





Article

Assessment of Growing Thermal Conditions of Main Fruit Species in Portugal Based on Hourly Records from a Weather Station Network

Mónica Santos ^{1,*}, Helder Fraga ¹, Margarida Belo-Pereira ^{1,2} and João A. Santos ¹

¹ Centre for the Research and Technology of Agro-Environmental and Biological Sciences, CITAB, Universidade de Trás-os-Montes e Alto Douro, UTAD, Quinta dos Prados, 5000-801 Vila Real, Portugal

² Instituto Português do Mar e da Atmosfera, Rua C do Aeroporto, 1749-077 Lisbon, Portugal

* Correspondence: monica.santos@utad.pt

Received: 24 July 2019; Accepted: 5 September 2019; Published: 10 September 2019



Abstract: Thermal conditions in mainland Portugal were evaluated using a new hourly database over the recent period of 2000–2018 (19 years). The number of hours within each different temperature interval was calculated from the long-term means of the hourly temperatures of a network of 63 meteorological stations. A geostatistical approach, using elevation, distance to coastline and latitude, was subsequently applied to provide gridded patterns at a high spatial resolution (1 km grid spacing). Eight fruit species (almond tree, carob tree, chestnut tree, citrus fruits, cork oaks, holm oaks, olive trees, and grapevines) were selected to assess their hourly thermal growing conditions. The results highlight the strong spatial variability of temperature levels in mainland Portugal, providing new insights into their spatial distribution. The number of hours in the year with cool conditions (4–12 °C) is higher in the northern-central regions, mainly in mountainous areas. Additionally, the number of hours in the year with temperate conditions (12–20 °C) emphasizes the importance of the distance to the coastline (maritime influence). The warm conditions (20–28 °C) are most prevalent in the south of the country and in the Douro valley, whereas the very warm conditions (number of hours with temperature between 28–36 °C) are essentially restricted to inner-southern Portugal and to the upper Douro valley. This study also reveals, with high accuracy, the thermal growing conditions of main fruit species in mainland Portugal, giving particular emphasis to olive trees and grapevines. These findings may help decision support systems providing more reliable and accurate guidelines to stakeholders, decision-makers, and farmers. The main maps are available in a widely used file format (shapefile), thus allowing their application to a wide range of other areas of interest.

Keywords: hourly temperature; spatial distribution; fruit species; olive trees; grapevines; Portugal

1. Introduction

Air temperature has a significant impact on health, environment, agriculture, society, and economy. Variability, extremes, and trends have been extensively investigated, based on daily, monthly, or annual data in Portugal [1–4]. However, studies based on hourly data are not currently available. In effect, hourly data provides a much more accurate picture of the thermal conditions at a given location or region, also contributing to improving our understanding of climatic patterns and regimes. This kind of information is very useful for assessing climatic conditions and suitability of a given region for growing specific crops or forest species. This is particularly relevant for mainland Portugal, where temperature is spatially heterogeneous, showing strong spatial gradients. In addition, there is a strong seasonality and large inter-annual variability in precipitation and temperature across the territory [3].

Mainland Portugal is located in the transitional region between the sub-tropical anticyclone and the sub-polar low-pressure systems [2], therefore its climate is influenced by the alternation of anticyclones and depression systems. However, locally the climate is also greatly influenced by the complex orography, latitude, and proximity of the Atlantic Ocean [5,6]. In fact, mainland Portugal presents large orographic heterogeneities, being more mountainous in the northern region (where maximum terrain elevation reaches 1993 m a.s.l.) than in its southern part (Figure 1a). These heterogeneities play a key role on the precipitation distribution [4] and on temperature pattern (Figure 1). With a predominantly mild Mediterranean climate [2], Portuguese climates feature typical warm and dry summers and cool and rainy autumn–winter periods, but with large inter-annual variability and seasonal irregularity. The annual mean temperature varies between about 9 °C, in the north and central mountains, to approximately 18 °C in the southern coast and inner Alentejo (Figure 1c).

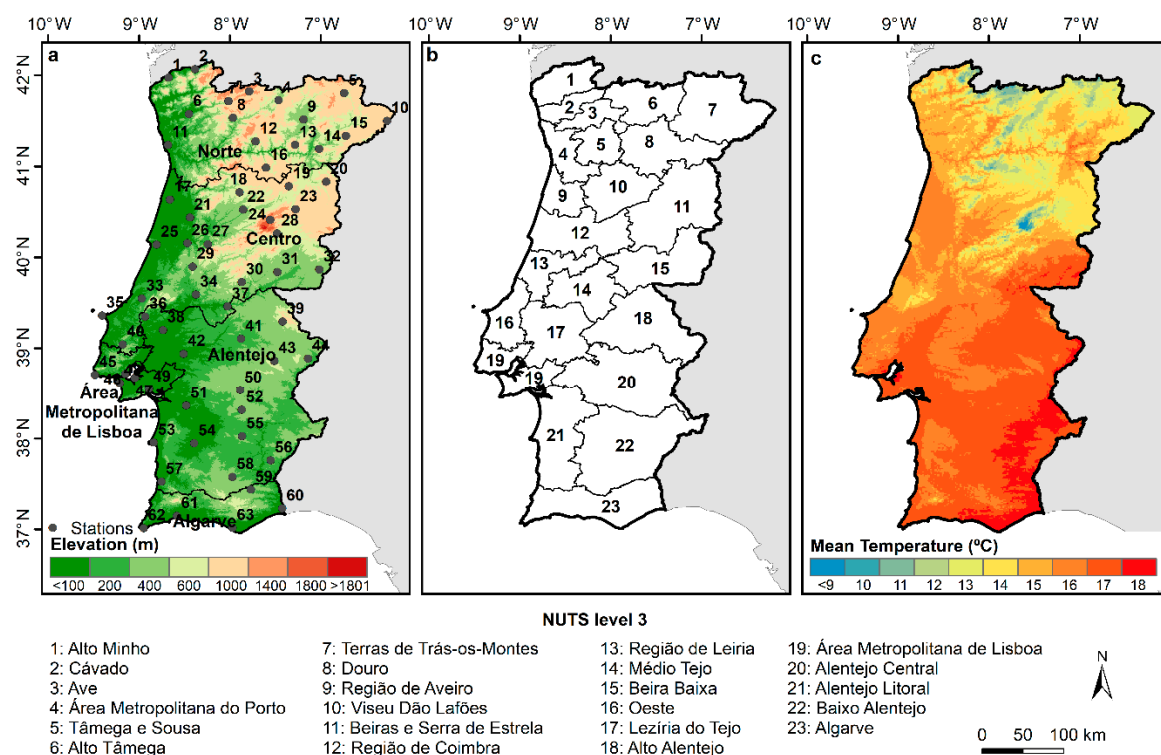


Figure 1. (a) Terrain elevation of mainland Portugal and location of the 63 selected meteorological stations. (b) Geographical borders of the 23 NUTS (Nomenclature of Territorial Units for Statistics) level 3 (see the list for their designations). (c) Annual mean air temperature for mainland Portugal during the period of 2000–2018.

The territory is administratively organized in NUTS (Nomenclature of Territorial Units for Statistics) level 2 (Figure 1a) and NUTS level 3 divisions (Figure 1b). These units will be used herein to summarize information on the prevailing thermal conditions throughout the country.

It is widely accepted that the two dominant global climatic drivers of plant distribution are temperature and water availability [5]. The plant growth and development is dependent upon the temperature surrounding the plant and each species has a specific temperature range, commonly characterized by a thermal optimum, minimum, and maximum thermal limits [6]. For fruit species, a certain heat accumulation is essential for adequate growth, physiological development and to obtain ripe fruits [7,8]. Many woody plant species growing in temperate climates also require a certain amount of exposure to cold temperatures to break winter dormancy and prepare to springtime warming [9]. Several studies have combined heat and chill indices for studying thermal requirements of different fruit species [10–16]. Santos, Costa, and Fraga [7] evaluated the thermal growing conditions of fruit

species in mainland Portugal using two bioclimatic indices: growing degree hours and chilling portions. These two indices were estimated based on gridded daily mean temperatures.

With its large range of climates, Portugal produces various types of fruits and crops. Agricultural soils cover more than 35% of the total area of Portugal [17]. Grapevines and olive trees are the fruit crops that occupy the largest area, of 178,770 ha and 361,483 ha, respectively [18]. In terms of fruit production, viticulture is responsible for the biggest production (802,278 t), followed by fresh fruits (542,203 t) and citrus fruits (402,924 t), according to the Portuguese statistics office [18]. In Portugal, some fruit species are located in very narrow areas. This is the case, for example, of carob and citrus fruits, which are mainly located in the Algarve region, while chestnut trees are located in the northeast of Portugal. Other species, such as olive trees and grapevines are distributed throughout several regions of the country, with a wide range of cultivated varieties and under very different thermal conditions. Olive tree (*Olea europaea* L.) is an important crop in Mediterranean countries, being drought-tolerant, as it may survive and produce fruits with low water availability [19,20]. Typically, grapevine (*Vitis vinifera* L.) is also a key crop in Mediterranean countries, comprising many of the world renowned winemaking regions located in areas with Mediterranean-type climates [21].

The objectives of the present study are twofold: (1) to provide a very high-resolution mapping (~1 km resolution) of the current thermal conditions over mainland Portugal on the hourly timescale, thus improving former classifications based on the daily timescale; (2) to evaluate the thermal growing conditions of main fruit species in Portugal, with special emphasis on the grapevines and olive trees.

2. Materials and Methods

In this study, an innovative hourly observational database is used to calculate the number of hours within different temperature intervals, i.e., to assess the empirical distribution of hourly temperatures. Furthermore, the number of hours per different temperature intervals of eight fruit species are analyzed separately, giving more emphasis to grapevines and olive trees, owing to their key role in the Portuguese economy.

The hourly temperature dataset used was obtained from the Portuguese national weather service's (Instituto Português do Mar e da Atmosfera, IPMA) network of meteorological stations in mainland Portugal. Of the original 133 stations, those with more than 20% of missing hourly data were rejected beforehand. Thus, 63 stations were selected for the 19-year period 2000–2018 (Figure 1). The geographical locations of the selected stations are shown in Figure 1. In general, these stations are representative of the altitudinal variation within the territory (Table S1 and Figure 1). The station with the highest elevation, Penhas Douradas (1380 m), is located in Serra da Estrela (the highest mountain range in mainland Portugal), while the station with lowest elevation is located in Figueira da Foz (4 m). The southernmost weather station is Sagres (37°01' N), while the northernmost is Monção (42°06' N). Regarding the longitude, it varies from 9°48' W in Cabo Raso to 6°27' W in Miranda do Douro (Table S1). A preliminary quality-checking of data was carried out. Box-plots of each station time series were plotted to represent the full empirical distributions of observed data and to detect possible erroneous values (not shown). Among the 63 selected stations, 21 stations have less than 5% of missing hourly data, 22 stations between 5% and 10%, 15 stations between 10% and 15%, and 5 stations between 15% and 20% (Figure S1). Hourly data were obtained by averaging 10-min instant data at each weather station.

A two-step methodology was followed in order to obtain the final maps of the number of hours within each temperature interval: (1) a geostatistical temperature interpolation in order to capture the spatial variability of the number of hours for different temperature intervals, and (2) a bias correction of the interpolated data. First, the number of hours for each different temperature interval was calculated from the long-term means (baseline of 2000–2018) of the hourly temperatures at each weather station separately. The following temperature intervals were selected: ≥ 4 – < 8 °C, ≥ 8 – < 12 °C, ≥ 12 – < 16 °C, ≥ 16 – < 20 °C, ≥ 20 – < 24 °C, ≥ 24 – < 28 °C, ≥ 28 – < 32 °C, and ≥ 32 – < 36 °C. The number of hours with temperature < 4 °C and > 36 °C was excluded from this study, because they occur in only a few days

of the year and with a restricted geographic distribution, thus not warranting a statistically robust analysis. In order to obtain the number of hours in different temperature intervals, the long-term means for the baseline 2000–2018 were chosen, as they allow overcoming possible biases in the database, e.g., owing to missing data. Furthermore, the aggregation of all years was the best option for this study purposes, which is focused on spatial variability rather than on temporal variability. However, through a sensitivity analysis shown in Figure S2, it was possible to attest that the choice of the hourly climatological means instead of the whole raw hourly data had only a negligible impact on the relative distribution of the number of hours (shape of the empirical distributions), showing differences of less than 2% in the relative number of hours for all temperature intervals and for all meteorological stations.

Second, the number of hours in each temperature interval and for all selected sites were subject to ordinary least squares (OLS) linear regressions, with three independent variables: latitude, elevation, and Euclidean distance to the coastline (at 1 km resolution). The aim was to perform a regression analysis (one for each temperature interval) with the number of hours as dependent variable and the geographical variables (latitude, elevation, and distance to coastline) as exploratory variables. From the multiple regression analysis, the regression coefficients were obtained and map algebra tools in GIS were applied to produce the final maps from the gridded variables at a 1 km grid resolution.

The resulting OLS maps presented the inherent error of the regression adjustment, i.e., they explain the influence of the geographic variables on the model [22]. On the other hand, the residuals of the regression fit at each meteorological station tend to reflect other factors beyond the independent variables, such as soil cover properties, local winds (e.g., breezes), or other mesoscale systems [1]. These factors may also influence the model, underlying important biases between interpolated and observed values. Hence, to improve the OLS results, bias corrections were carried out based on the number of hours for the different temperature intervals, computed for the network of 63 meteorological stations and over the same baseline period (2000–2018). An inverse distance weighted (IDW) interpolation of the biases (residuals) to the 1 km grid was then added to the OLS of the number of hours, separately for each temperature interval. The IDW interpolation determines each grid point value using a linearly weighted combination of a set of sample points. The weight is a function of the inverse distance, assuming that the variable value being mapped decreases with the distance [23,24]. Kriging, spline, and polynomial interpolations were also tested, but the IDW method was eventually chosen, since it provided the lowest mean squared error (not shown). The aforementioned procedure was independently repeated for the number of hours within the different temperature intervals. The percentages of hours by the different temperature intervals in a year (relative frequencies of occurrence) were then calculated and their spatial variability was examined.

The thermal conditions associated with different key agricultural and forest species in Portugal were assessed. A total of eight species were selected: almond tree (*Prunus dulcis* D. A. Webb), carob tree (*Ceratonia siliqua* L.), chestnut tree (*Castanea sativa* Mill.), citrus fruit species (e.g., oranges, lemons, clementine's and mandarins), cork oak (*Quercus suber* L.), holm oak (*Quercus ilex* L.), olive tree (*Olea europea* L.), and grape vines (*Vitis vinifera* L.). Their land coverage was retrieved from the fifth level of Land Use and Occupation Map: COS2007 (Source: Direção-Geral do Território, <http://www.dgterritorio.pt/>). Owing to the high relevance of olive trees and vines to the Portuguese economy, they were specifically analysed within their main demarcated regions. This procedure enabled to highlight the prevailing thermal conditions in each region. For this purpose, the 50 Denominations of Origin (DOs) or sub-regions for the grapevines, and the 6 Protected Designations of Origin for olive trees (PDOs) were considered. As for the other species there are no protected designations of origin, it was not possible to apply the same methodology.

3. Results

3.1. Distribution of Temperature Intervals

A first inspection at the temperatures recorded at each weather station was carried out, thus providing some basic information regarding their levels of magnitude, temporal variability, and spatial distribution before applying any interpolation approach (Figure 2). The mean temperature over mainland Portugal for the period of 2000–2018 ranges from 9 °C at the Penhas Douradas, in Serra da Estrela, to 18.2 °C in Faro. In the NUTS of Alentejo, Lisboa e Vale do Tejo and Algarve, the mean temperature is over 16 °C in all meteorological stations. The lowest values of mean temperature (<13 °C) are recorded in the inner-north of the country. The maximum temperature varies from approximately 32 °C up to 46 °C, but maximum temperatures below 39 °C are mostly restricted to high elevation areas or to the western coast, which is significantly influenced by the Atlantic Ocean. The minimum temperatures range between −13 °C and 2 °C. The lowest minimum temperatures are located mainly in the inner-northern Portugal.

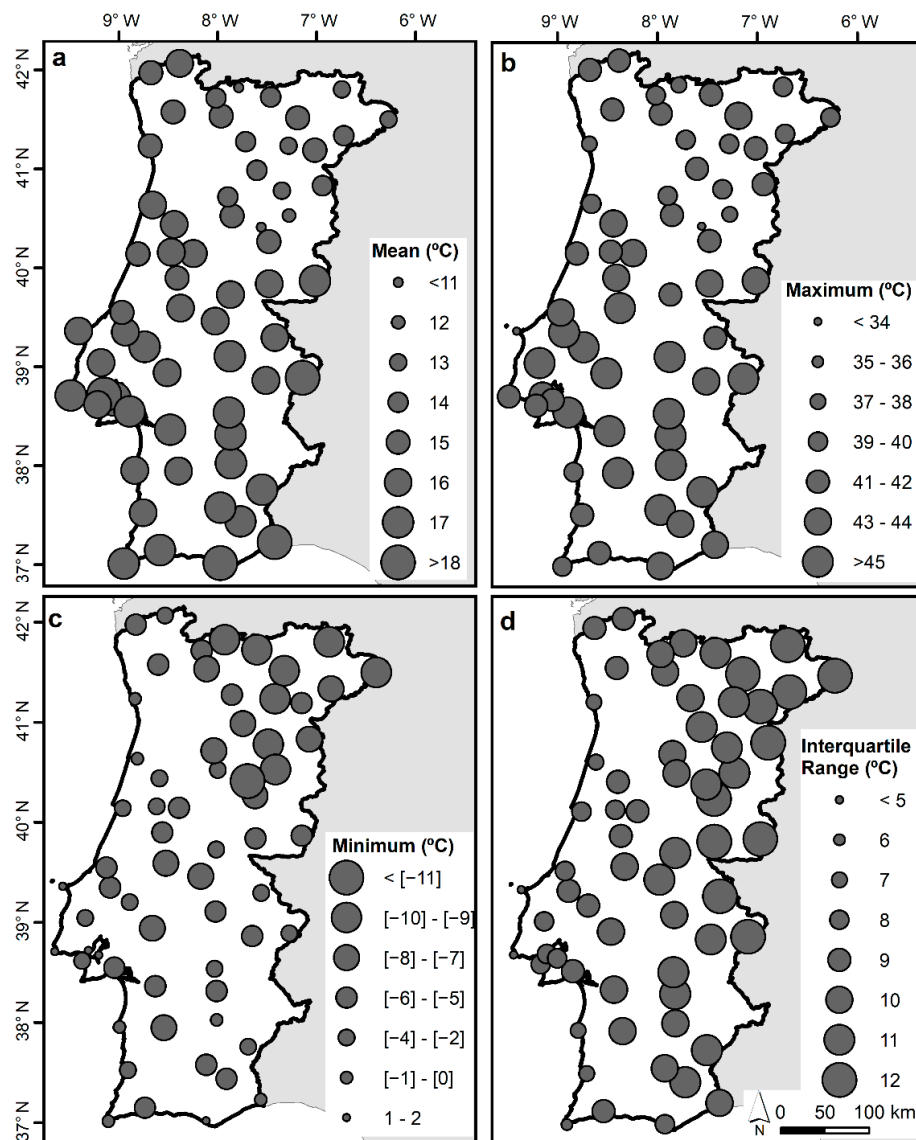


Figure 2. (a) Mean temperature, (b) maximum temperature, (c) minimum temperature, and (d) interquartile ranges (75th–25th percentiles) for the period of 2000–2018. The dots are scaled according to the level of magnitude of the temperature.

The interquartile range indicates that the regions farthest from the Atlantic Ocean present greater differences between maximum and minimum temperatures, owing to the more continental climatic features. Hence, temperatures tend to decrease from the south to the northeast (higher latitudes and elevations), showing more moderate values in the Atlantic-facing areas. The relevance of each regressor (latitude, elevation, and distance to coastline) depends on the temperature interval. For instance, the distance to coastline is particularly important in the number of hours with temperatures within the intervals of 12–16 °C and 16–20 °C, while elevation is important in the number of hours with temperatures in the interval of 4–8 °C. Despite the differences among temperature intervals, the three regressors are statistically significant according to the Student's *t*-test at 5% significance level (cf. corresponding 95% confidence intervals in Figure 3). Overall, the regression coefficients are coherent with the corresponding temperature ranges and may thereby be considered reliable, with plausible representations of the spatial variability of temperatures throughout Portugal.

The multivariate linear coefficients are positive for the independent variable's latitude, elevation, and distance to the coastline in the dependent variable number of hours within the intervals of 4–8 °C and 8–12 °C. The spatial distribution of lower temperatures follows a pattern where the roles of elevation, latitude, and distance to coastline are similar. Temperature usually decreases with elevation and it is therefore more likely to observe lower minimum temperatures in the higher mountains [25]. In addition, there is a general cooling trend in winter as the distance to coastline and latitude increases. The multivariate linear coefficients are negative for elevation and distance to coastline in the number of hours with the temperature ranges of 12–16 °C, 16–20 °C, and 20–24 °C, thus highlighting the predominance of mild temperatures in the coastal regions (Figure 3). The same coefficients are positive for latitude between 4 °C and 16 °C, showing the predominance of lower temperatures in the northern region. For the higher temperature intervals (24–28 °C, 28–32 °C, and 32–36 °C), the distance to coastline acquires more relevance, since the highest temperatures are commonly recorded in the interior of the country (Figure 3).

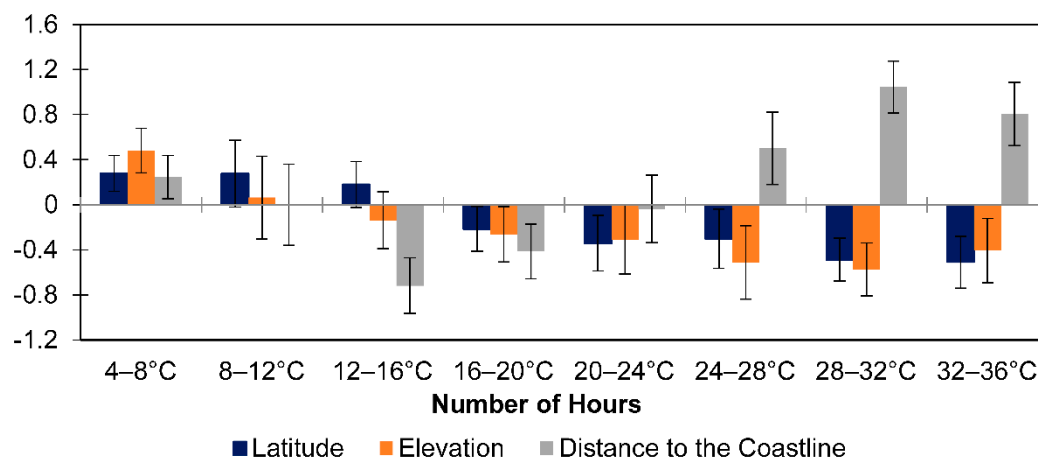


Figure 3. Multivariate linear regression coefficients of the three selected regressors (latitude, elevation, and distance to coastline), along with their corresponding 95% confidence intervals.

After applying the geostatistical interpolation approach described above, the maps of Figure 4 highlight the strong spatial variability of temperatures in mainland Portugal, also showing spatially coherent patterns. The annual number of hours with temperature between 4–8 °C (NH 4–8 °C) occurred along the southern and western coasts and maximum values in the mountainous areas and in the northeast. The NH 4–8 °C ranges from approximately 38% in Serra-da-Estrela to 3% in the Algarve coast. The NH 8–12 °C ranges from 13% to 21% in the southern part and presents values above 20% in the northern part, with a maximum in the northwestern quadrant (Figure 4b).

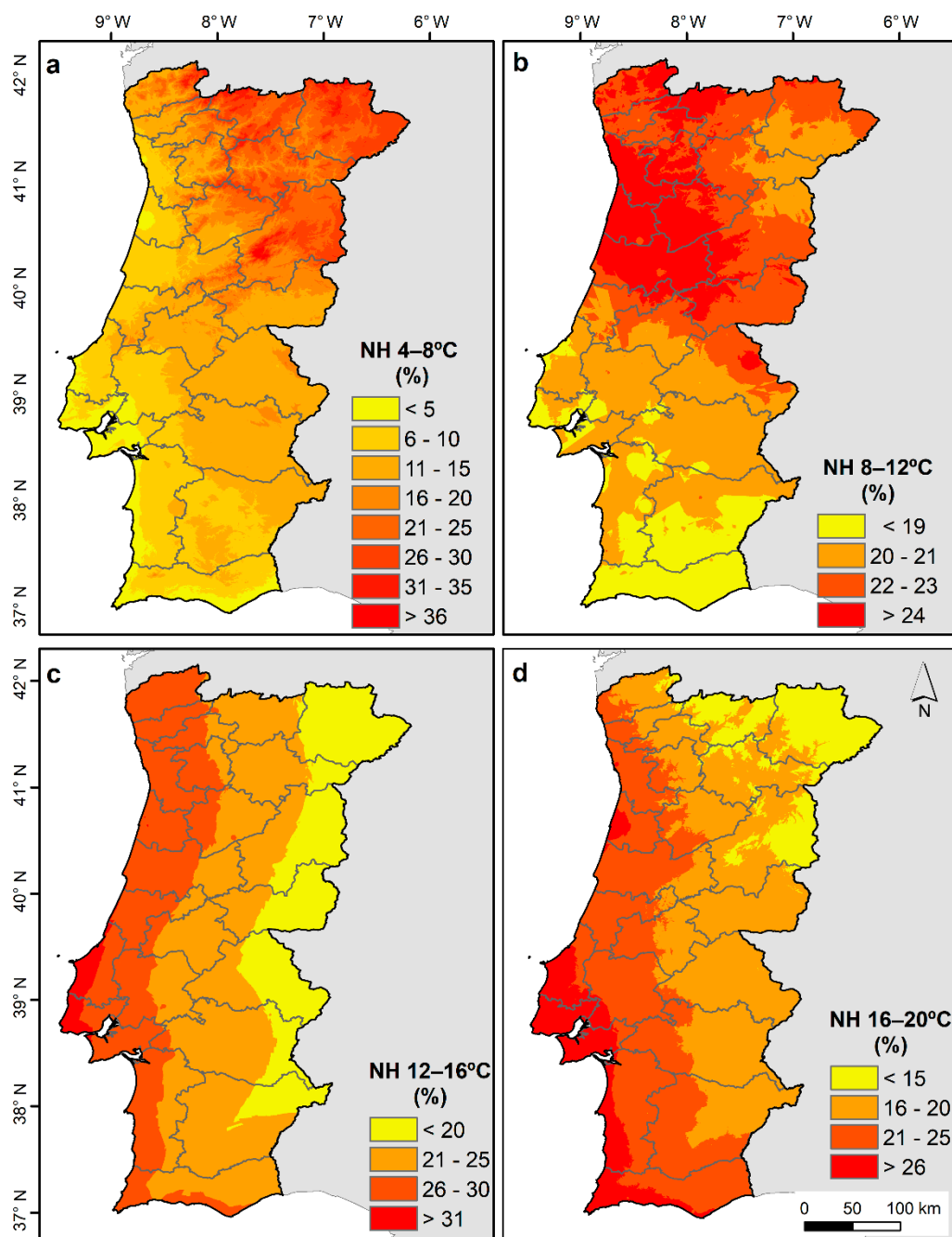


Figure 4. Cont.

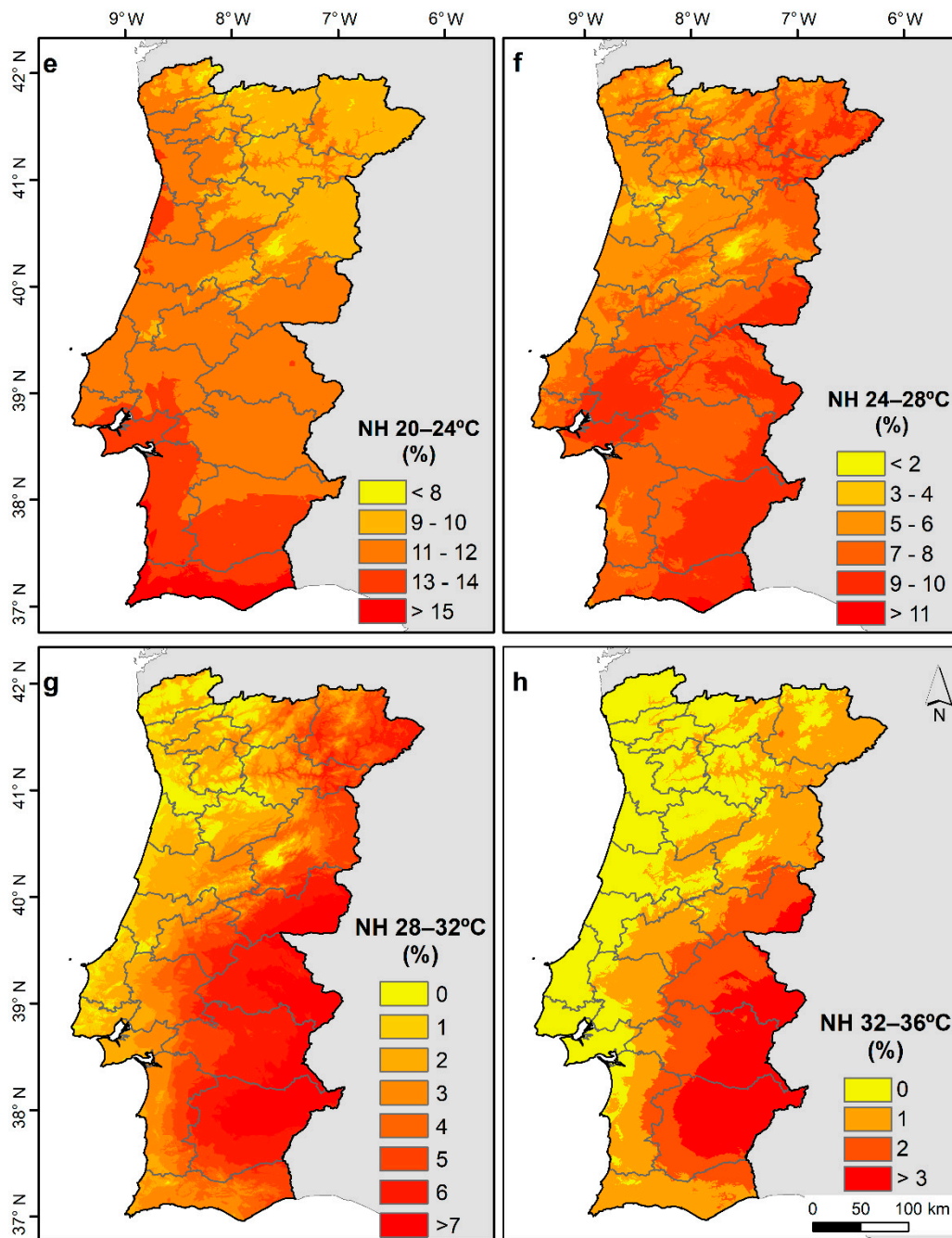


Figure 4. Relative number of hours in the year (in %) by different temperature intervals: (a) 4–8 °C, (b) 8–12 °C, (c) 12–16 °C, (d) 16–20 °C, (e) 20–24 °C, (f) 24–28 °C, (g) 28–32 °C, (h) 32–36 °C, over mainland Portugal, for the period of 2000–2018 after applying the geostatistical interpolation (cf. Figure 1b for designations of mapped NUTS level 3).

The maps with the number of hours with temperature between 12–16 °C and 16–20 °C (Figure 4c,d) essentially highlight the continentality effect (distance to the coastline), particularly in the former interval, with higher percentage along the coast, as these temperatures are close to the sea surface temperatures. The NH 20–24 °C ranges from about 15% in south to about 6% in the mountains of the north and centre of the country. The NH 24–28 °C ranges from less than 2% in the Serra da Estrela to about 11% in the southeast, Tagus valley and the inner Douro valley. The NH 28–32 °C varies from roughly 0% to 7%, with a clear gradient from the northwest to the southeast. The NH 32–36 °C shows a similar pattern, but with generally lower percentage and an enhanced contrast (Figure 4h).

For the sake of succinctness, the previous eight classes were grouped into the following four thermal categories: cool (4–12 °C), temperate (12–20 °C), warm (20–28 °C), and very warm (28–36 °C) (Figure 5). Although this categorization is empirical, it reflects the main climatic conditions occurring in the country, the regional heterogeneities and the share of each category to the local climate. This information may be very useful to accurately and briefly classify local thermal conditions. The number of hours in the year with cool (4–12 °C) conditions ranges from approximately 65% in Serra da Estrela to 18% in the south of Portugal. The number of hours in the year with temperate (12–20 °C) conditions highlights the continentality effect (distance to the coastline), with much lower percentage over inner regions, mostly in the northeast. Along the coast, more than 50% of the hours of the year, on average, have temperate temperatures between 12 °C and 20 °C. On average, the number of hours of the year with warm conditions (20–28 °C) varies between 8% at the highest mountain to 25% in Alentejo and Algarve regions. Finally, the very warm conditions (number of hours with temperature between 28–36 °C) are essentially restricted to inner southern Portugal and to the upper Douro valley (Figure 5d).

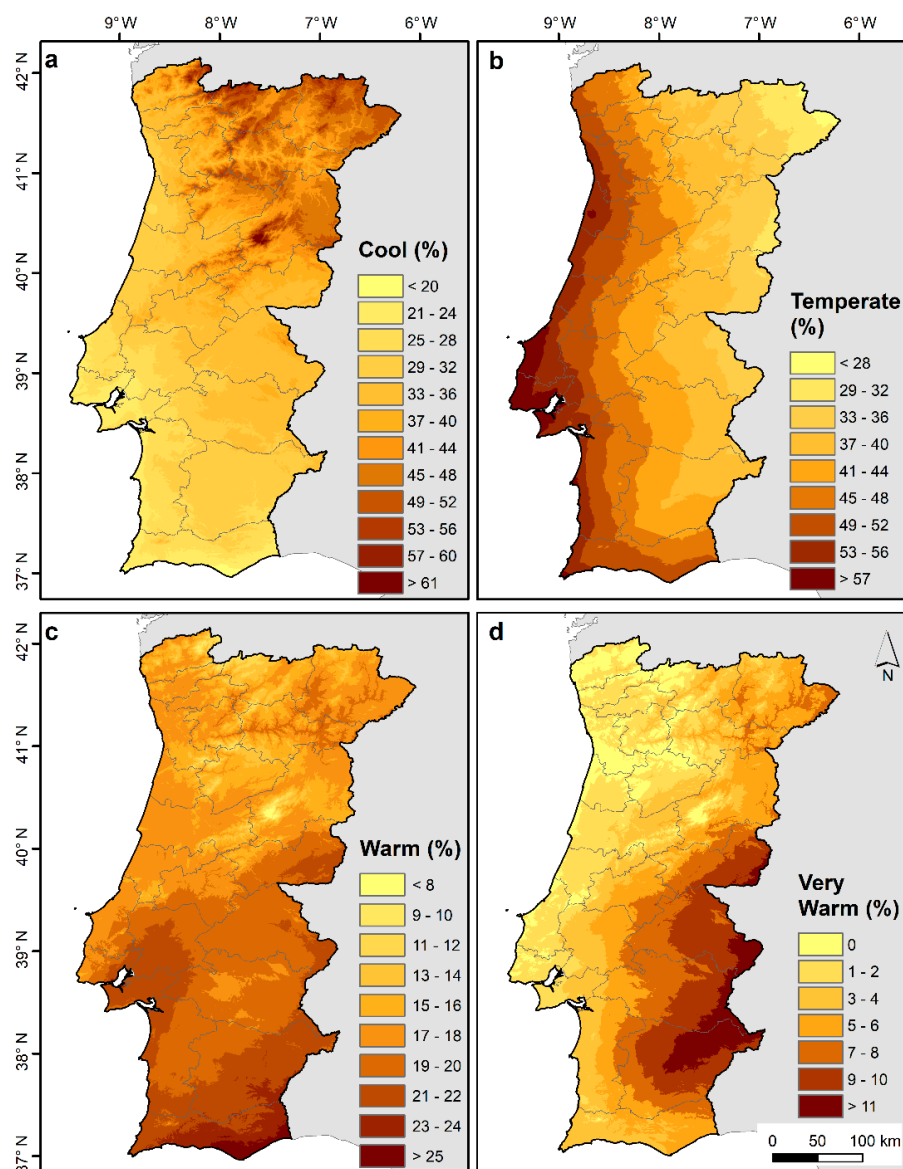


Figure 5. Typical relative number of hours during a year (in %) with (a) cool (4–12 °C), (b) temperate (12–20 °C), (c) warm (20–28 °C), and (d) very warm (28–36 °C) conditions over mainland Portugal, for the period of 2000–2018 (cf. Figure 1b for designations of mapped NUTS level 3).

The distribution of the number of hours by NUTS level 3 highlights the differences between the north and the south of the country. The NUTS level 3 with the highest percentages of the number of hours with temperature between 4–8 °C are Terra de Trás-os-Montes, Alto Tâmega, Douro, Beiras and Serra da Estrela (north of the country). The NH 8–12 °C shows a more homogeneous distribution over all NUTS level 3 (Figure 4b). The NUTS located near the Atlantic Ocean (Oeste, Área Metropolitana de Lisboa, Área Metropolitana do Porto, Região de Aveiro, and Região de Leiria) have higher percentages of NH 12–16 °C. In relation to the NH 16–20 °C and NH 20–24 °C, in addition to these NUTS, stand out those of Alentejo Litoral and Algarve. From temperatures above 24 °C, the NUTS with the highest percentages are located in Alentejo, Tagus Valley (Médio Tejo and Lezíria do Tejo), Algarve, and the interior of the country (such as Beira Baixa and Terras de Trás-os-Montes) (Figure S3).

3.2. Thermal Growing Conditions of Main Species

After a classification of the prevailing thermal conditions in mainland Portugal, based on an hourly observational dataset, the spatial distribution of different fruit species throughout the country was overlaid with them in order to identify their main thermal growing conditions. Even though previous studies have already addressed the connections between thermal conditions and fruit/forest species distributions in Portugal [7,26], the accuracy allowed by the hourly temperatures in the current characterization is unprecedented. Some fruit species in mainland Portugal are located in limited areas (e.g., carob, almond, chestnut, citrus trees), with well-defined climates, whereas others, such as olive trees and vines, are distributed over much wider climatic ranges (Figure 6).

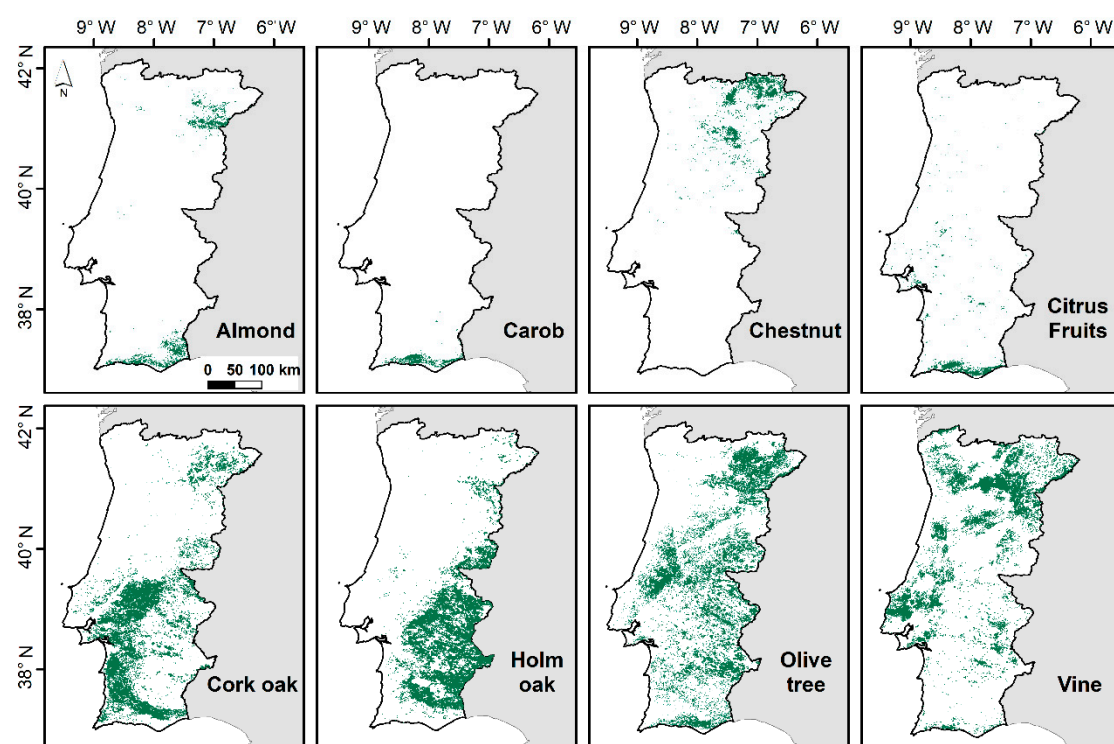


Figure 6. Spatial distributions of the eight outlined species over mainland Portugal (Source: COS 2007).

Overall, higher heat demanding species (carob, citrus, and holm oak trees) are located in the warmest areas (>52% of hours per year with temperatures between 16 °C and 36 °C), while chestnuts are located in much cooler regions (~49% of hours per year with temperatures between 4 °C and 12 °C). Chestnut trees require moderate chilling accumulation, while carob and citrus trees do not have chill requirements. Thus, chestnut trees have a distribution more restricted to the northeastern part of the country and the highest frequency of NH 4–8 °C as compared with the other species (Figure 7).

The distribution of classes of the vineyard, which is present over vast areas of the country (Figure 6), is representative of the average conditions in mainland Portugal, characterized by more than 50% of the hours with temperatures between 12–24 °C (Figure 7a), highlighting the influence of the ocean as a moderating agent of temperature. The holm oak trees, located mainly in the southeast of the country, have the highest number of hours within the range of 32–36 °C, in comparison with the remaining selected species (Figure 7b). On the opposite side, are the chestnut trees, located in the northeastern part of the country (NUT 3-Terras de Trás-os-Montes), with the lowest number of hours with temperatures between 32–36 °C and the major number with lower temperatures, between 4–8 °C (Figure 7).

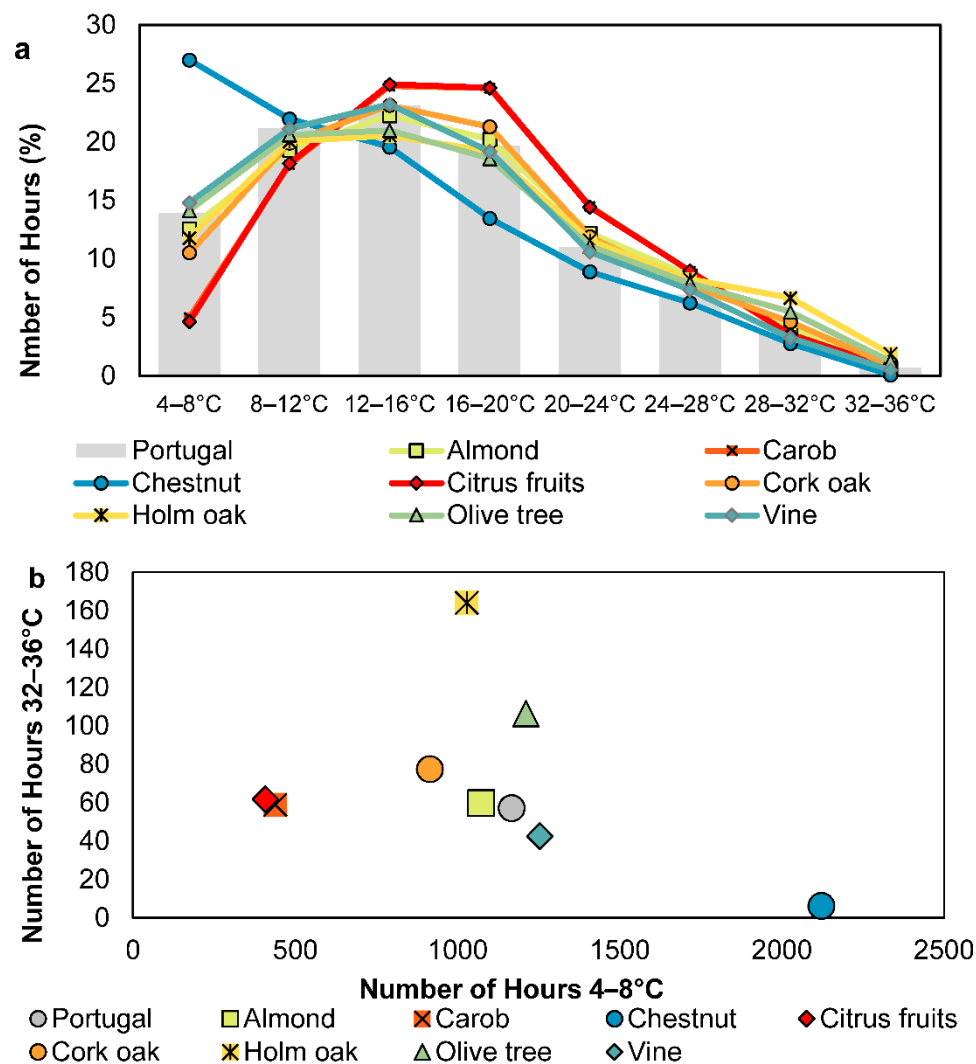


Figure 7. (a) Mean of the relative number of hours (in %) by the different temperature intervals, for the period of 2000–2018 and over mainland Portugal, for the eight selected fruit species. (b) Scatterplot for eight fruit species as a function of their corresponding means of the number of hours with temperature between 4–8 °C and the number of hours with temperature between 32–36 °C, over mainland Portugal and for years 2000–2018.

3.3. Thermal Growing Conditions of Grapevines and Olive Trees

Vines and olive trees are present in much of the country, within a wide range of Portugal's thermal conditions, which may be partially attributed to their different cultivated varieties. Figure 8 shows a considerable variation among the 50 subregions for wines (designations of origin) in the frequency of the four hourly temperature intervals between 4 °C and 20 °C. The geographical distribution

is correspondingly large. Figure 9 shows a more homogenous distribution in frequency of hourly temperature intervals among the six Protected Designations of Origin of olive oil. Its natural distribution is correspondingly restricted. These territorial units are commonly associated with more homogeneous conditions, in terms of climate, soils, and agricultural practices, thus tending to present some typicity in their wines and olive oils [27–29]. The DO/sub-regions located in the northern-central inner Portugal (Trás-os-Montes: Valpaços, Planalto Mirandês, and Chaves; Távora-Varosa; and Beira-Interior: Castelo-Rodrigo and Pinhel), register the highest percentages of the number of hours with temperatures between 4–8 °C, resulting in higher chilling conditions and accumulations. The DO/subregions located on the central coast (Palmela Setúbal, Carcavelos, Colares, Bucelas, Arruda, Torres-Vedras, Alenquer, Lourinhã, Óbidos) show higher percentages of number of hours with temperate conditions, i.e., temperatures between 12 °C and 20 °C. The DOs/sub-regions with the highest percentages of NH 20–24 °C are located in the Algarve, while the DOs/sub-regions with the highest percentages of NH 24–28 °C are located in the southeast of Portugal (Tavira, Alentejo: Moura and Granja Amareleja). The DO/sub-regions that present higher percentages of hours with temperatures above 28 °C, are located mainly in the Alentejo (Figure 8).

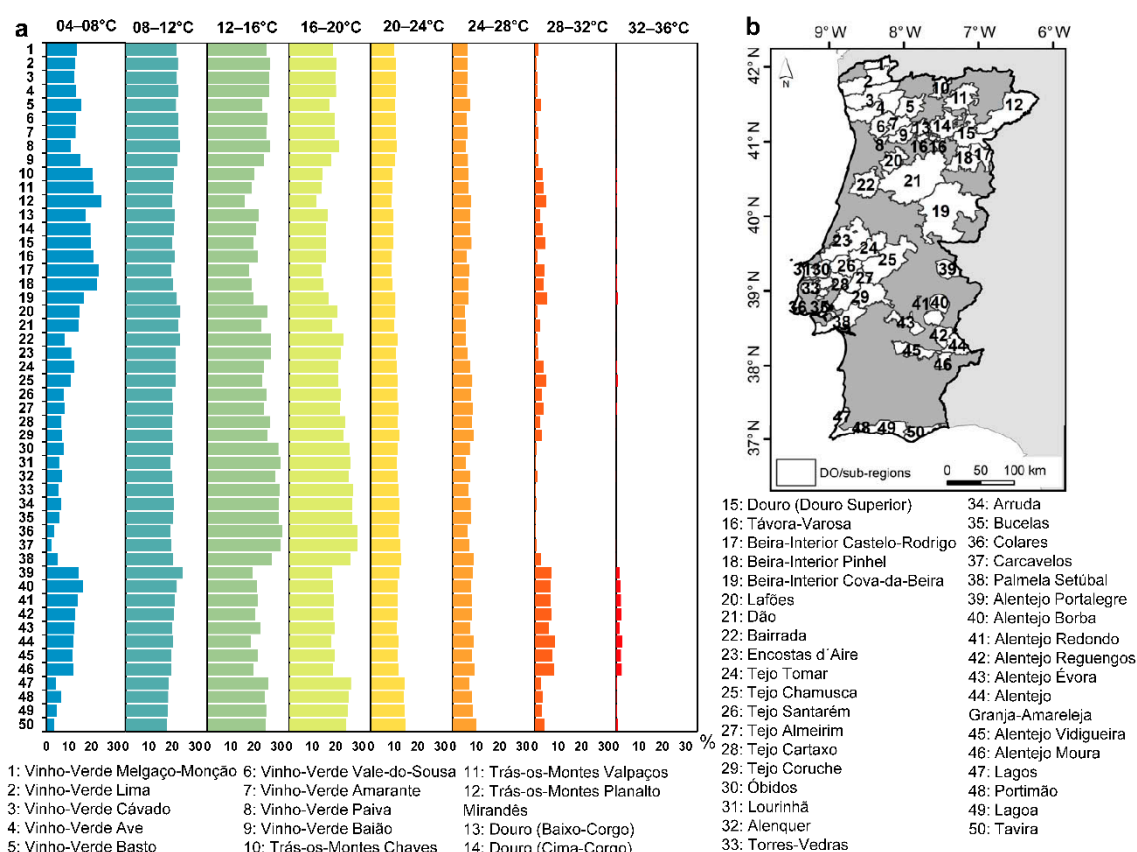


Figure 8. (a) Relative bar chart (in %) for the number of hours by different temperature intervals and for each DO/sub-region of wine. (b) Geographical location of the protected denominations of origin (DOs) and sub-regions (see the list for their designations). Area-means are computed only over the land with vineyard areas (source: COS2007).

Areas of Protected Designations of Origin (PDO) olive oils are mainly found in the interior of the country, where more typical Mediterranean-climate conditions are found (with drier and warmer conditions). Nevertheless, there are important differences between them. The Trás-os-Montes PDO presents a higher percentage of hours with temperatures between 4–8 °C, thus being more adequate for olive tree varieties with higher chilling requirements. The number of hours with temperature between 8–12 °C are very similar between the PDOs. The PDO with the highest number of hours with moderate

temperatures (12–20 °C) is the Ribatejo. For the number of hours with temperature >28 °C, the PDOs with the highest percentages are located in the southeast of Alentejo: Moura and Alentejo Interior (Figure 9).

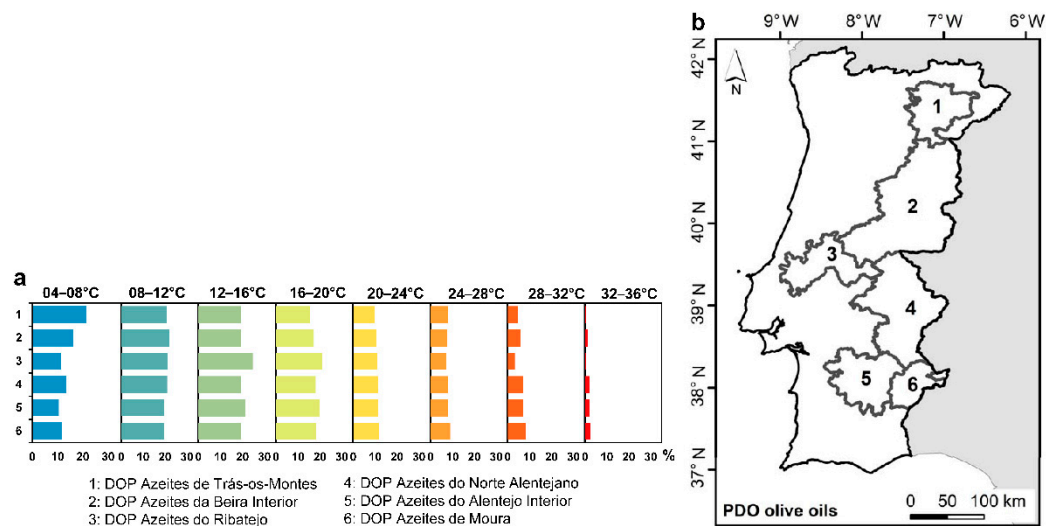


Figure 9. (a) Relative bar chart (in %) for the number of hours by different temperature intervals and for each Protected Designation of Origin (PDO) of olive oil. (b) Geographical location of the PDO of olive oil (see the list for their designations). Area-means are computed only over the olive tree land cover areas (source: COS2007).

4. Discussion and Conclusions

This study provides an innovative analysis of the near-surface air temperature in mainland Portugal, based on hourly observations over the recent period of 2000–2018 and from a large weather station network (63 meteorological stations). The whole process is fully implemented in a GIS and the final maps are published on Supplementary Material, in a widely used file format (shapefile), thus allowing their future application to a wide range of assessments. Although a longer data period would be preferable, typically 30 years, as is recommended by the WMO (World Meteorological Organization), data prior to 2000 have important gaps and inconsistencies that may strongly limit the statistical robustness of the results. In addition, of the 133 meteorological stations with hourly data available, only 63 are used, due to the significant number of data gaps. The present study is a trade-off between the density and temporal consistency of the meteorological station network. A set of hourly temperature maps is obtained using the most recent data available, thus providing accurate information on the current thermal conditions throughout the country.

In the first part of the study, the results allow a detailed geographical characterization of the thermal conditions in mainland Portugal, at a high spatial resolution of 1 km. Such information is of great value to growers and stakeholders in the agrarian sector [30], as it provides a comparison of the different climatic conditions in each agrarian zone. Additionally, the results provide information concerning the relationship between geographical variables and temperature. Thus, final maps can be automatically updated with new hourly temperature data and easily managed within a GIS environment, thus permitting future improvements resulting from new data inputs.

Overall, the outcomes highlight a strong spatial variability and strong seasonality of temperatures in mainland Portugal. The NH 4–8 °C patterns mainly reflect wintertime conditions, whereas the NH 32–36 °C patterns are a manifestation of summertime conditions. The number of hours in the year with cold conditions (4–12 °C) is higher in the northern-central regions, mainly in mountainous areas. On the other hand, the number of hours in the year with temperate conditions (12–20 °C) is largely influenced by the distance to the coastline, presenting much lower values over inner Portugal, mostly

in the northeast. Still, the very warm conditions (number of hours with temperature between 28–36 °C) are essentially restricted to inner-southern Portugal and to the upper Douro valley.

The present study results are also key to understanding climate change impacts on each agrarian region in Portugal. Taking into account previous studies regarding climate change projections for Portugal [7,12,21,31], it is expected that temperatures should increase. It should be noted that extreme temperatures (>30 °C) are expected to be more frequent under future climates. Hence, the number of hours in each class of these maps are expected to shift under future climatic conditions.

In the second part of the study, some application examples are shown, through the extraction of information for the NUTS level 3 administrative divisions in mainland Portugal. This work may be replicated in the future, in other territorial units up to the local level or other socio-economic sectors. The most striking correspondence between geographical distribution of cool and very warm areas and occurrence of the species is that of chestnut and holm oak (Figure 5a,d and Figure 6). Carob and citrus trees do not have chill requirements while chestnut trees require moderate chilling accumulation. In fact, in carob and citrus trees, the low temperatures may cause chilling and freezing injuries on plants and consequently limit crop production and yield [32,33]. The chestnut trees located in the northeastern part of the country, are the species with the major number of hours with lower temperatures. In addition to the moderate chill requirement, the chestnut trees present a high sensitivity to summer droughts [34]. Of note also, the holm oak trees, located mainly in the southeast of the country, have the highest number of hours within the range of 32–36 °C. However, according to Terradas [35], holm oak is less adapted to extreme drought in comparison with other evergreen Mediterranean tree species, such as carob, olive, or cork oak. The areas of species like: holm oak, olive, almond, and cork oak are those that have more hours with temperatures between 28–36 °C (very warm conditions).

More specifically, vine and the olive trees are analyzed by region to accurately characterize their current growing conditions and to identify regions with similar features. It is important to highlight that there are different varieties/cultivars of grapevines and olive trees that tend to be grown in the most suitable areas of each region. Many of these varieties are either native or have been empirically selected in each region over several decades or even centuries [7]. As such, they already tend to be grown in the most favourable pedoclimatic conditions so as to be economically viable and sustainable, thus warranting some correspondence between their spatial distribution and bioclimatic suitability. Santos, Costa, and Fraga [7] selected eight main fruit species in Portugal, to analyze the potential shifts in their thermal conditions, using two bioclimatic indices (growing degree hours and chilling portions) and based on the daily grid dataset from E-OBS [36]. For the future, increases of heat accumulation and decreases of chilling accumulation are projected over most of Portugal. Inner southern Portugal is expected to undergo the most detrimental climatic changes for temperate fruit and nut trees, since decreases of heat accumulation and significant reductions of winter chill are expected in this region [7]. The results for the current period, presented herein, are in line with this preceding study, though the present study allows a more detailed and accurate characterization of the thermal conditions in mainland Portugal by using hourly data.

This knowledge is of great importance for different socio-economic sectors, such as agriculture and forestry, e.g., by assisting bioclimatic zoning and suitability assessments. An accurate characterization of the bioclimatic conditions of a given territory is an asset that may potentiate a better planning and management. The resulting knowledge may help decision support systems provide more reliable and accurate guidelines to stakeholders, decision-makers, or farmers. Furthermore, the application to the fruit species undertaken in the present study is a mere illustration of a possible usage of the obtained information. It may be applied to a much wider range of areas of research fields and practical applications such as territorial planning, biodiversity, hydrology, agriculture and forestry systems, and civil protection.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2076-3417/9/18/3782/s1>, Table S1: Geographical coordinates (latitude, longitude and elevation) of the Portuguese meteorological stations used in this study; Figure S1: Map of failures in the hourly data (%), at the 63 selected meteorological stations, for

the period 2000–2018; Figure S2. Distribution of climatic data and raw data of the number of hours, by different temperature intervals (see legend), for all meteorological stations and for the period 2000–2018; Figure S3. Number of hours (%) for NUTS level III (cf. Figure 1 for locations of NUTS), by different temperature intervals (see legend), Shapefiles S4. Final Maps.zip.

Author Contributions: Conceptualization, M.S., H.F., and J.A.S.; Methodology, M.S., H.F., M.B.-P., and J.A.S.; Software, M.S., H.F., and J.A.S.; Validation, M.S. and J.A.S.; Formal analysis, M.S. and J.A.S.; Investigation, M.S., H.F., and J.A.S.; Resources, M.S., H.F., M.B.-P., and J.A.S.; Data curation, M.B.-P.; Writing—original draft preparation, M.S.; Writing—review and editing, H.F., M.B.-P., and J.A.S.; Visualization, M.S., H.F., M.B.-P., and J.A.S.; Supervision, J.A.S.; Project administration, J.A.S.; Funding acquisition, J.A.S.

Funding: This study was funded by the Clim4Vitis project—“Climate change impact mitigation for European viticulture: knowledge transfer for an integrated approach”, funded by European Union’s Horizon 2020 research and innovation programme, under grant agreement no. 810176. This work was also funded by R&D project INNOVINE&WINE—Vineyard and Wine Innovation Platform, NORTE-01-0145-FEDER-000038, co-funded by FEDER (Fundo Europeu de Desenvolvimento Regional) through the Programme NORTE 2020 (Programa Operacional Regional do Norte 2014/2020).

Acknowledgments: This work is supported by National Funds by FCT-Portuguese Foundation for Science and Technology, under the project UID/AGR/04033/2019. Helder Fraga thanks the FCT for CEECIND/00447/2017.

Conflicts of Interest: The authors declare no conflict of interest.

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