Article

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Identifying Optimal Zones for Avocado Cultivation in Iberian Peninsula: A Climate Suitability Analysis

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Abstract: In recent decades, the cultivation of avocados has expanded throughout the Iberian Peninsula, with most of the production occurring on the southern Atlantic and Mediterranean coast, as well as in the Canary Islands and the north. This expansion is due to high demand and high prices, which have made the crop very attractive. However, climatic suitability criteria have not always been followed, putting sustainability at risk. Avocados originate from tropical and subtropical areas and have very specific climatic requirements that must be met to ensure good production. This study analyzed key climatic variables, including winter cold damage, pollen viability, and flowering and fruit set temperatures. Using daily climate data from 1975 to 2022, advanced spatial analysis techniques were applied to produce suitability maps. The results indicate that the expansion of the crop is possible in certain areas of southern Andalusia, but not in the rest of the peninsula. Minimum winter and March temperatures are the main limiting factors. This work provides valuable insights into the potential for sustainable agricultural intensification, the sustainability of agricultural decision-making, and resilience to climate change.

Keywords: Geospatial analysis; optimal zones; climate resilience; mediterranean region

1. Introduction

In recent years, the area under avocado cultivation has expanded beyond its usual production areas in the tropics and subtropics, into a diversity of climatic environments and geographical regions. This includes the Mediterranean region. Avocado cultivation, driven by changing consumer preferences and evolving climatic conditions, represents a promising avenue for sustainable agricultural practices in the Iberian Peninsula.

The avocado (*Persea americana* Mill.), in addition to being a staple food, has also gained global attention as a versatile raw material to produce cosmetics, soap and oil [1]. The avocado is native to Mexico and Peru. It is cultivated in tropical and subtropical regions all over the world. Mexico, Peru and Chile are the main producers worldwide [2]. Since 2010, the global avocado market has experienced a high annual growth rate of 12% on average over a decade [3]. Spain is the leading avocado producer in the European Union, with more than 23,953 hectares in 2023 [5]. The provinces of Malaga and Granada are particularly important avocado-producing areas in Spain [6–9].

The first avocado plantations in Spain date back to the 16th century, but it was not until the mid-20th century that they were planted for commercial purposes in the Almuñécar area, and it was not until the 1990s that the avocado became popular on both the Malaga and Granada coasts. Sugar cane cultivation was widespread in these areas, mainly because of the area's climatic conditions, which were also well suited to avocado cultivation. In recent decades there has been an expansion of cultivation in the Mediterranean area, mainly in Cádiz, Huelva and the Valencian Community.

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Production is also increasing in the islands of the Canary archipelago and in specific areas of the northern coasts of the Iberian Peninsula, from Galicia to the Basque Country. Of the total area, some 14,000 are in Andalusia, 3,000 in the Valencian Community and 2,500 in the Canary Islands [5]. Historically, provinces such as Malaga and Granada have been at the forefront of avocado cultivation, capitalizing on their temperate climate and fertile soils to produce abundant crops [6–8,10]. The production of avocados in Spain is the result of a complex interplay between several factors, including environmental considerations, farming practices and socio-economic conditions. These factors must be analyzed to ensure a sustainable expansion of the crop.

The sustainability of this thriving sector is facing an unprecedented challenge due to the accelerating effects of climate change. This phenomenon poses a significant threat to avocado production worldwide. Climate variability, rainfall patterns and the occurrence of extreme weather events have a critical impact on avocado productivity. These factors affect tree health, yield and resilience to environmental stressors. As climate patterns continue to evolve, the necessity for comprehensive assessments of climatic suitability and adaptive cropping strategies becomes increasingly pressing, particularly in regions such as Andalusia where agriculture plays a pivotal role in livelihoods and food security. Despite its tropical origin, the avocado can be found up to 43° latitude, due to its genetic diversity [12]. To be fruitful, the avocado plant needs warm temperatures all year round and sunny, windless locations [13]. In general, avocado trees must be protected from strong winds and freezing temperatures. In general, avocados grow best at temperatures between 20–25°C during the days, and at temperatures above 10°C at night. It has been reported that the maximum temperature for vegetative development is 20 °C, and that the avocado tree requires a minimum temperature of 10 °C to 17 °C and a maximum temperature of 28 °C to 33 °C for fruit set [16].

The yield of avocados is subject to significant fluctuations due to temperature variations. In Mediterranean climates, such as those found in California, Hodgson [17] identified three key climatic factors that can impede avocado cultivation: frost events during the winter season; low average minimum temperatures experienced during the critical flowering and fruit set stages; and sudden heat waves occurring during the fruit set period. These temperature-related constraints can have a detrimental impact on avocado production, emphasizing the importance of understanding the role of air temperature as an indicator of avocado ripening time in such climatic regions.

Avocado, like all subtropical crops, is very sensitive to frost, and although there are slight differences in avocado races, it is considered that below -1 °C the tree can suffer severe damage, so planting should be avoided even in places with low frost probability [18–21].

1.1. Optimal and Low Temperatures Experienced during the Critical Flowering and Fruit Setting Stages

The relationship between temperature and avocado flowering, fertilisation, and fruit set has been the subject of extensive investigation. Lahav et al. (1982) [15] indicated that optimum temperatures for fruit set were between 20 °C and 30 °C during the day during the fruit set phase, however Whiley and Winston [22], found optimum temperature ranges of between 23–27 °C during the day and 10 °C during the night More recently Lemus et al. [23] and Torres et al. [24] agree that maintaining daily temperatures of 20 to 25 °C and night temperatures above 10 °Care optimal for fruit set, finally Intagri [25], determined this optimal range of 28 °C to 33 °C.

The impact of low temperatures during the flowering and fruit set stages of avocado cultivation remains a subject of debate.

Several studies have reported that low temperatures can have detrimental impacts on these reproductive processes. Tomer [26] and Sedgle [27] found that temperatures below 10 °C delayed flowering and fertilisation in avocados. Other research suggests that low temperatures do not necessarily have a detrimental effect, but rather may only delay or retard the flowering and fruit set processes [28–30] according to, Rotem and Leshem [31] observed that good avocado yields could still be obtained even after several consecutive nights with minimum temperatures of 10 °C. Interestingly, Argaman [32] in Israel clearly showed that temperatures as low as 7-8 °C for two consecutive nights did not affect flowering processes. However, Sedgley and Annells [33]; Sedgley and Grant [34]

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indicated that at lower temperatures (10 °C), two days after pollination no pollen tubes are observed entering the ovule.

Some studies have reported that fruit set does not occur when mean daily temperatures fall below 13 °C [17]. Similarly, Gillespie [29] observed that there was little or no fruit set if mean night temperatures were below 8 °C. Oppenheimer [28] also noted that successful fruit set required temperatures of at least 12-13 °C. Regarding pollen germination, temperatures above 20 °C have been found to be optimal [35]. Intagri [25] indicated that minimum temperatures above 10-17 °C are necessary for fruit set. These contradictory findings underline the complex and nuanced relationship between temperature and avocado reproductive development. The contradictory evidence also highlights the need for further research to fully elucidate the role of low temperature extremes and their specific impacts on avocado reproductive development in Mediterranean climates.

It is also the case that relative humidity exerts an influence on anther dehiscence. Low relative humidity conditions have the effect of accelerating pollen release, as evidenced by studies conducted by Loupassaki et al. [27], who observed that increasing relative humidity by more than 50% has the beneficial effect of improving pollen germination.

The utilization of the number of days with optimal climatic factors at different crop stages has been demonstrated to be an efficacious approach for the characterization of climatic conditions and the identification of suitable growing areas in other crops, including grapevine, tomato and olive [38–40].

1.2. Heat Waves during Fruit Set

Previous research has documented the detrimental effects of high temperatures at various stages of avocado development. It is suggested that high temperatures during flowering and fruit set are responsible for early abortion and low yields [41,42]. Sedgley [22] demonstrated that high day (33 °C) and night (28 °C) temperatures can negatively impact pollen tube growth and fruit set in avocados. This finding was corroborated by Argaman [43], who observed similar effects under controlled climatic conditions with daytime temperatures between 32 °C and 35 °C and nighttime temperatures of 22 °C. During the early stages of fruit set, avocados appear to be particularly susceptible to high temperatures, as Sedgley and Annells [33] reported that a daytime temperature of 35 °C could result in complete fruit drop within 10 days of fertilisation.

The timing and duration of these temperature-related occurrences in relation to flowering and fruit set are of particular importance in the Iberian Peninsula, as high temperatures accompanied by low relative humidity can be especially critical [44,45]. Furthermore, Tzatzani et al. [46] demonstrated that high temperatures during the summer can affect the dry matter content of fruits, while low temperatures in autumn can delay ripening, and both influence fruit set [47,48]. Therefore, it is necessary to create models that incorporate spatial information to expand knowledge of minimum and maximum temperatures and the risk of extreme events [49–52].

For decades, geospatial techniques have gained considerable interest among the scientific community in the study of earth and hydrological sciences to solve and understand diverse problems and develop complex approaches in natural resource management [53]. These techniques have been successful for decision-making in agricultural management to minimize risks. Despite the great influence of temperatures on the distribution and productivity of crops and the importance of the agricultural sector in the area, no study has analyzed the climatic suitability of avocado growing areas in the Iberian Peninsula.

This research aims to carry out a spatial analysis to identify suitable climatic zones as well as the limiting variables in the expansion of this crop in the Iberian Peninsula.

2. Materials and Methods

2.1. Study Area

The Iberian Peninsula (IP), a geographical area located in southwestern Europe, encompassing Spain and Portugal, serves as the focal point of this study. The IP's strategic position within the

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general atmospheric circulation patterns, characterized by dynamic north-to-south movements depending on the season, contributes to its diverse climatic landscape. As a transitional zone between warm and cold air masses (subtropical and polar), the IP exhibits a marked climatic heterogeneity, further exacerbated by the region's varied topography [54]. According to the climate classification system proposed by Beck et al. [54], the IP can be broadly divided into four major climatic groups. The central and southern regions predominantly feature temperate climates with extremely dry and hot summers. The northwestern Iberian Peninsula, along with much of the western Portuguese coast and numerous mountainous interior areas, experience a temperate climate with dry and mild summers. In the Cantabrian region, the Iberian System, a portion of the northern plateau, and vast swaths of the Pyrenees (excluding the highest elevations), the climate is temperate without a distinct dry season and mild summers. Finally, the eastern, southeastern, and central areas of the IP are characterized by cold steppe climates.

2.2. Database and Interpolation Method

The dataset utilized in this study was sourced from 71 stations within the European Climate Assessment & Dataset (ECA&D) [55–57], which provided the daily maximum and minimum temperature records for the period of 1975–2022. The quality control procedures outlined in the Algorithm Theoretical Basis Document project, developed by the Royal Netherlands Meteorological Institute for the ECA&D, were rigorously applied to this ECA&D database [55]. The resulting blended series successfully passed the standard homogeneity test, the Buishand range test, the Pettitt test, and the Von Neumann ratio test, as described by Wijngaard et al. [58] and the ECA&D [55]. For those series presenting missing values, the recommendations provided by the World Meteorological Organization (WMO, 2011) [59] and Allen et al. [60] were followed to complete the data. The daily data from each selected station were subsequently processed and analyzed, with the annual values for each of the indices used in this study being calculated. The locations of all the selected stations are depicted in Figure 1, and their detailed geographical coordinates are presented in Table 1.

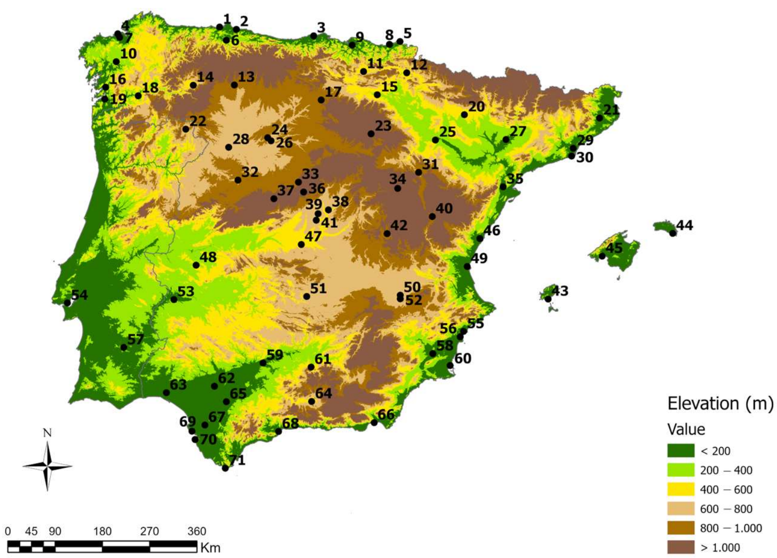

Figure 1. Digital elevation model of the Iberian Peninsula and Balearic Island; and location of weather stations. The numbers in Figure 1 correspond to the station numbers in the Table 1.

Table 1. Elevation and geographic coordinates of the selected weather stations (sorted by latitude) from the Iberian Peninsula and Balearic Island.

N°	Station	Elevation (m)	Latitude (°N)	Longitude (+°E, −°W)	Nº	Station	Elevation (m)	Latitude (°N)	Longitude (+°E, −°W)
1	Avilés	127	43.57	−6.04	37	Ávila	1130	40.66	−4.68
2	Gijón	3	43.54	−5.64	38	Torrejón	611	40.48	−3.45

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3	Santander	64	43.46	−3.82	39	Madrid	667	40.41	−3.68
4	Coruña	58	43.37	−8.42	40	Teruel	900	40.35	−1.12
5	Fuenterrabía	4	43.36	−1.79	41	Getafe	617	40.30	−3.72
6	Oviedo	336	43.35	−5.87	42	Cuenca	945	40.07	−2.14
7	Alvedro	98	43.31	−8.37	43	Escodoba	6	38.87	1.38
8	Igueldo	251	43.31	−2.04	44	Mao	91	39.85	4.21
9	Bilbao	42	43.30	−2.91	45	Palma de Mayorca	3	39.55	2.62
10	Santiago	370	42.89	−8.41	46	Castellón	35	39.95	−0.07
11	Vitoria	521	42.85	−2.65	47	Toledo	515	39.88	−4.05
12	Pamplona	442	42.82	−1.64	48	Cáceres	459	39.48	−6.37
13	León	916	42.59	−5.65	49	Valencia	11	39.48	−0.37
14	Ponferrada	534	42.56	−6.6	50	Albacete	674	39.01	−1.86
15	Agoncillo	353	42.45	−2.33	51	Ciudad Real	628	38.99	−3.92
16	Pontevedra	108	42.44	−8.62	52	Los Llanos	704	38.95	−1.86
17	Villafría	890	42.36	−3.63	53	Talavera la Real	185	38.88	−6.83
18	Ourense	143	42.33	−7.86	54	Lisboa	77	38.72	−9.15
19	Vigo	261	42.24	−8.62	55	Alicante	81	38.37	−0.49
20	Huesca	541	42.08	−0.33	56	Alicante	43	38.28	−0.57
21	Girona	143	41.91	2.76	57	Beja	246	38.02	−7.87
22	Braganza	690	41.80	−6.73	58	Murcia	61	38.00	−1.17
23	Soria	1082	41.78	−2.48	59	Córdoba	90	37.84	−4.85
24	Villanubla	846	41.70	−4.85	60	San Javier	4	37.79	−0.8
25	Zaragoza	247	41.66	−1.01	61	Jaén	582	37.78	−3.81
26	Valladolid	735	41.65	−4.77	62	Sevilla	34	37.42	−5.88
27	Lleida	192	41.63	0.60	63	Huelva	19	37.28	−6.91
28	Zamora	656	41.52	−5.73	64	Granada	567	37.19	−3.79
29	Barcelona	412	41.42	2.12	65	Morón de la Frontera	87	37.16	−5.62
30	Barcelona	4	41.29	2.07	66	Almería	7	36.83	−2.45
31	Daroca	779	41.11	−1.41	67	Jerez de la Frontera	27	36.75	−6.06
32	Salamanca	790	40.96	−5.50	68	Málaga	7	36.67	−4.49
33	Segovia	1005	40.95	−4.13	69	Rota	21	36.64	−6.33
34	Molina de Aragó	1056	40.84	−1.89	70	Cádiz	1	36.50	−6.26
35	Tortosa	44	40.82	0.49	71	Tarifa	32	36.02	−5.6
36	Navacerrada	1894	40.78	−4.01					

2.3. Interpolation Method

While there are numerous algorithms available for generating estimates at unsampled locations, geostatistical methods offer several important advantages [61]. Geostatistical techniques acknowledge that the spatial variation of any continuous variable is often too irregular to be accurately modeled by a simple mathematical function. Instead, the studied variable is considered a random process, taking on a series of outcome values according to a specific probability distribution.

Geostatistics provides a wide range of methods, collectively known as kriging, that enable the estimation of values at unsampled locations. These kriging techniques consider the values at neighboring sampling points and utilize a variogram model that accounts for the distance and degree of variation between all sampling locations, thereby minimizing the variance of the estimation error [61].

For discrete sampling locations, the variogram is estimated as:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \{Z(x_i) - Z(x_i + h)\}^2 \quad (1)$$

where (h) is the experimental semivariance value at distance interval h, Z(xi) are the measured sample values at sample points xi, in which there are data at xi and xi+h; N(h) is the total number of sample pairs within the distance interval h. When some points of a variogram plot are determined by calculating variogram at different lags, a model (theoretical variogram) should be fitted to the points.

All geostatistical estimators are variants of the linear regression estimator Z*(x):

$$Z^*(x) - m(x) = \sum_{i=1}^{n} w_i\,(x) \cdot [Z(x_i) - m(x_i)] \quad (2)$$

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where each datum, Z(xi), has an associated weight, wi(x), and m(x) and $m(x_i)$ are the expected values of Z*(x) and Z(xi) respectively. The kriging weights are computed to minimise the estimation variance, Var[Z*(x) − Z(x)], while ensuring the unbiasedness of the estimator, E[Z*(x) − Z(x)] = 0.

The chosen model for the trend, $m(x)$ characterizes any type of kriging. Thus, $m(x)$ is unknown in the ordinary kriging technique and is considered to fluctuate locally, main taining the stationarity within the local neighborhood. When an estimate is computed at any unsampled location, the weights, $w_i(x)$, corresponding to each sample point, are generated solving a system of linear equations where the fitted (theoretical) variogram controls the spatial variability of the studied variable [62].

Cross-validation analysis is used for evaluating effective parameters for cokriging interpolations. In this analysis, each measured point in the area is individually removed, and its value is estimated based on neighbouring measurement points. Then the point is replaced, and the next point is removed and estimated, and so on. Finally, the estimations are compared with measured values in all points, and statistical parameters are deter-mined [64].

All operations, including the spatial representation and visualization of the variables, were conducted in the GIS software ArcGIS v. 10.1. The geostatistical analysis was performed with the extension Geostatistical Analyst of ArcGIS.

2.4. Study Variables

To evaluate the suitability of the Iberian Peninsula for avocado cultivation, two main groups of variables were considered. These factors have proven to be highly influential for the success of avocado crops (Table 2).

Table 2. Selected variables and cut-off values.

Grups		Description*	Cut-off value
Cold damage	V1	Number of days in November with t > 0 °C.	25
	V2	Number of days in December with t > 0 °C	21
	V3	The number of days in January with t > 0 °C	10
	V4	The number of days in February with t > 0 °C	18
	V5	The number of days in March with t > 0 °C	28
Flowering and fruit set	V18	The number of days in March with 20 ≤ T ≤25 °C	1
	V22	The number of days in March with t ≥ 10 ºC	2
	V28	The number of days in April with 20 ≤ T ≤25 °C	2
	V32	The number of days in April with t ≥ 10 °C	7
	V37	The number of days in March with HR >= 50%	13
	V39	The number of days in April with HR >= 50%	7

*t: daily minimum temperature; T: daily maximum temperature, HR: relative air humidity.

Cold Damage: The number of days in each month (November to March) where the minimum temperature was above 0 °C was counted during these critical growth periods, minimizing the risk of frost-related damage.

Flowering and Fruit Set: According to the information (see section 1), the maximum daily temperature for flowering and fruit set should be between 20 and 25 °C, during the months of March and April. The minimum daily temperature must be above 10 °C, and the relative humidity should be at least 50%. Therefore, the days of these months where the temperature and relative humidity were within these ranges were counted.

Although a total of 39 variables, both favorable and unfavorable, were initially analyzed for the months of November to April, only the 11 favorable variables were chosen for this study, as they

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effectively exclude the unfavorable ones. For example, the number of days in March with maximum temperatures between 20 and 25 °C (V18) excludes those variables where the temperature is below 20 °C and above 25 °C.

To determine the cut-off values, four to five plots with historical production series were selected by crop experts to corroborate that they do not have any climatic conditions. Once the geostatistical cokriging model had been constructed, the minimum values of the variables selected in these plots were obtained. These minimum values constitute the cut-off values, as they indicate the minimum number of days that the conditions of the selected variables must be fulfilled (Table 2). In order to ensure the greatest possible accuracy in the assessment of climatic suitability, the geostatistical model was constructed with the 5% percentile value for all variables. This ensures that if the model determines that a point on the terrain meets a condition, it does so with a 95% probability of being correct.

Once the values of each variable had been obtained, the values of the Cokrigin raster layer were reclassified (Figure 2), with a value of 1 assigned to those points (green pixels) that met the cut-off condition and a value of 0 assigned to those that did not (red pixels). This enabled the optimal and non-optimal zones for each variable to be observed on the maps generated. Finally, in order to construct the map with the ideal zones, taking into account all the variables together, another raster layer was created whose value is the multiplication of the values assigned in the previous step. This ensures that those points in which all the conditions have been fulfilled will be assigned a value of 1, however, with only one variable that does not meet the suitability condition the final value will be 0. With this procedure we ensure strict climatic suitability.

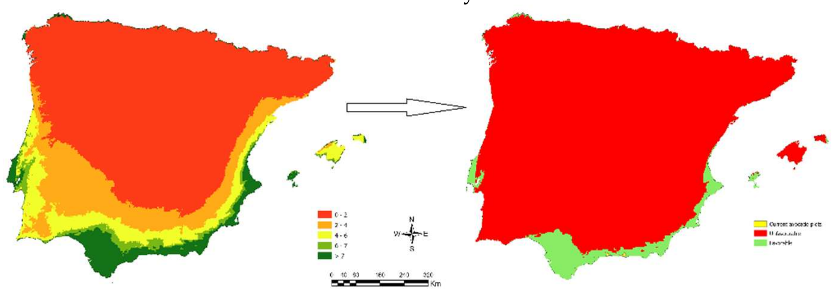

Figure 2. Determination of favorable areas (meet the cut-off value), based on the spatial distribution of each variable. As an example, variable 32 is shown, cut-off value: 7 days with t ≥ 10 °C in April.

3. Results and Discussion

3.1. Cold Damage

The minimum values derived from the analysis of the selected plots were as follows: 25 frost-free days in November, 21 frost-free days in December, 10 frost-free days in January, 18 frost-free days in February and 28 frost-free days in March. The areas that meet these conditions can be found in Figure 3.

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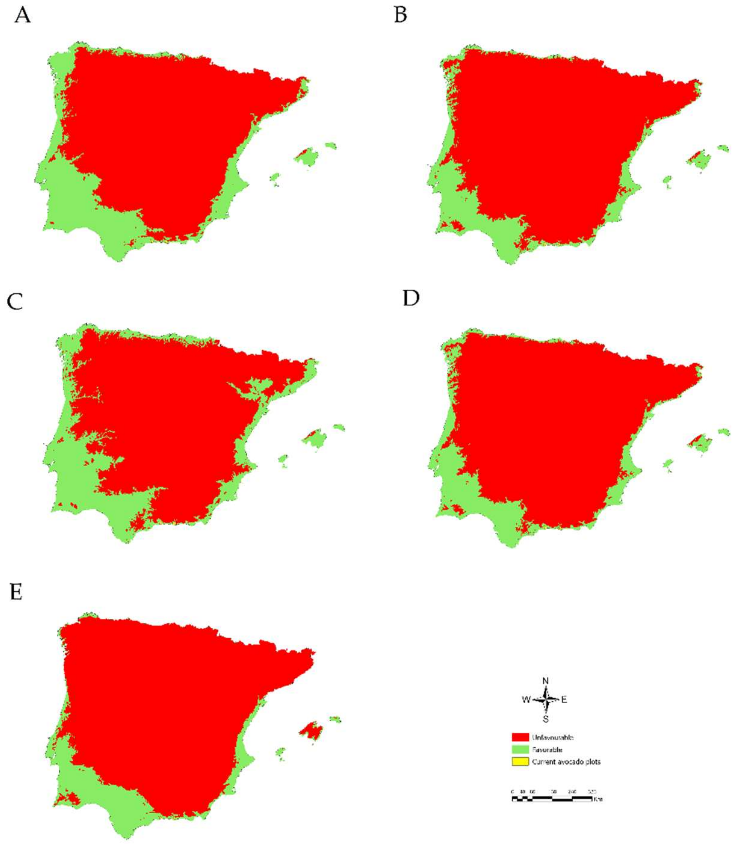

Figure 3. Geographical distribution of favorable zones for avocado cultivation in terms of winter cold in Iberian Peninsula and Balearic Island: A Areas with more than 25 days with t>0 °C in November. B Areas with more than 21 days with t>0 °C in December. C Areas with more than 10 days with t>0 °C in January. D Areas with more than 18 days with t>0 °C in February. E Areas with more than 28 days with t>0 °C in March.

Areas with favourable winters for avocado cultivation have been identified on all the coasts of the Iberian Peninsula and in the south-west of the Iberian Peninsula. Similarly, favourable conditions prevail in the Balearic Islands. However, for the northern coast of the Iberian Peninsula, the most restrictive factor in delimiting favourable zones is the number of days with temperatures above 0°C during the months of December and March. March was the most limiting month for identifying suitable areas, as it reduced the favourable area for the crop on the Portuguese Atlantic coast (limiting it to the south coast), reduced the favourable area on the Catalan coast to the north-east of the Peninsula, and on the coast to the north of the Peninsula, where it was limited to areas in close proximity to the sea. García Martín et al. (2022) [65] found a similar distribution in the peninsula for frost days, with a date before 15 February for the last winter frost, which is in agreement with the findings of our study. On the other hand, it is evident that the proximity to the sea reduces the incidence and intensity of frost [66], allowing the cultivation of cold-sensitive species.

3.2. Flowering and Fruit Set

3.2.1. V18 the Number of Days in March with 20 °C ≤ T ≤25 °C

The March days with maximum temperatures between 20 and 25 °C limited the favorable avocado growing area to a large extent (Figure 4). The entire northern and eastern half of the Iberian Peninsula is unfavorable, including the Balearic Islands. The same result was found throughout Portugal. This result indicates that the month of March, although it has very few frosts, the maximum temperatures reached during the days are not sufficient for a correct flowering, and therefore, even

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if the crop can prosper, the yields would not be ideal. The aforementioned condition resulted in a significant reduction in the cultivable land area in the southern region of the province of Cádiz.

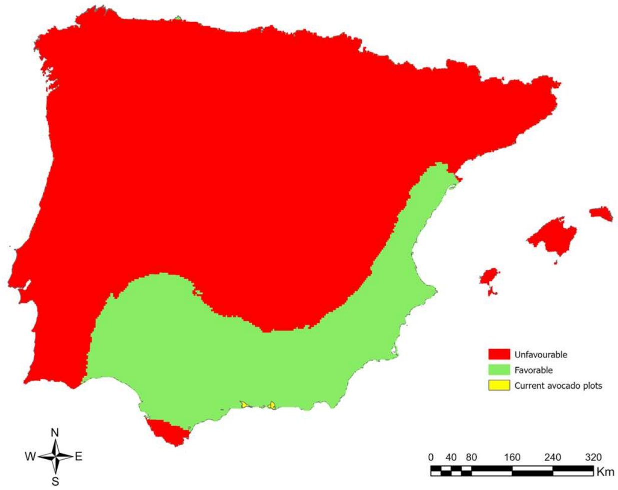

Figure 4. Geographical distribution of favorable areas for avocado cultivation in terms of maximum March temperatures on the Iberian Peninsula and Balearic Islands.

3.2.2. V22 the Number of Days in March with t ≥ 10 °C

Figure 5 shows once again that March temperatures are very limiting for avocado cultivation in the Iberian Peninsula and the Balearic Islands. Specifically, only the areas coloured in green have more than 2 days with daily minimum temperatures above 10 °C, limited to the southern Atlantic and Mediterranean coast and a small strip on the eastern Mediterranean coast. This limitation implies disorders in flowering and fruit set, which is often the cause of the great variability of avocado yields [17]. Calabrese (1992) [62] indicated that in subtropical climates, it is the conditions of thermal insufficiency at flowering and fruit set that are the most limiting for the crop.

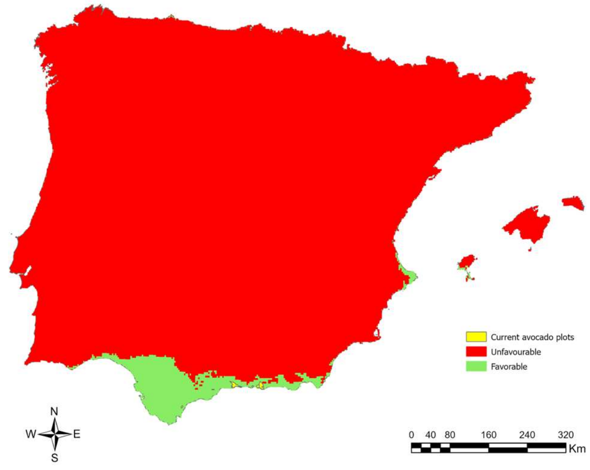

Figure 5. Geographical distribution of favorable areas for avocado cultivation in terms of minimun March temperatures on the Iberian Peninsula and Balearic Islands.

3.2.3. V28 the Number of Days in April with 20 ≤ T ≤25 ºC

The days with maximum temperatures between 20 °C and 25 °C during the month of April do not represent an additional restriction in the areas delimited by the previous variables, although it is very limiting in the Balearic Islands (Figure 6). Instead, they indicate favourable areas for cultivation throughout the south of the peninsula and the east near the sea. April is a warm month, but not as warm as the summer months. The minimum temperature is achieved over a large area for more than two days.

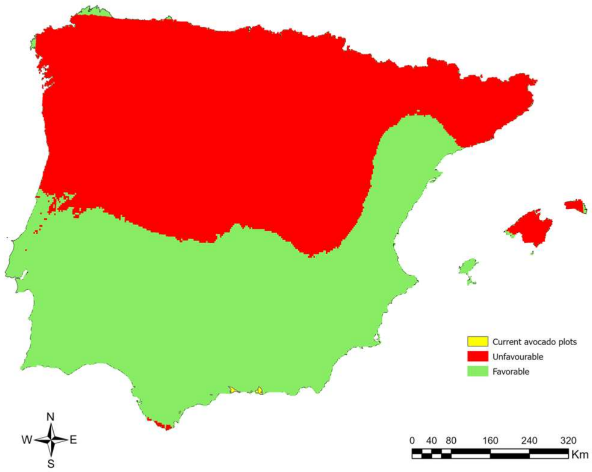

Figure 6. Geographical distribution of favorable areas for avocado cultivation in terms of maximum April temperatures on the Iberian Peninsula and Balearic Islands.

3.2.4. V32 the Number of Days in April with t ≥ 10 °C

The minimum temperatures in April (when the avocado is in full bloom) drastically reduce the area suitable for avocado cultivation in the Iberian Peninsula, restricting it to a small strip of the southern Mediterranean coast and the provinces of Cádiz and Huelva, on the southern Atlantic coast (Figure 7). The island of Ibiza (Balearic Islands) is also eligible. Colilles Cascallar (2020) [68], who analysed the possible areas of cultivation on the peninsula, found a very similar distribution.

Figure 7. Geographical distribution of favorable areas for avocado cultivation in terms of minumum April temperatures on the Iberian Peninsula and Balearic Islands.

3.2.5. V37 the Number of Days in March and April with HR >= 50%

These variables have a more peculiar distribution as they are more widely spread over the area analyzed (Figure 8). Relative humidity conditions are not limiting during the month of April in most of the peninsula. The month of March is more restrictive, classifying as unfavorable areas that were

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favorable for the previous variables. This is the case of the south and part of the province of Cádiz, which recorded no more than 13 days with RH>50%.

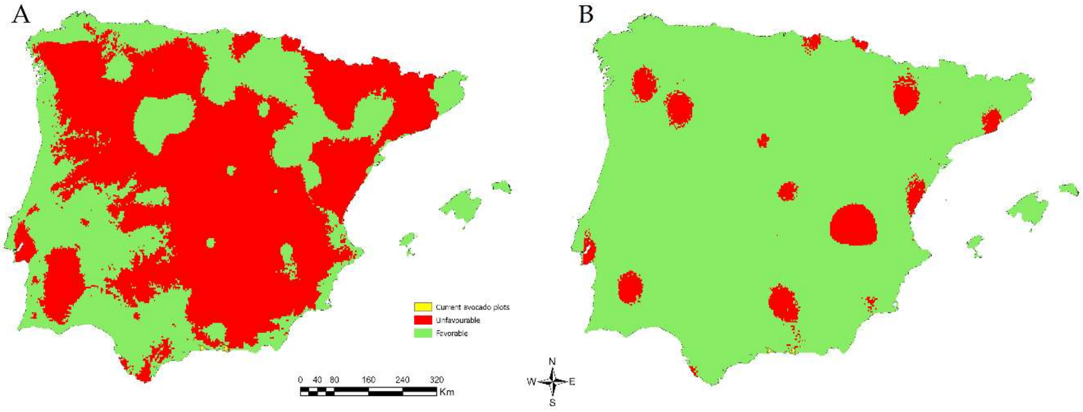

Figure 8. Geographical distribution of favorable areas for avocado cultivation according to relative humidity conditions in March (A) and April (B) in the Iberian Peninsula and the Balearic Islands.

3.3. Optimal Areas for Avocado Cultivation in the Iberian Peninsula and Balearic Islands

Figure 9 shows the zones that met all the requirements to show the climatic suitability for avocado cultivation in the Iberian Peninsula. It can be seen that the farms used for the cut-off values fall within the favorable zones.

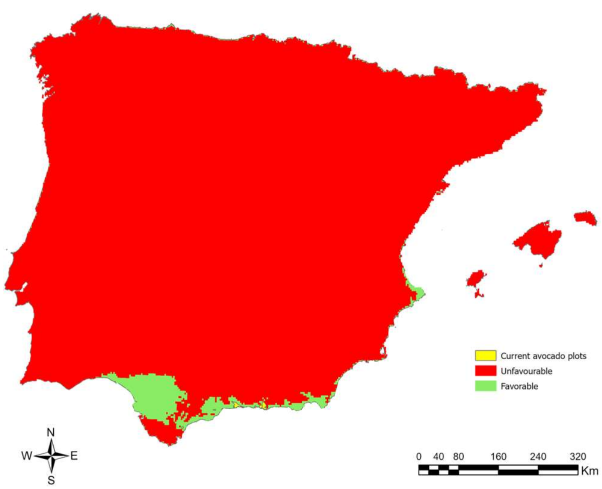

Figure 9. Geographic distribution of favorable areas for avocado cultivation according to all the variables analyzed in the Iberian Peninsula and the Balearic Islands.

The area identified as favorable is small in relation to the total area of the peninsula, indicating the high climatic requirements of this crop, undoubtedly due to its climatic distance from its original areas. On the other hand, a large area has been identified for the expansion of the crop. All these areas belong to the Autonomous Community of Andalusia, in the provinces of Huelva, Seville, Cádiz, Málaga, Granada and Almería.

A small-scale analysis was carried out to better identify the ideal areas within the optimum avocado cultivation area in the six provinces of Andalusia, and in Valenciana region in order to facilitate their location by the agricultural sector.

3.4. Optimal Areas for Avocado Cultivation in Andalusia

A total of six of the eight provinces of Andalusia have been identified as climatically suitable for the cultivation of avocados (Figure 10). The province of Cádiz is notable for having the largest number of hectares designated for this purpose (411,400 ha), with the province of Málaga following closely behind with 268,400 ha. When considering the entire region of Andalusia, the total area of climatically suitable land for avocado cultivation is 1,342,000 ha.

Figure 10. Geographic distribution of favorable areas for avocado cultivation according to all the variables analyzed in the six Andalusian provinces.

3.5. Optimal Areas for Avocado Cultivation in Comunidad Valenciana

In the Valencian Community, climatically suitable areas have been identified in Valencia and Alicante with 16,500 ha and 45,100 ha respectively (Figure 11).

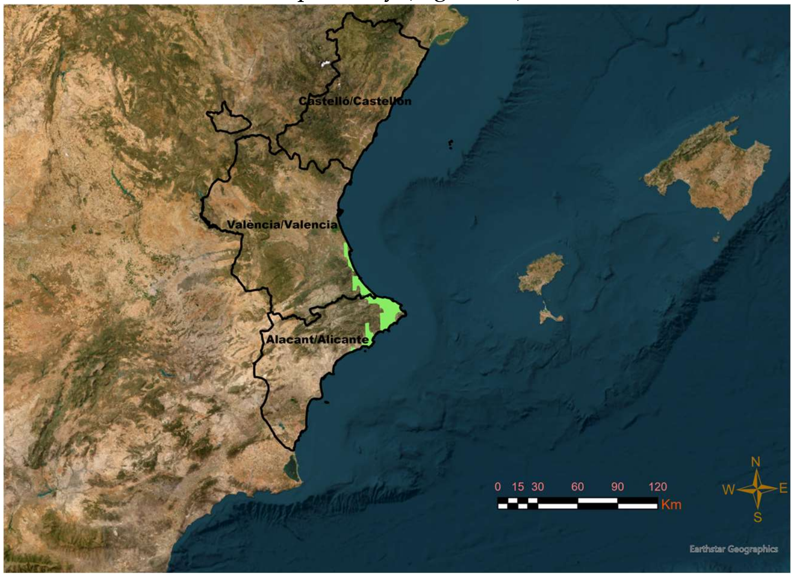

Figure 11. Geographic distribution of favorable areas for avocado cultivation according to all the variables analyzed in the provincias of Valencia.

5. Conclusions

In summary, our study provides a comprehensive assessment of the optimal avocado growing areas in the Iberian Peninsula, highlighting provinces such as Cadiz, Seville, Malaga and Huelva as

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prime regions for avocado cultivation. The coastal areas of Granada and Almería and the coastal region of Alicante and Valencia also have favorable conditions for avocado cultivation, highlighting the diversity of opportunities within the regions.

The most limiting variables for avocado cultivation in the Iberian Peninsula and in the Balearic Islands, are the minimum temperatures, especially in March, but also in April, as they drastically reduce the suitable area for cultivation to areas near the coast and inland in the province of Cádiz.

The methodology developed in our study, has made it possible to locate areas that are climatically suitable for avocado cultivation, with high demands on compliance with the climatic variables that determine suitability.

This methodology can be highly useful for a globally expanding sector that needs to locate new cultivation areas adapted to the strict climatic requirements of avocados, which would help reduce production uncertainties in new cultivation zones. Additionally, the phenomenon of global warming is altering the agroclimatic characteristics of areas traditionally deemed unsuitable for avocado cultivation, so reevaluating these areas in the new climatic context could help identify new cultivation zones. This is especially important in areas close to major consumption centers like Europe or North America, as it would enable local production, reducing the carbon footprint of avocado cultivation and making it more environmentally friendly.

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