recurrent and intensified extreme events, such as severe rainfall events, droughts, or heatwaves are also expected, production damages in the upcoming decades will increase.

However, in the debate about tree species suited to cope with the ongoing global changes, sweet chestnut is frequently discussed as a potentially future-proof tree species for Central Europe (Conedera et al. 2021), mainly for its current southern distribution range, which corresponds climatically to what is expected for Central Europe in the near future. This suggestion is typically derived from Species Distribution Models (SDMs; Guisan and Zimmermann 2000, Elith and Leathwick 2009, Naimi and Araújo 2016, Noce et al. 2019) that use species occurrence data to infer the environmental envelope in which a species can potentially persist (Thurm et al. 2018). For chestnut, such static approaches to defining future ranges are particularly challenging since the ‘chestnut civilization’ has had a significant impact on both the present distribution and the structure of species in forests (Conedera et al. 2021). For instance, as Zlatanov et al. (2013) suggested, SDMs typically ignore biotic interactions and successional dynamics and thus may not reflect that in the absence of forest management, chestnut could become outcompeted by other species.

Based on this background, our study aims to provide some clues on how climate change may impact the environmental suitability of chestnut in Central Italy, as well as to offer an overview of the possible adaptation measures (medium and long term) that are currently available for chestnut. Latium region was chosen as study area for the following reasons: *(i)* high presence of chestnut stands (Gasparini et al. 2022; ISTAT 2023); *(ii)* chestnut can be considered a native species on the volcanic hills of the region (Krebs et al. 2004, 2019); *(iii)* many of the pests and diseases that have affected chestnut trees, even due to climate changes, are well known and efficiently contained and mitigated by specific management approaches (Vettraino et al. 2005, Spina and Romagnoli 2010); *(iv)* chestnut chain is the most relevant socio-economic regional forest chain; *(iv)* this location shows a paradigmatic example of the potential conflicts between chestnut stands services (productive and environmental); (v) chestnut presence is located in areas rather homogeneous in terms of vegetation, soils, and climate.

Finally, this paper intends to develop predictions in the next decades on a local scale and to give more detailed knowledge regarding the species and its suitability for future, in order to support new policies and management options for defining specific strategies, considering the adaptive capacity of the species in terms of resilience from pathogenic attacks and response to silvicultural treatments.

Materials and Methods

Study area

According to the last Italian National Forest Inventory (Gasparini et al. 2022), in Italy chestnut forests cover an area of about 780,000 ha, mainly (70%) managed as even-aged coppices for poles, timber production for constructing buildings or other structural elements (Carbone et al. 2020), and the remaining 30% as orchards for fruit production, growing preferably between 400 and 1,000 m s.l.m., preferring oceanic climates and areas not subjected to excessive thermal variations. Particularly, on the pre-Apennine volcanic reliefs of Latium chestnut finds its environmental optimum (Mattioli et al. 2016, Corona et al. 2017) rather homogeneous in terms of vegetation (*Doronico-Fagion* phytosociological alliance, with ingression of acidophilic elements of the *Quercetalia robori-petraeae* phytosociological order), soils (fertile, volcanic, deep and loose with acid pH, mainly classified as andisols and identified as “black soil”) and bioclimate (mesomediterranean sub-humid) (Blasi et al. 2004), covering an area of about 36,000 ha (Gasparini et al. 2022, ISTAT 2023).

Model approach

We applied a SDMs approach, a set of algorithms for processing and extrapolating species distributions based on quantitative or rule-based models (e.g., Guisan and Zimmermann 2000, Guisan and Thuiller 2005, Elith and Leathwick 2009) to chestnut stands in Latium. SDMs are also known as bioclimatic envelope models, correlative ecological niche models, or habitat suitability models, because they explore the relationships and the equilibrium between the geographical distribution of species and a set of environmental variables (Guisan and Zimmermann 2000, Austin 2002, Peterson et al. 2011).

Here, the Overview/Conceptualization, Data, Model fitting, Assessment and Prediction (ODMAP) - standard protocol, described in Zurell et al. (2020), was applied.

This is a standard protocol for reporting SDMs to improve their method reproducibility, ensuring transparency and consistency in their development and application, which consists of the five basic modeling steps that provide its name. Each step (section) contains unique information that clarify and present the data and the method applied in this research (Zurell et al. 2020). In Table 1 we identified and showed eleven obligatory subsections of Overview section.

[Here Table 1]

The potential distribution of chestnut under the effect of climate change in the medium and long term has been simulated using the Maximum Entropy (MaxEnt) algorithm (ver. 3.4.2). The MaxEnt algorithm (developed for SDMs) is a machine learning method that iteratively trains multiple models on presence-only data and bases its choice on the one that presents the maximum entropy on the set of calibration data (training). Among the modeling approaches, MaxEnt is widely used because of its good performance with small sample sizes, compared to other modeling methods (Philips and Dudik 2008, Babalik et al. 2021). It is a general-purpose method for making predictions or inferences from incomplete information, which minimizes the relative entropy between two probability densities (one estimated from the presence data and one, from the landscape) defined in covariate space (Phillips et al. 2006). Moreover, it has a simple and precise mathematical formulation, designed to accept presence-only data as input. On the other hand, it has limited geostatistical functionality, so it is necessary to pre-process the data in GIS environment, as well as post-processing the results.

Pre-processing and SDM calibration

The MaxEnt algorithm needs two kinds of input data: presence-only data (species data), topographic and bioclimatic predictors (Fig. 1).

[Here Fig. 1]

Presence-only data is a list made by geo-localized points with the presence of chestnut in Latium, that has been extracted from a “Chestnut map” obtained through Qgis 3.4 Madeira software by selecting chestnut polygons (a layer with the chestnut surfaces in Latium) within the forest type map available at “Geoportal of Latium” (https://geoportale.regione.lazio.it/geoportale/).

With the need to geolocate chestnut stations in Latium in a format that MaxEnt could use, the “Chestnut map” was superimposed with an empty 30 arc-seconds regular grid (about 1 x 1 km) and the cells containing chestnut surfaces have been selected. The polygons containing chestnut surfaces within the map were converted into a layer made by the centroids of the selected cells, and then it was converted into a geolocalized file of chestnut presence useful for Maxent (csv file of the chestnut locations).

Nineteen Bioclimatic Predictors (19 BPs) and elevation data have been extracted from WorldClim (https://www.worldclim.org/data/cmip6/cmip6_clim2.5m.html), a database full of high spatial resolution global weather and climate data that can be used for spatial mapping and modeling. BPs have been evaluated for the calibration phase of SDMs (Tab-2; Fig. 1, at the spatial resolution of 2.5minutes (about 4.5 km at the equator) in order to develop a model with the current chestnut distribution area available in the “WorldClim” dataset for the years 1970-2000 (assumed as actual/historic situation) (https://www.worldclim.org/data/worldclim21.html).

[Here Table 2]

Therefore, data were extracted with a buffer of around 1.25 minutes (half the resolution of the BPs) within the study area, in order to also include the chestnut stands located at the borders of the study area itself.

Simulations accuracy

The accuracy of the simulations executed has been evaluated with the analysis of ROC curve ("Receiver Operating Characteristic") as described by Swets (1988). ROC curves are used to evaluate the predictive performance of a model based on a response variable; in this case, it has been taken into consideration the only-presence data of the species (as described in the previous paragraph) based on the 30 arc-seconds regular grid assumed as actual/historic situation. The area subtended by the ROC curve, called AUC (Area Under the Curve), is an index of the model quality: the greater the area subtended by the curve, the greater the discriminating power of the model (Phillips et al. 2006). The range of values that AUC can take is between 0.5 (minimum accuracy) and 1.0 (maximum accuracy).

To calculate the degree of agreement between the different simulations we produced two additional maps ("Degree agreement maps"), discussed in the results, which show the Relative Standard Deviation (RSD), considered as the ratio between standard deviation and the mean of percentage anomalies, for each time horizon considered.

Future projection

The Coupled Model Intercomparison Project phase 6, taken in the Sixth Assessment Report (AR6) of the IPCC climate report 2022 (Kikstra et al. 2022) uses a new generation of scenarios called the "Shared Socioeconomic Pathways" (SSPs; see "Parting of the pathways"): these are five socio-economic and technological trajectories that world could follow this century by the change of several factors, such as population, technological and economic growth, and could lead to significantly different future emissions and warming outcomes, even without climate policy. Each trajectory has a baseline in which no climate policies are enacted after 2010 - resulting in between 3°C and 5°C of warming above pre-industrial levels by 2100.

These five SSPs are processed in “WorldClim” database for nine different ESMs that develop climate forecasts to understand climate and predict future climate change.

Hausfather and Peters (2020) suggest that climate impact studies using models developed for AR6 should include scenarios that reflect plausible outcomes, such as SSP2-4.5, SSP4-6.0 and SSP3-7.0 (defined “possible futures”) and therefore, clearly outline the climate impacts for 3°C in addition to those for 5°C.

To predict the future distribution in the medium and long term according to Kikstra et al. (2022), a reference was made to the following four (of the nine above-mentioned) ESMs: CNRM-ESM2-1, CanESM5, MIROC-ES2L, MRI-ESM2-0, led by two chosen intermediate scenarios that assume as plausible a temperature increases of 2.5°C (SSP2-4.5) and 4°C (SSP3-7.0) (Fig. 2).

[Here Fig. 2]

Following the calibration process, and assuming topographic predictors unchanged, we used the same spatial resolution of 2.5 minutes (about 4.5 km at the equator). The medium and long term period, used for the transfer or projection of data, defined as Time Horizons (THs) are: 2041-2060 and 2081-2100. These two THs have been chosen among the four time horizons available in “WorldClim” database (2021-2040; 2041-2060; 2061-2080 and 2081-2100).

The climatic ensemble approach adopted for future projections (Fig. 2) assumes that the nineteen used predictors (19 BPs), adequately developed and defined for the study area, have been used for four ESMs and two SSPs, and simulated in the two Time Horizons (THs): 2041-2060 and 2081-2100. For both THs, eight maps were firstly produced (four ESMs * two SSPs) and then aggregated in two final maps, showing likely scenarios of chestnut bioclimatic suitability projected in medium and long term. Future scenarios are constructed by calculating the percentage anomaly of ensemble (“Percentage anomalies maps”) as the difference between the average “future” values for each TH (2041-2060 and 2081-2100) compared to the control period (1970-2000).

Simultaneously, MaxEnt returns a table with the percentage estimates of the relative contributions of each BP to the distribution model. Based on these results, the three most relevant BPs are selected and used to calculate the anomaly of each of these predictors and to compare them with the "Percentage anomalies maps" in order to analyze the future distribution of chestnut bioclimatic suitability in relation to the BPs most contributive to the model and produce the final maps.

Results

Output data validity

The ROC curves have been processed and grouped according to the four ESMs and the two SSPS. All models used have an AUC > 0.7 (Fig. 3).

[Here Fig. 3]

The "Degree agreement maps" produced are shown in Figure 4 and Figure 5.

[Here Fig. 4]

[Here Fig. 5]

Figure 4 and Figure 5 show agreement palette ranging from green (low percentage, equal high degree of agreement) to red (high percentage, equal slow degree of agreement), showing the percentage values of the Relative Standard Deviation (RSD). In both cases, RSD values vary from 0.3% to 55.8%. The lower the percentage value of the RSD, the greater the agreement among the different simulations executed.

Figure 4 and Figure 5 show that the agreement among the different simulations is greater in areas where is predicted an increase in terms of chestnut bioclimatic suitability, supporting the validity of the projections elaborated.

Transfer and future projections

Percentage anomalies maps at medium and long term scenarios are shown in Figure 6 and Figure 7.

[Here Fig. 6]

[Here Fig. 7]

These maps show areas with positive anomalies in blue (with a scale varying from 0.0% to 45.1%), which means an increase in future bioclimatic suitability for chestnut in Latium, and areas with negative anomalies in red (with a scale varying from -30.1% to 0.0%) which, on the contrary, predict a loss of future bioclimatic suitability for chestnut. Both simulations show an overall increase in terms of bioclimatic suitability.

Bioclimatic Predictors ranking in the model

Table 3 shows the ensemble mean of the contribution of each BP in terms of gain of model fitting. This contribution is provided by Maxent algorithm and expressed in percentage (Tab. 3).

[Here Table 3]

The results show that among BP the highest values and therefore a higher impact in determining the future distribution of chestnut in Latium have been found for the following BPs: BIO19 (Precipitation of the coldest quarter); BIO6 (Minimum temperature of the coldest month); BIO8 (Mean temperature of the wettest quarter). These most relevant BPs have been used to calculate their anomalies and analyze the variations in the THs under consideration (Fig. 8, Fig. 9 and Fig. 10).

[Here Fig. 8]

[Here Fig. 9]

[Here Fig. 10]

Anomaly map for BIO19 (Fig. 8) presents blue palette where the anomaly is positive, and therefore an increase in rainfall is expected for the coldest quarter (with anomaly values from 0.24% to 5.85%) and red palette (with anomaly values from -0.56% to -0.24%) in areas where precipitation is expected to decrease for the coldest quarter. The map shows a positive anomaly (rainfall increase in the coldest quarter) in almost the entire region, with a gradient of increase from South to North.

Anomaly map for BIO6 (Fig. 9) shows an increase in the minimum temperature of the coldest month in the Northern and innermost areas of the region (see dark red), compared to coastal areas (see neutral shades) for both the two THs analyzed. The anomaly values range from 2.86% to 3.29%.

Anomaly map for BIO8 (Fig. 10) shows a general increase of the mean temperature of the wettest quarter in the whole region, compared to a little decrease (neutral shades) only in North-West of the region (i.e. Tuscia). The anomaly values here range from -0.81% to 4.88%.

Discussion

This study analyzes the potential bioclimatic suitability of chestnut under the effect of climate change, simulating possible scenarios as proposed by Kikstra et al. (2022) over two distinct Time Horizons (THs): 2041-2060 and 2081-2100.

Results achieved show shifts in the environmental conditions that may have implications for chestnut forest stands cultivation and distribution, with a general increase of the potential bioclimatic suitability. This increase is more evident on the volcanic reliefs, rather than in the other areas, especially on the Cimini Mountains, Colli Albani and Sabatini Mountains, North-West of the region (i.e. Tuscia), in Latera complex. On the other hand, around Tolfa Mountains a loss in terms of bioclimatic suitability of this species is expected.

These predictions, differently from what was suggested by Bindi et al. (2011), Costa et al. (2017), Rahman et al. (2019), whose climate models predicted the expansion of bio-climatically suitable areas for chestnut stands in Northern and Central Europe and a reduction due to water shortage and more extreme weather events in the southern areas of Europe, highlights the peculiarity of the climatic and environmental conditions of the Latium reliefs where chestnut finds optimal growth conditions, as well as the soil conditions (particularly volcanic soils) (Krebs et al. 2004, 2019). Indeed, precipitation, temperature and their annual fluctuations are important factors to regulate chestnut tree growth, so changes in these factors may also lead to improved optimal climatic conditions for chestnut growth.

The Anomaly map of BIO6 indicates an increase in the minimum temperature of the coldest month in the innermost areas of the region compared to coastal areas for both the THs considered. Chestnut is a mesophilic species and the best conditions for its growth are moderate temperature and humidity (Furones Pérez et al. 2009, Gomes-Laranjo et al. 2009, Freitas et al. 2022) so a generalized increase of the temperature parameter will favor the increase of chestnut bioclimatic suitability, particularly in the Northern innermost areas of the region. Air temperature increases are projected over the upcoming decades in the main areas of European forests (Míguez-Soto et al. 2019, Puletti et al. 2019, Freitas et al. 2022), also including Italy (Bo et al. 2020, Pecchi et al. 2020). Higher temperatures induce early phenological phases, anticipated seasonal growing periods, and usually, yield reduction (Santos et al. 2020, Freitas et al. 2022), so this hypothesis, especially with respect to the reliefs of Cimini Mountains, Colli Albani area and Sabatini Mountains, is in line with the growth of bioclimatic suitability highlighted by the simulations.

The anomaly map of the predictor BIO8 shows a little increase in the whole region. Chestnut phenology requires warm temperatures during the vegetative season, which happens quite late with respect to other species: foliation (April/May), flowering (May/July), and fruits' ripening (September/November). During the wettest quarter (October/December) a fair increase in the mean temperature throughout the region favors fruit ripening, explaining the increase in bioclimatic suitability.

The anomaly map of BIO19 shows a positive value in the whole region and therefore a general increase in terms of rainfall in the coldest quarter of the year. This means a potential water reserve that would allow the species to enter the phase of vegetative activity in conditions of suitable water availability and to avoid stress damage. Mathbout et al. (2018) suggest that winter precipitation favors soil water retention promoting the beginning of fruit setting for chestnut stands. Considering the high sensitivity to summer droughts (Conedera et al. 2009) and the problems of water stress that chestnut coppices show where they grow below 500 m a.s.l., also on the volcanic hills of Latium, the altitude plays a decisive role for the future bioclimatic suitability of this species, and at the same time, this is a limiting factor given the low maximum altitude of those reliefs. Moreover, the contribution of altitude as a topographic variable that can modify bioclimatic suitability was not considered because the spatial resolution of data does not allow this predictor to work properly. Consequently, it is not possible to estimate the altitudinal shifts of the species.

In addition, the question of whether or how to deal with collinearity in SDMs, which according to Dormann et al. (2013) is still much debated and unresolved, is considered an element of uncertainty, because all BPs deal with temperature and precipitation. To overcome this critical issue a climatic ensemble with different ESMs and SSPs has been adopted, and all of them have shown good accuracy in predictions (AUC > 0.7) demonstrating the relevance of this study.

Another criticism of the used approach is that several Authors consider the use of only-presence data a fundamental limitation (e.g. Ward et al. 2009, Noce et al. 2017). Moreover, it should be noted that environmental predictors show a redundancy appearing related (or collinear) as they come from the same variables (temperature or precipitation) operated at different scales (year, season, month), or even combined.

In brief, using this approach it is important to take into account: *(i)* reliability and accuracy of species only-presence data; *(ii)* significance of selected environmental variables; *(iii)* related data quality, and *(iv)* parametrization or configuration of the applied model (Thuiller 2003, Thuiller et al. 2009, Nenzén and Araújo 2011, Chakraborty et al. 2016); because all the above elements can cause a large variance in the predictions (Thuiller et al. 2004, Pearson et al. 2006, Cheaib et al. 2012). Given the potential future increase in chestnut habitat suitability in Latium region, it is possible to suggest implementing the presence of the species in areas where it will be suitable by increasing managed chestnut populations through the planting of young trees, or by encouraging the restoration of abandoned chestnut stands. Therefore, it is reasonable to set up the management of coppice stands grown in the best site conditions with long rotation ages (up to 50-70 years), at least above 500 m a.s.l. and, likewise, not to exceed the minimum number of standards releases required by regional forestry regulation in order to yield high quality wood assortments. For the restoration of abandoned chestnut stands, it will be necessary to work with appropriate forest management (e.g., coppicing without standards release) to promote the growth and survival of chestnut even in post-cultural succession situations.

In fact, chestnut shows low competitiveness when subjected to postcultural succession in abandoned stands (Pezzi et al. 2011, Zlatanov et al. 2013, Mattioli et al. 2016, Manetti et al. 2020).

Conclusions

Forest assessment is rapidly evolving as new techniques and tools become available. However, the exploitation of the latter, as well as their implementation within operative management processes, should be evidence-based (Corona 2018). Under this perspective, this research aims to analyze potential future scenarios concerning chestnut bioclimatic suitability in the Latium region, under the impact of climate change. According to achieved results it can be stated that: *(i)* in Latium, for both THs considered (2041-2060 and 2081-2100) sweet chestnut stands will find optimal growth conditions in the future, especially in the Northern area of the region, thanks both to an increase of rainfall in the coldest quarter of the year and of the minimum temperatures of the coldest months; *(ii)* the climate ensemble approach used in this study shows a good accuracy (AUC > 0.7) and has allowed to provide useful information on the present and future suitability of chestnut stands within the Latium region; *(iii)* the predictors extracted from "WorldClim" allowed to identify some fundamental predictors of chestnut growth and development and therefore results to be useful in order to simulate possible climatic future scenarios in other regions; (iv) MaxEnt algorithm, coupled with a standard ODMAP protocol, confirms to be efficient to simulate potential bioclimatic suitability of species and their eventual shifts under climate change, as well as to outline suitable adaptation strategies, which are essential for decision-makers in the forest sector; v) an increase of the bioclimatic suitability of the chestnut stands will allow to plan new policies and management options for this species, considering its adaptive capacity in terms of resilience from pathogenic attacks and response to silvicultural treatments that could lead to new yield and quality models under future climate changes (Corona 2014, 2019).

On the other hand, to achieve a full picture of the future bioclimatic suitability for chestnut (but it will be the same for each forest species) other factors must be included within the projection models such as soil type, pathogenic attack and forest fires.

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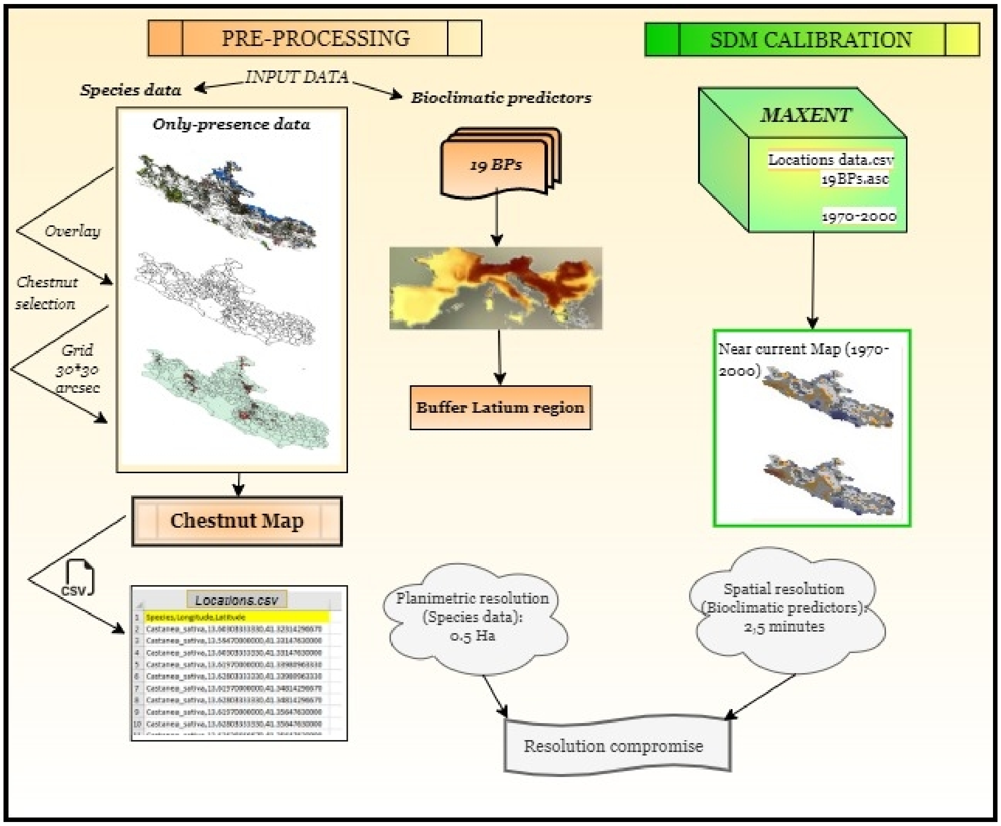

Figure 1 – Pre-processing and SDM calibration flowchart.

227x186mm (72 x 72 DPI)

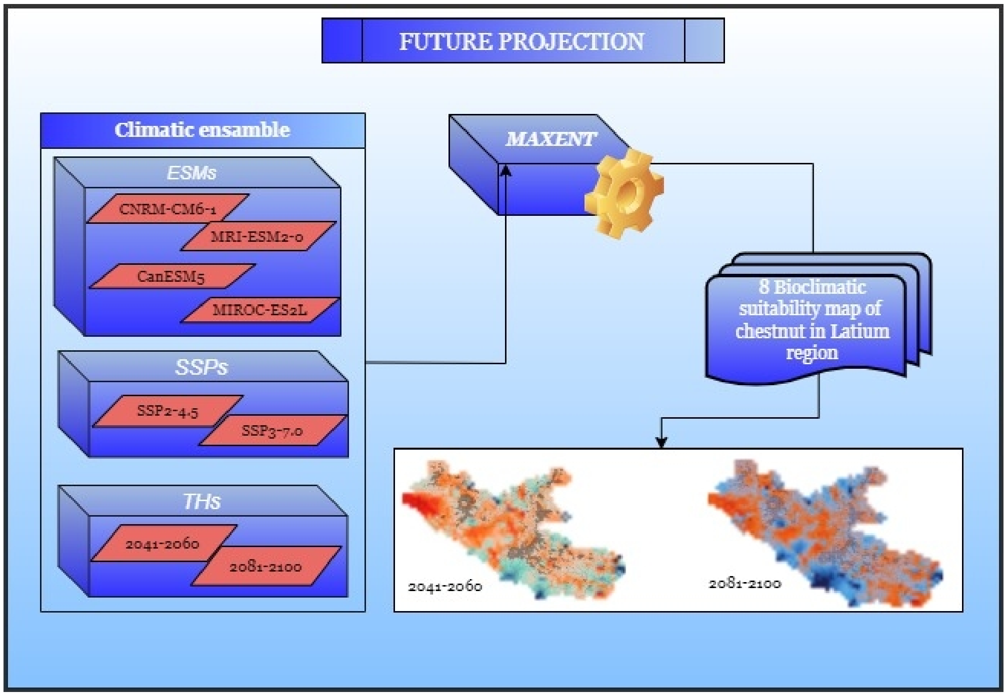

Figure 2 – Future projection flowchart.

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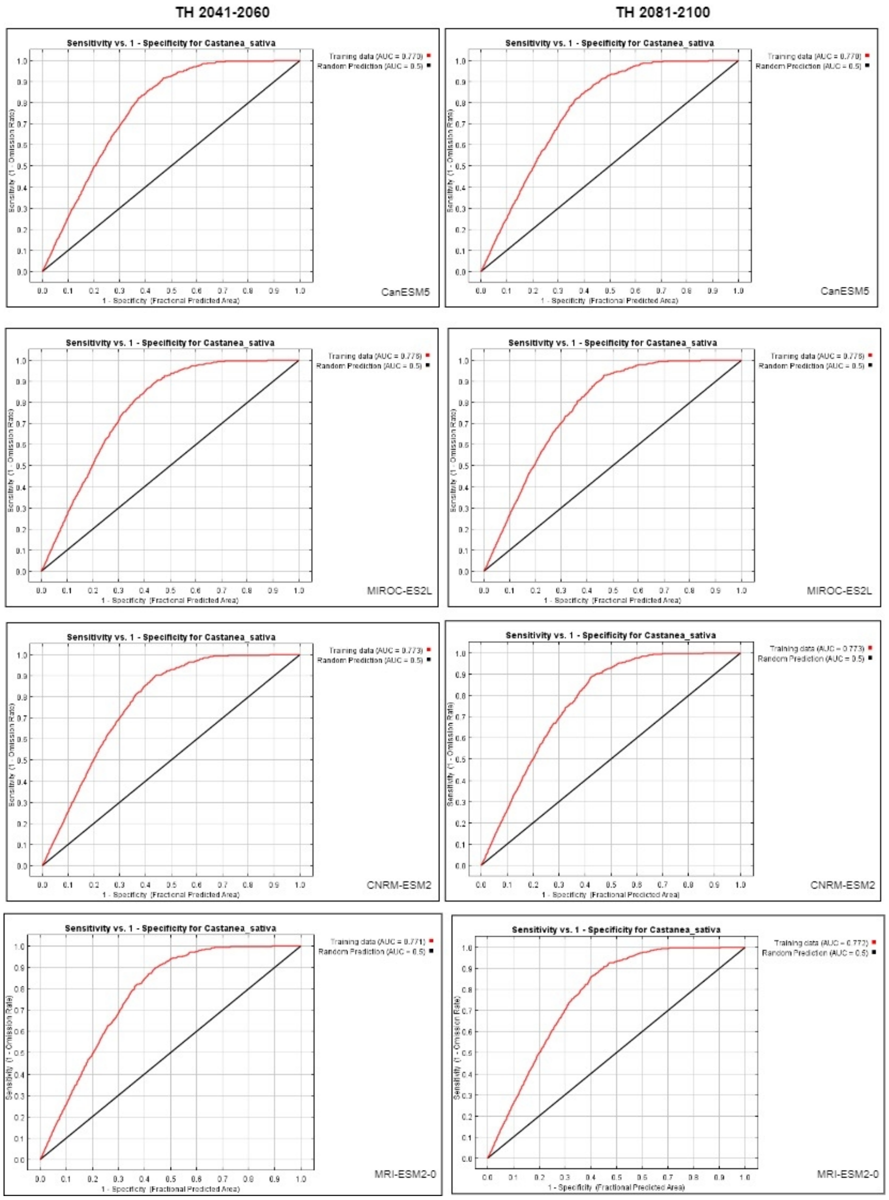

Figure 3 – ROC curves of the four ESMs used for the modeling distribution of chestnut, for each of the two THs considered (2041-2060; 2081-2100).

291x395mm (72 x 72 DPI)

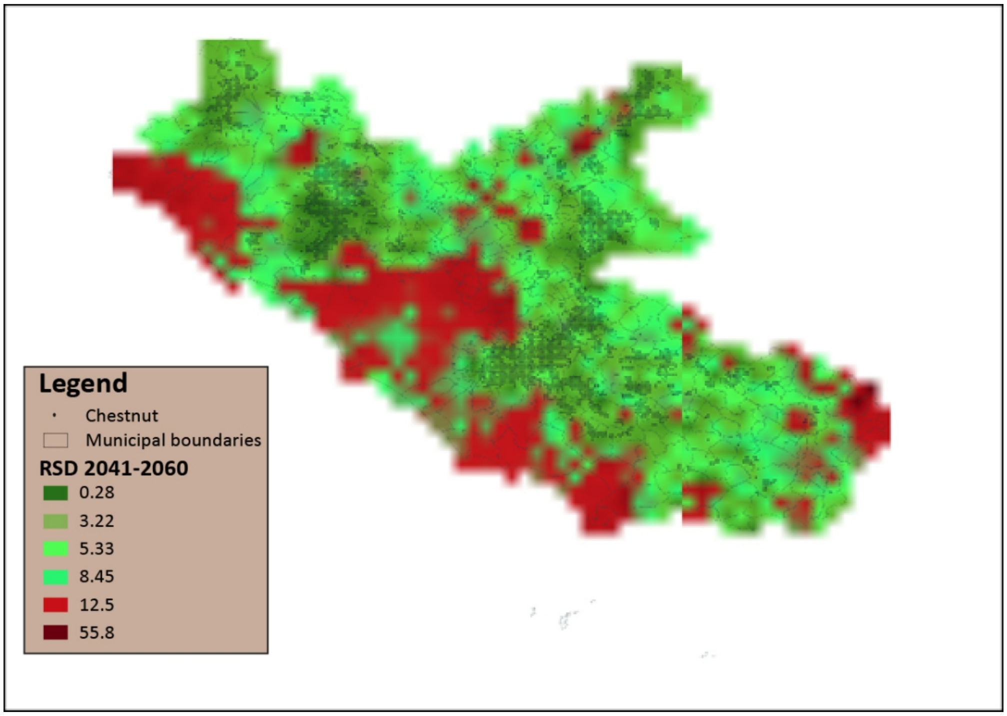

Figure 4 – Degree agreement maps between the members of the ensemble for the medium term (2041-2060). The green (low %) to red (high %) color scale shows the percentage values of the RSD.

103x73mm (300 x 300 DPI)

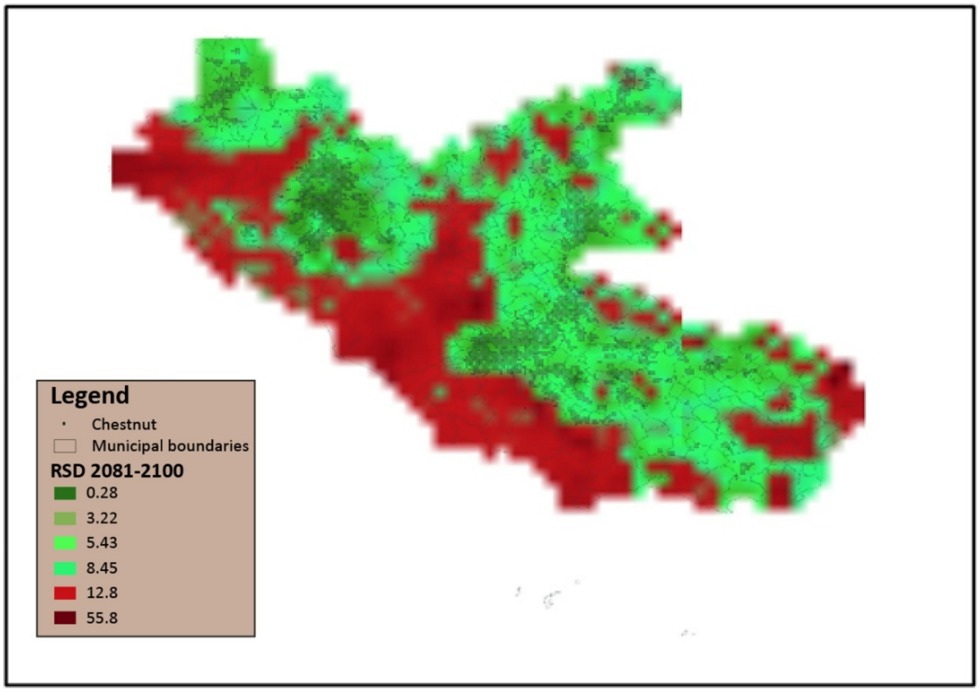

Figure 5 – Degree agreement maps between the members of the ensemble for the long term (2081-2100). The green (low %) to red (high %) color scale shows the percentage values of the RSD.

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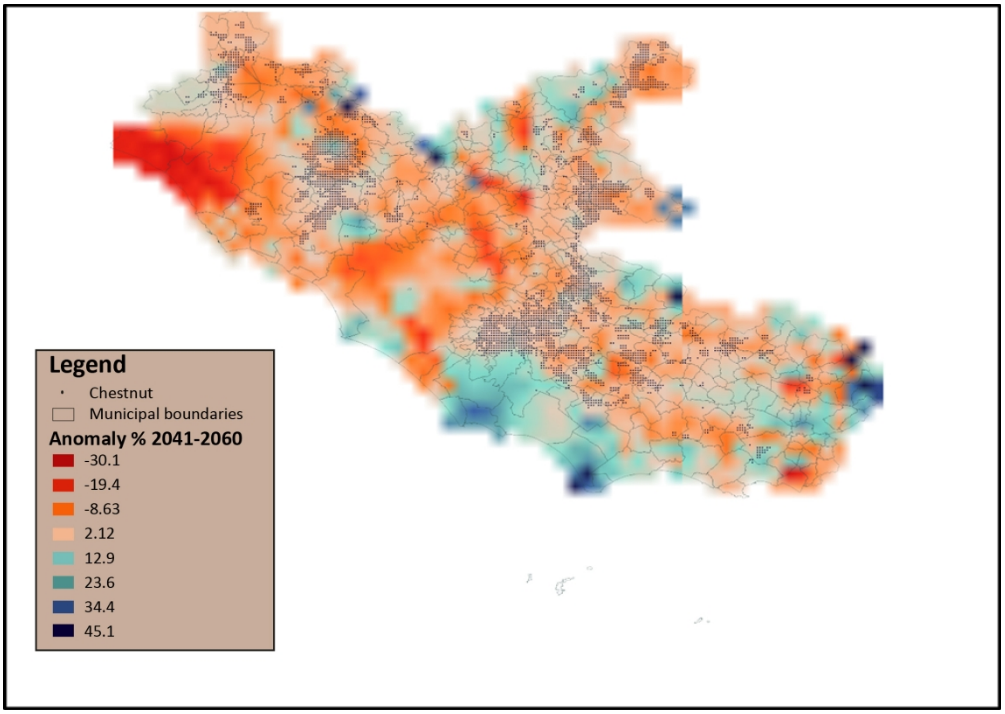

Figure 6 – Percentage anomaly map of chestnut bioclimatic suitability in Latium region in medium term (2041-2060).

170x120mm (300 x 300 DPI)

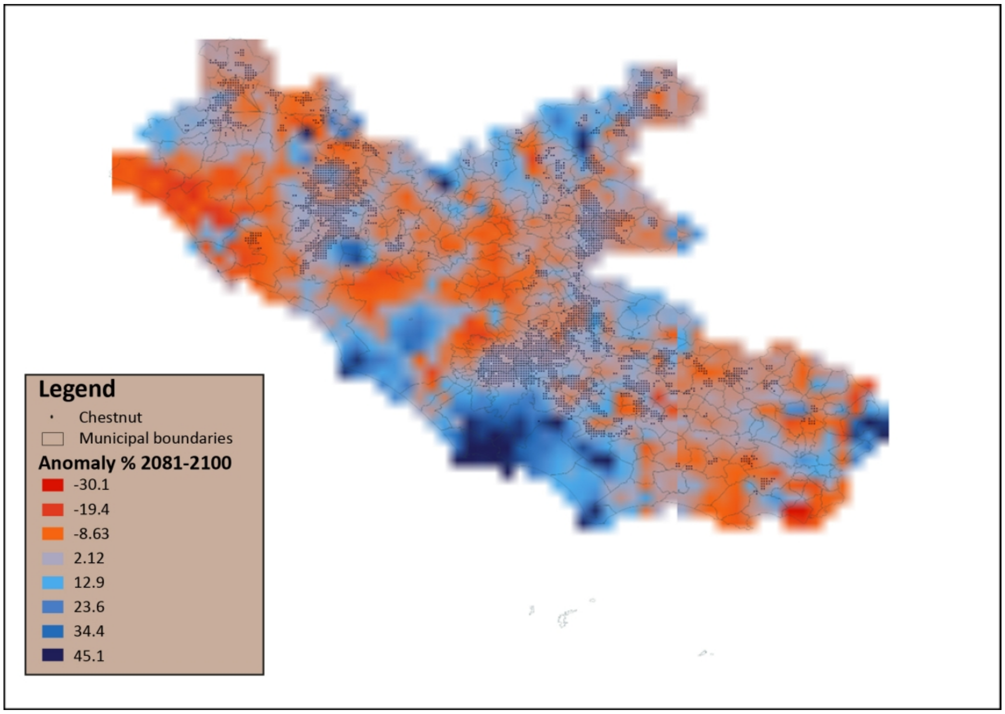

Figure 7 – Percentage anomaly map of chestnut bioclimatic suitability in Latium region in long term (2081-2100).

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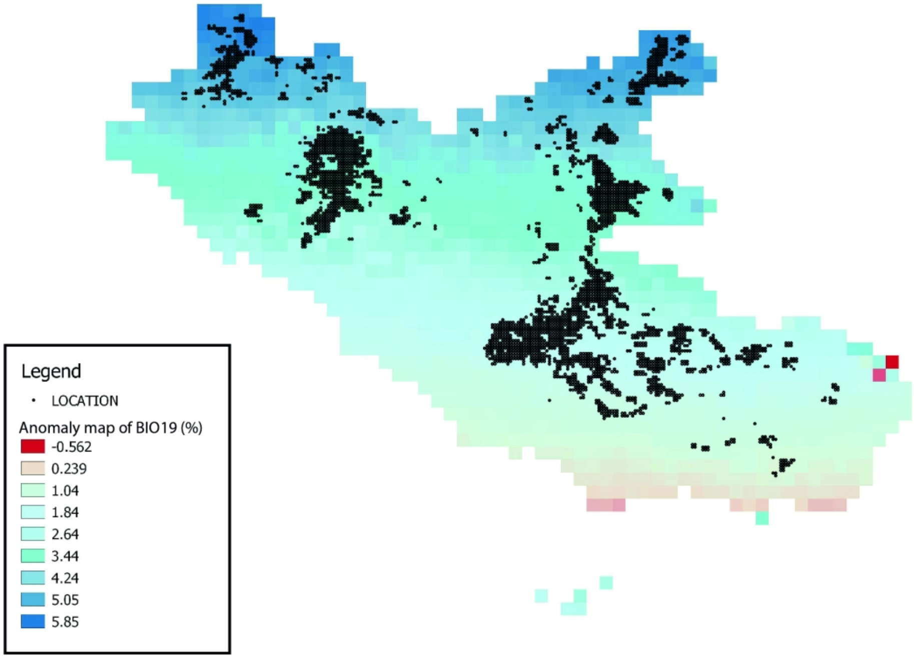

Figure 8 – Anomaly map of BIO19 (precipitation of coldest quarter) expressed in percentage.

223x157mm (300 x 300 DPI)

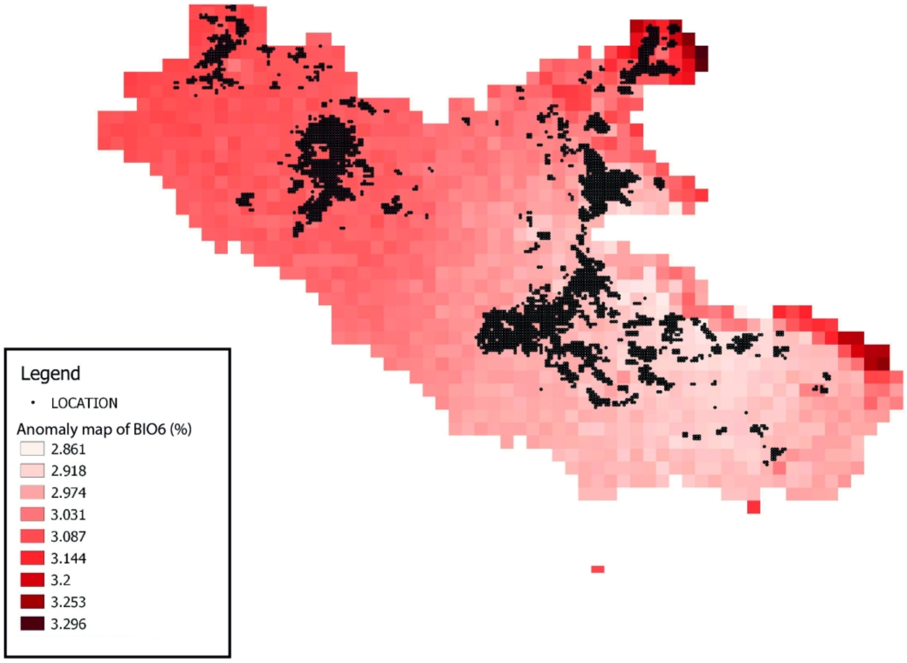

Figure 9 – Anomaly map of BIO6 (minimum temperature of coldest month) expressed in degrees.

207x146mm (300 x 300 DPI)

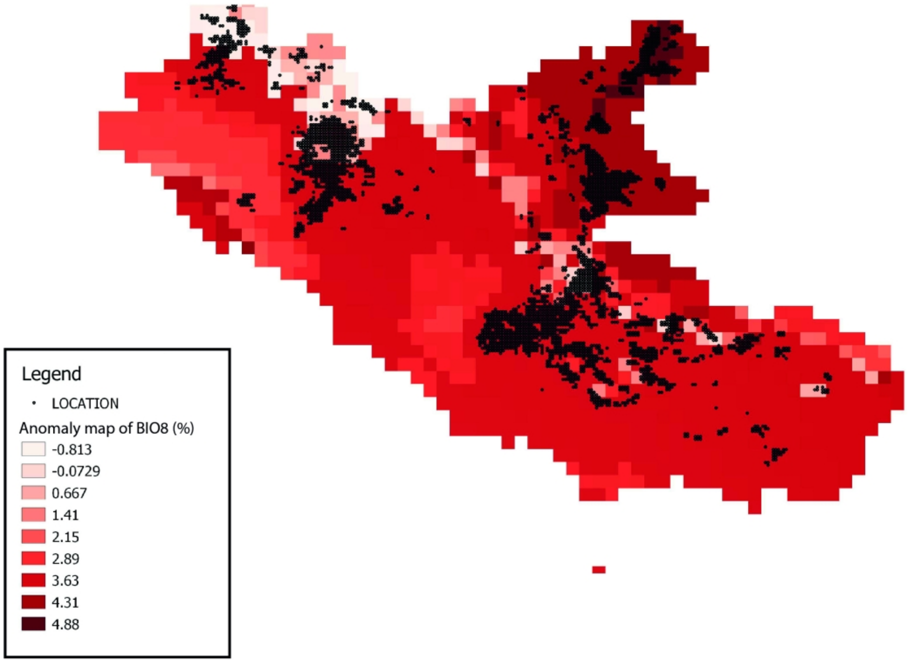

Figure 10 – Anomaly map of BIO8 (mean temperature of wettest quarter) expressed in degrees.

250x177mm (300 x 300 DPI)

Table 1 - The Overview section of the ODMAP standard protocol applied.

SUBSECTION	ELEMENT	VALUE
Model objective	Model objective	Forecast and transfer
	Target output	Bioclimatic suitability map
Focal *taxon*		*Castanea sativa* Mill.
Location		Latium region
Scale of Analysis	Spatial extent	Regional level
	Spatial resolution	Planimetric resolution: 0.005 km^2
	Temporal extent	2041-2060 and 2081-2100
	Temporal resolution	2.5 minutes (4.5 km)
	Boundary	Political
Biodiversity data	Observation type	Forest type map available at "Geoportal of Latium" Study area coordinates (41°44' to 41°21' N, 12°40' to 12°59' E)
	Response data type	Presence-only
Predictor types		Climatic and topographic
Hypotheses	Hypotheses	Chestnut stands find optimal growth conditions in Latium region. Will it be the same for the future? Is it possible to identify the potential impacts of climate change on chestnut stands in Latium? The environmental predictors extracted from the "WorldClim" database will be sufficient to predict future distribution of the species?
Assumptions	Model assumptions	Redundancy of environmental predictors. Model's performance is tested in a limited space (Latium). No observation bias problems
Algorithms	Modeling technology	Maximum Entropy (Maxent) algorithm
	Model complexity	The model settings were chosen to yield a simple, smooth response surface
Workflow	Model workflow	Refer to the flowchart (Fig. 1 and Fig. 2)
Software	Software	MaxEnt (Version 3.4.2); Qgis 3.4 Madeira
	Data availability	Geoportal of Latium (https://geoportale.regione.lazio.it/geoportale/) WorldClim (https://www.worldclim.org/data/cmip6/cmip6_clim2.5m.html)

Table 2 – List of the bioclimatic predictors used for the calibration phase of SDM.

Predictor ID	Description	Unit
Bio1	Mean annual temperature	°C*10
Bio2	Mean diurnal range	°C*10
Bio3	Isothermality	n. a.
Bio4	Temperature seasonality	°C*10
Bio5	Max temp. of warmest month	°C*10
Bio6	Min temp. of coldest month	°C*10
Bio7	Temperature annual range	°C*10
Bio8	Mean temp. of wettest quarter	°C*10
Bio9	Mean temp. of driest quarter	°C*10
Bio10	Mean temp. of warmest quarter	°C*10
Bio11	Mean temp. of coldest quarter	°C*10
Bio12	Annual precipitation	mm
Bio13	Precipitation of wettest month	mm
Bio14	Precipitation of driest month	mm
Bio15	Precipitation seasonality	n. a.
Bio16	Precipitation of wettest quarter	mm
Bio17	Precipitation of driest quarter	mm
Bio18	Precipitation of warmest quarter	mm
Bio19	Precipitation of coldest quarter	mm

Table 3 - Values of percentage contribution (%) to MaxEnt modelling of bioclimatic predictors for each Time Horizon considered (2041-2060 and 2081-2100) without considering topographic variables.

Predictor ID	**Description**	**2041-2060 (%)**	**2081-2100 (%)**
Bio1	Mean annual temperature	0.24	0.06
Bio2	Mean diurnal range	0.10	0.11
Bio3	Isothermality	1.03	1.04
Bio4	Temperature seasonality	1.34	1.54
Bio5	Max temperature of warmest month	0.01	0.03
Bio6	Min temperature of coldest month	2.56	2.43
Bio7	Temperature annual range	0.04	0.20
Bio8	Mean temperature of wettest quarter	2.00	1.35
Bio9	Mean temperature of driest quarter	0.69	1.04
Bio10	Mean temperature of warmest quarter	0.51	0.25
Bio11	Mean temperature of coldest quarter	1.33	1.26
Bio12	Annual precipitation	0.08	0.06
Bio13	Precipitation of wettest month	0.03	0.09
Bio14	Precipitation of driest month	0.39	0.28
Bio15	Precipitation seasonality	1.10	1.18
Bio16	Precipitation of wettest quarter	1.36	0.51
Bio17	Precipitation of driest quarter	0.54	0.39
Bio18	Precipitation of warmest quarter	0.84	0.80
Bio19	Precipitation of coldest quarter	2.53	3.26