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Educational Strategies for Teaching Climate and Bioclimate in Response to Global Change

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Abstract: This work establishes the relationship between climate, bioclimate, and forest ecosystems and highlights the need to teach these topics in educational institutions. It was found that such knowledge is not currently taught in universities, leading to scarce or non-existent teacher training in these areas. However, the teaching of bioclimatic aspects over a three-year period as a basis for land use planning, has shown highly positive results. The objective is to propose the teaching of bioclimatology to future managers and teachers in order to obtain a balanced environmental development. The analysis of bioclimatic diagrams makes it possible to stipulate the duration of the water reserve in the soil. This is essential for agricultural and forestry management. The edaphic factor and the bioclimatic ombrotclimatic (Io) and thermoclimatic (It/Itc) indexes condition the types of forests and crops that can exist in a territory, with the particularity that the ombrotype is conditioned by the edaphic factor, which allows a decrease in the ombrothermal index, expressed by the ombroedaphoboxerophilic index (Ioex). The humid ombrotypes condition the presence of *Abies pinsapo*, *Quercus pyrenaica*, *Q. broteroi*, and *Q. suber*, and the dry ones *Q. rotundifolia* and *Olea sylvestris*.

Keywords: indexes; series; forests; research; learning; knowledge; landscape development

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1. Introduction

In its latest report (the Sixth Assessment Report (AR6)), the Intergovernmental Panel on Climate Change (IPCC) [1] addresses a wide range of issues, including global warming of 1.5 °C and its projected increase in the coming years, as well as the social response to the threat of climate change. This report examines the impact of climate change on matters of significant social concern, such as droughts, floods, food security, health, increased migration, and social conflicts.

Previously, Amblar et al. [2], using data from the IPCC's Fifth Assessment Report (AR5), reviewed regional projections based on global data from the Spanish Meteorological Agency (SMA) to track the progression of climate change, which, as indicated by Tang et al. [3] in their study on urban agglomerations, is accelerating. Their findings demonstrate a rise in carbon emissions, which are a key driver of global warming.

Del Río et al. [4,5] analyzed climate change in Spain, focusing on temperature and precipitation trends. The same authors also explored the potential of deciduous forests and the impact of climate change on these ecosystems in Spain [6].

In an earlier study focused on the Northern Hemisphere, Fang and Lechowicz [7] examined the distribution of the genus *Fagus*, concluding that temperature is the primary limiting factor for its distribution. The variability of positive and negative trends in precipitation and temperature allows for the identification of specific areas where these trends are most pronounced [8–10], which is critical for decision-making in habitat management.

These previous studies on climate change and its influence on certain forest types are relevant to planning our study in the south of the Iberian Peninsula.

The research focused on climate change and biogeographical, bioclimatic, climatic, and edaphic bioindicators, vegetation, plant dynamics, and landscape study aspects allow us to propose sustainable forest management models worldwide, with management proposals to mitigate the profound and irregular global climate change. For this, we have conducted studies in places as different as Palestine, Italy, Spain, Portugal, the Caribbean, Mexico, and Brazil.

In the assumption of wanting sustainable development, previous studies must be established from the methodological point of view for the achievement of the intended objective. These studies must be specific to each territory. The following factors should be studied: physical-chemical environmental factors, biogeography, bioclimatology, vegetation (biological indicators) and vegetation series, in order to then propose a management model. This implies that each territory has a specific vegetation series, which gives the concept of vegetation series a universal applicability.

Bioclimatology is an ecological science that has gained importance in recent decades and seeks to demonstrate the relationship between living beings (Biology) and climate (Physics). It differs from climatology in that the information, indexes, and units it uses are related to and defined by species and phytocenosis/plant communities.

The development of bioclimatology as a fundamental discipline in the service of Vegetation Science, Agriculture, and Forestry Sciences has been one of the most significant scientific advancements in recent times. The progress of this science has enabled the diagnosis of many plant communities and, above all, has improved the definition of the main vegetation bands observed during altitudinal ascent, as well as the establishment of agricultural and forestry models for sustainable development.

Advances in geobotanical knowledge are producing promising results in the management of the natural environment. Among the different factors that contribute to the existence of certain plant ecosystems, precipitation, and temperature are the most important. Each region, or group of biogeographic regions, has a unique altitudinal zonation of plant ecosystems, which is caused by the progressive decrease in mean annual temperature with increasing altitude (thermoclimate).

If the climate (temperature and precipitation) is correlated with the altitudinal zoning of plant ecosystems, we will observe certain rhythms or changes across the Earth as a function of temperature and precipitation. Consequently, based on these changes, we can distinguish between the physical continent or bioclimatic floors and the biological plant content or vegetation series. The concept of vegetation series has universal applicability and is, therefore, relevant to any location on the planet.

Bioclimatology as a science has made remarkable advances in the last 30 years, particularly through the work of Professor Rivas-Martínez [11], who developed a bioclimatic classification of the Earth, expanded and verified in his work Globalbioclimatic (Bioclimatic Classification of the Earth) Rivas-Martínez [12]. This model has been refined in successive works [13,14]. The classification establishes a set of indices of great importance for the analysis of climatic and dynamic plant communities, making it highly relevant for land management.

The modification of bioclimatic indices is leading to changes in vegetation cover, with a tendency towards dominance of more xerophytic and thermophilic plant communities. For example, the thermo-Mediterranean holm oak groves in the Axarquía region (Málaga, Spain) are being replaced by wild olive groves (*O. sylvestris*) due to a decrease in the ombroclimate [15].

Although all the indexes presented are valuable for the study of vegetation, we highlight Io = annual ombrothermal index, Ic = continentality index, and It/Itc = compensated thermicity/thermicity index. The annual ombrothermic index Io = (Pp/Tp) $\times$ 10, where Pp = positive annual precipitation (for the Ti months above 0 °C) and Tp = positive annual temperature (sum of the Ti months above 0 °C, in tenths of degrees Celsius). The continentality index or annual thermal interval Ic = Tmax − Tmin, where Tmax is the average temperature of the warmest month of the year, and Tmin is the average temperature of the coldest month of the year. Other indexes that can compensate for the summer season aridity are the Ios2 = ombrothermic index of the warmest two-month period of the summer quarter and the Ios3 = ombrothermic index of the summer quarter [13].

In the case of plant communities that develop in rocky areas with steep slopes, the parameter that conditions their presence is the soil. All places have a type of substrate and orography that determine their greater or lesser capacity to retain water. Depending on the geomorphological and edaphic characteristics, well-structured soils have a water retention capacity (RC) of 100%. Otherwise, there are losses through runoff and drainage that cause the RC to vary. Water is also lost through evapotranspiration (ETP) [16].

Climatology and bioclimatology are fundamental to understanding and explaining agricultural and forestry management, which is currently being impacted by climate change. Consequently, it is essential to understand the tools available to humanity to mitigate these changes, as climate change is causing serious natural disasters, leading to economic losses and the loss of human lives. Global warming is already an unequivocal fact, as reflected in several reports from the Intergovernmental Panel on Climate Change.

The third assessment report showed that there had been a temperature increase of approximately 0.4 °C to 0.8 °C, affecting physical and biological systems in different parts of the globe.

It is in the fourth assessment report that clear evidence is presented that climate change and global warming are a reality that affects us all. Global atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have increased markedly in recent years as a result of human activities since 1750. The linear 100-year trend is estimated to be between 0.56 °C and 0.92 °C. This temperature increase is distributed over the entire planet, with a stronger impact in the upper northern latitudes.

According to estimates in the latest IPCC report, the warming trajectory could reach around 3.5 °C by 2100. The adaptive capacity of some human and natural systems is limited when global warming reaches 1.5 °C. According to the IPCC, reaching around 4 °C means mass extinctions of species, loss of biodiversity, water and food shortages, and an increase in migration and conflicts over access to resources. Currently, a temperature increase of 1.2 °C has been reached and is expected to reach 1.5 °C by 2030–2035. If temperatures exceed 1.5 °C and reach 2 °C, the risks would be irreversible.

Vegetation is conditioned by storms and anticyclones, which in turn influence the different macro and bioclimates of the world (thermoclines and ombroclimates), affecting the conservation and exploitation of forests, both in terms of quantity and quality. Therefore, knowledge of the local bioclimatic indicators is essential for exploiting forests, as in the case of *Quercus suber* forests. The use of bioclimatic indexes for forest management should be mandatory: continentality index, ombrothermal, and thermicity, since there is a close correlation between these indexes and the aforementioned forest management [17].

Once the bioclimate has been established for each plant ecosystem and each crop, it is necessary to carry out a landscape analysis, which must be in line with the territorial bioclimate in order to achieve successful reforestation. Assuming a new world economic order based on sustainable development, these reforestations, which would act as CO_2 sinks, can mitigate climate change, provided that there is a parallel reduction in CO_2 emissions and a change in energy policies. The landscape analysis leads us to propose the use of the concept of vegetation series/set of plant communities, which we have stated has universal applicability, as a basis for establishing a model of sustainable development [18].

In the vegetation series, we can speak of plant dynamics when the dynamics are natural, and the process is assumed by the ecosystem, not when there is excessive human intervention that contradicts the natural process. In the event that this dynamic is artificially accelerated by climate change and anthropogenic activities, the vegetation series undergoes drastic modifications, which means that the vegetation series cannot recover and, therefore, disappears, with new formations appearing in its place, transforming the landscape.

Therefore, in each biogeographic territory, with a specific bioclimate and soil, there is a specific vegetation series that has its own dynamics. Thus, a specific management model must be established.

When territorial management leads to the establishment of reforestation, it must be done on a bioclimatic basis. As previously mentioned, this process must be based on bioclimatic principles and take into consideration the vegetation series, for which it is essential to establish the bioclimatic values under which the forest operates. This implies the use of non-standard management models, so there must be a specific forest model for each territory.

The consequences of deforestation and fires cause profound transformations, which in many cases lead to a significant loss of biodiversity, occurring rapidly and on a large scale. The loss of floristic biodiversity results in faunal losses, disruption of biological control mechanisms, and the emergence of insect pest outbreaks. This loss of floristic diversity is due, among other causes, to inadequate or poorly planned forest management.

At present, sustainable development is possible, as there is advanced botanical research, both bioclimatic and edaphic. This knowledge is prevalent in Europe and has spread to countries in the Americas, through which we can assess the nutritional status of the soil, allowing for balanced territorial development [17]. The aim of this study is to highlight the value of bioclimatology as a science for mitigating climate change and for forest management, both for afforestation and for the diagnosis of plant communities and landscape units. Furthermore, due to the value of bioclimatology, we propose the promotion of its teaching in universities and research centers.

We propose this objective because, after analyzing the curricula of several universities in Spain, we observed that studies on bioclimatology are practically non-existent in research centers and universities.

In reviewing the curricula of the 14 Higher Technical Schools, we focused mainly on the degree programs in "Agricultural Engineering", "Agricultural and Natural Environment Engineering", and "Forestry and Natural Environment Engineering". In all these degrees, the dominant subjects in teaching are "General Biology", "Agricultural Botany", "Forest Botany", and Ecology, with some exceptions where "Botany" is only studied. The analysis of the Botany programs reveals that in all cases, systematics and plant morphology are studied, although, in some cases, biogeography, vegetation, and landscape are covered to a limited extent, and occasionally, Iberian and Macaronesian Geobotany is included. Only in one instance did we find a subject on Bioclimatology. Consequently, Bioclimatology is not being taught as a fundamental science in agricultural and forestry management.

It is evident that if future environmental managers and teachers do not receive this training, they will not be able to apply bioclimatology to management or teaching at lower educational levels. This implies that such knowledge does not reach rural social strata, which is particularly concerning as these communities are the most in contact with their environment and would benefit greatly from it.

2. Materials and Methods

2.1. Educational Aspects

In order to address one of the fundamental objectives of this study, given the lack of knowledge of bioclimatology among graduates, we posed a series of questions to students over three consecutive academic years to diagnose their level of understanding and to plan subsequent instruction. The questions were directed to 36 student teachers, who will later teach this knowledge at educational levels below the university level.

The questions asked were the following: Do you consider the plant-soil relationship important and strictly necessary? What does bioclimatology mean to you? Do plants, as bioindicators, provide you with information for management?

These questions were posed to assess the student knowledge level, with the aim of subsequently teaching bioclimatic concepts and bioclimatic indexes, which are detailed in this study, as well as their impact on the sustainable development and conservation of territories.

2.2. Data and Index

Climate change and bioclimatology in southern Spain are studied based on data from 11 weather stations from the SMA and Climate-Data.org https://es.climate-data.org/europe/espana/andalucia-252/ (accessed on 10 September 2024), as well as on bioclimatic studies by Rivas-Martínez and Rivas-Martínez et al. [11–14,19,20], and Rivas-Martinez and Rivas-Saenz (1996–2020) [21]. Additionally, the study on vegetation cover carried out by Cano-Ortiz, together with our previous investigations, allows us to obtain bioclimatic indices and maps (ombrotypes and thermotypes) [17].

However, since plants can self-regulate their water losses, which is detected through the value of residual evapotranspiration e = 0.2ETP according to Montero Burgos and González Rebollar [22], this residual evapotranspiration value (e) indicates the plants' capacity to withstand drought. Therefore, to explain the types of vegetation, it is necessary to consider the parameters (e) and retention capacity (RC). Vegetation is primarily conditioned by rainfall. The ombroclimatic index (Io) does not fully explain the presence of plant communities influenced by the substrate; therefore, Cano et al. [16] propose the ombroedaphospheric index (Ioex) to explain the presence of *Juniperus* and *Pinus* communities.

This ombroedaphospheric index is applicable to all situations where the water retention capacity of the substrate is low due to the characteristics of the substrate.

The Ioex index is obtained by subtracting the residual evapotranspiration (e) from the positive precipitation (Pp). The resulting value is divided by the positive temperature (Tp), and the result is multiplied by the RC value in parts per unit (0.25, 0.50, 0.75).

$$\text{Ioex} = \text{Pp} - \text{e}/\text{Tp} \times \text{RC}$$

Applying this formula, the values of Ioex1, Ioex2, and Ioex3 are obtained, with Ioex2 being the most representative value.

As for the thermicity index, it is the sum in tenths of a degree of T (mean annual temperature), m (mean minimum temperature of the coldest month), and M (mean maximum temperature of the coldest month). It is, therefore, an index that weights the intensity of cold, a limiting factor for many plants and plant communities. The correlation between the values of this index and vegetation is quite satisfactory in warm and temperate climates. In cold climates, where It/Itc values are below 120, it is more meaningful and accurate to use the value of the annual positive temperature (Tp). It = (T + m + M) × 10.

This thermicity index must be weighted as Itc = compensated thermicity index in the extratropical zones of the Earth (north and south of the 23° N and S parallel). The compensated thermicity index (Itc) aims to weight the value of the thermicity index (It) due to the "excess" of cold or temperance, which occurs during the cold season in the territories of continental or hyper-oceanic climates on Earth so that their continentality can be comparable. According to Rivas-Martínez [12], if the simple continentality index (Ic) is between 8 and 18, the value of Itc is considered equal to It (It = Itc). However, if the continentality index does not reach or exceed the mentioned values, it is necessary to compensate for the thermicity index by adding or subtracting a compensation value (C). Itc = It ± C. In extratropical zones with markedly hyper-oceanic conditions (Ic < 8.0), the compensation value (C) is calculated by multiplying by ten the result of the subtraction between 8.0 and the Ic of the station: C = (8.0 − Ic) × 10. This value (C) is subtracted from the thermicity index: Itc = It − C.

In continental or semi-continental extratropical climates (Ic > 18.0), the compensation value (C) is added to the thermicity index: Itc = It + C. This compensation value is calculated according to the figure of the simple continentality index (Ic). Thus, when continentality is moderate (18.0 < Ic ≤ 21.0), the compensation value (C1) is obtained by multiplying by f1 (f1 = 5) the result of the subtraction between the Ic of the station and 18. When continentality is pronounced (Ic > 21.0), the compensation value is calculated by a summation, whose partial values (C1, C2, C3, C4) are proportionally higher due to the increase in the multiplying factor (fi) as a function of the increase in continentality. Therefore: Itc = It + (C1 + C2 + C3 + C4).

2.3. Study Area

We analyze the bioclimatic studies in specific cases from several locations, covering 11 localities. These studies are fundamental for spatial planning. For this purpose, various bioclimatic indices are formulated, which, together with biological indicators, help us to create bioclimatic maps and diagrams that are very useful for generating the management model.

The method used consists of creating tables with bioclimatic indices as well as the respective bioclimatic maps of thermotype and ombrotype, which represent the bioclimatic character of a territory according to the value of its It/Itc and Io indices. These are then applied to generate a model for sustainable forest development, similar to its application in agriculture to minimize impact, which yields promising results for sustainable development. It is necessary to create bioclimatic maps of an ombroclimatic and thermoclimatic nature (Figures 1 and 2).

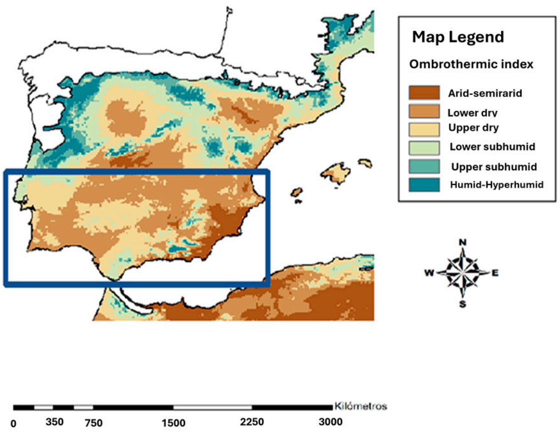

Figure 1. Map of ombrotypes of the Iberian Peninsula. Ombrotypes of the study area. This figure was obtained and modified from the general map of Cano-Ortiz et al. [17].

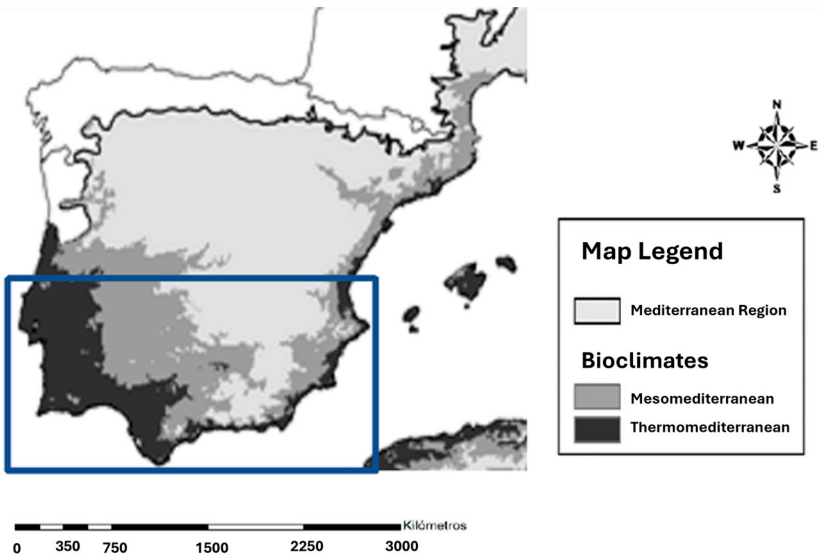

Figure 2. Map of thermotypes of the Iberian Peninsula. Thermotypes of the study area. This figure was obtained and modified from the general map of Cano-Ortiz et al. [17].

The 11 localities studied are distributed from the southwestern to the southeastern Iberian Peninsula, for which we have meteorological data and phytosociological inventories, allowing us to establish a correlation analysis between the values of the phytosociological indexes and the abundance of species.

2.4. Species

For the forest and non-forest areas of the southern Iberian Peninsula, there is a need to propose sustainable development models that allow productivity despite climate change based on knowledge of physical, bioclimatic, and biogeographical factors, and vegetation series. Although the bioclimatic diagrams of Rivas-Martínez [20] express not only the bioclimatic indices of interest for forest management, we consider the works of Thornthwaite [23–25] and Thornthwaite and Mather [26] to be of particular interest, as they also address climatic classification and especially potential evapotranspiration. Thanks to these studies, Montero Burgos and González Rebollar [22] publish bioclimatic diagrams that utilize potential evapotranspiration (ETP) and residual evapotranspiration (e), where e = 0.2ETP, which we consider very useful for agricultural and forestry sustainability studies; therefore, they will be used in this work. To obtain the ETP values, we followed the studies of Turc [27] and Soriano et al. [28], and the climatic data are from SMA and Climate-Data.org.

For the classification of thermotypes and ombrotypes, we follow Rivas-Martínez [12]. To explain the presence of edaphoxerophilic plant communities in rainy climates with climatophilic forests, we apply the ombroedaxeric index $Ioex = (Pp - e)/Tp \times RC$ [16]. Based on the latest IPCC report, we increase the temperature by 1.5 °C to assess the possible changes in the values of the bioclimatic indices. The bioclimatic influence on the distribution of climax communities is expressed through CCA statistical analysis and linear regression to identify which factors influence their distribution. For the study of the increase in ambient relative humidity in the south of the Iberian Peninsula and its possible tropicalization, we conducted a linear regression analysis. Using the XLSTAT [29] and Past.exe software, we analyzed the abundance of 11 species in the CCA, 10 in the regression analysis, and three bioclimatic indices. Qrot = *Q. rotundifolia*. Qsub = *Q. suber*. Qfag = *Q. faginea*. Joxy = *Juniperus oxycedrus*. Osy = *O. sylvestris*. Phal = *Pinus halepesis*. Aune = *Arbutus unedo*. Apins = *A. pinsapo*. Sten = *Stipa tenacissima*. Qpyr = *Q. pyrenaica*. Qbro = *Q. broteroi*.

Qrot represents sclerophyllous forests dominated by oaks. Qsub represents sclerophyllous forests on siliceous substrates and subhumid to humid environments. Qfag are marcescent trees that develop in the foothills and on strong soils. Joxy is a juniper species indifferent to edaphic conditions and skeletal soils. Osy is a species of wild olive tree distributed in dry, thermo-, and meso-mediterranean environments with a wide Mediterranean distribution. Phal is a coniferous species that develops in environments ranging from semi-arid to subhumid, located, in the latter case, in rocky areas, always on basic substrates and with a wide Mediterranean distribution. Aune is a species of the Ericaceae family, which forms tall thickets that replace humid forests on siliceous substrates. Apins is a conifer endemic to very rainy environments and basic substrates from southern Spain. Sten is a hemicryptophyte of the Gramineae family, which presents its ecological optimum in arid, semi-arid, and dry environments, always on basic substrates, distributed in the east and south of the Iberian Peninsula and North Africa. Qpyr is a deciduous tree of the Fagaceae family, developed on siliceous soils, in robust soils, and in environments with high rainfall. Qbro is a marcescent tree similar to Qfag, but whose optimum distribution is in the west of the Iberian Peninsula.

For the analysis of possible tropicalization, historical data from 37 meteorological stations with 24 years of data obtained from the Andalusian Agroclimatic Information System (AAI) (2000–2024) [30] are used. The selected variables include maximum temperature, minimum temperature, average temperature, accumulated precipitation, maximum relative humidity, minimum relative humidity, and average relative humidity.

3. Results

3.1. Teaching Analysis

After surveying 14 universities and observing the lack of content in the curricula related to Bioclimatology and Geobotany, we applied several questions to the students over three years, both before (B1–B3) and after (A1–A3) the teaching. We verified the low level of prior knowledge, which substantially improved after the teaching (A1–A3), with a positive trend in the acquisition of bioclimatic knowledge (A2–A3) (Figure 3).

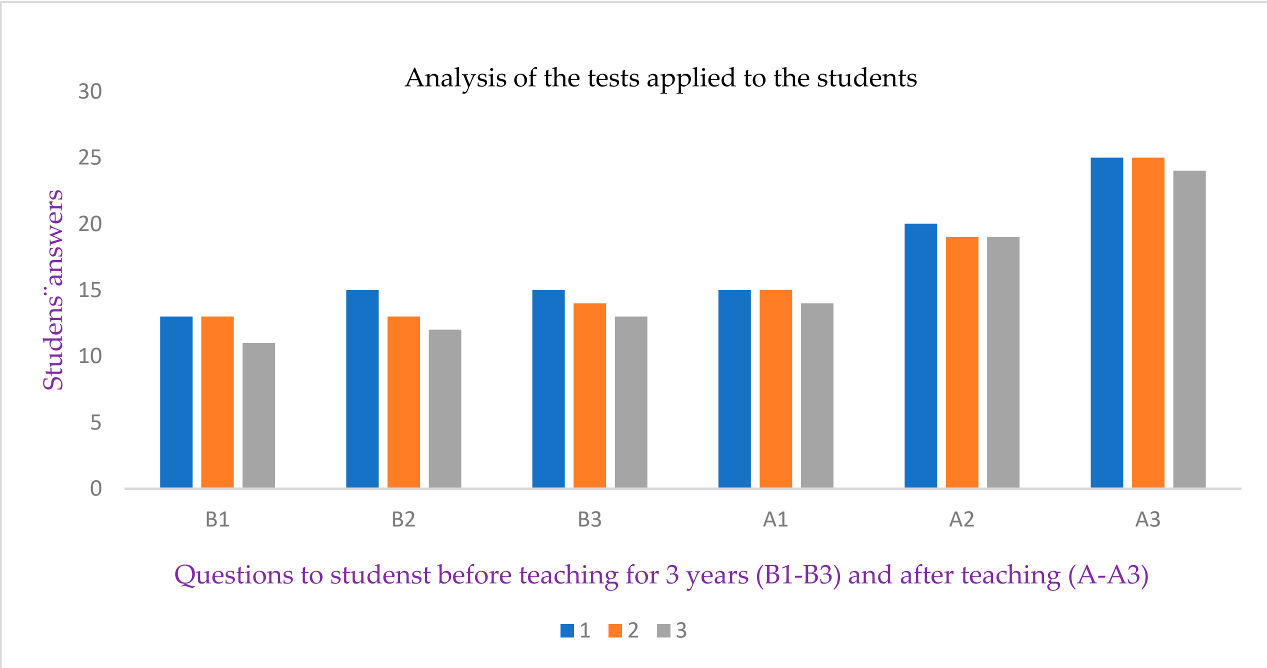

Figure 3. Comparative analysis between questions asked to university students during three years before teaching (B1–B3) and after teaching (A1–A3), with 1, 2, and 3 being the three questions.

3.2. Analysis of Bioclimatic Diagram

In the bioclimatic analysis, meteorological stations in the south of the Iberian Peninsula are used, obtaining values for each of them such as P, ETP, e, Pp, Tp, Io, Ic, It/Itc, Ios2, Ios3, Ioex, and Pav. All these indexes are based on the relationship that exists between climate and vegetation, which is why they are called bioclimatic, as they are not strictly precipitation and temperature values but reflect a correlation between physical parameters and species.

In the analysis of the climatic and bioclimatic parameters, the following was observed: (1) Most of the sampled territory has 12 months of Pav, meaning there is no cold standstill, with cold standstill being understood as when the mean monthly T drops below 7.5 °C. According to Montero Burgos and González Rebollar [22], this lack of cold standstill occurs in areas with a thermo-Mediterranean thermotype and dry ombrotype. However, places with a Pav of 8–9 months are dominant in the northwest of the provinces of Jaén and Granada, with the particularity that both territories have a higher meso-Mediterranean thermotype. (2) However, the value of the ombroclimatic index above 4 is due to the screen effect of mountain storms. In the case of the meteorological station of Jodar (Andalusia), with a dry lower meso-Mediterranean bioclimate, it has a Pav of 12 months since T is always higher than 7.5 °C (Figure 4). (3) When water availability (D) is higher than (ETP), the vegetation is at its ombric optimum. The regulation period (R) starts when (D) is lower than (ETP). This period lasts until the availability (D) becomes lower than (e), and from this moment on, there is stress for the plants (S).

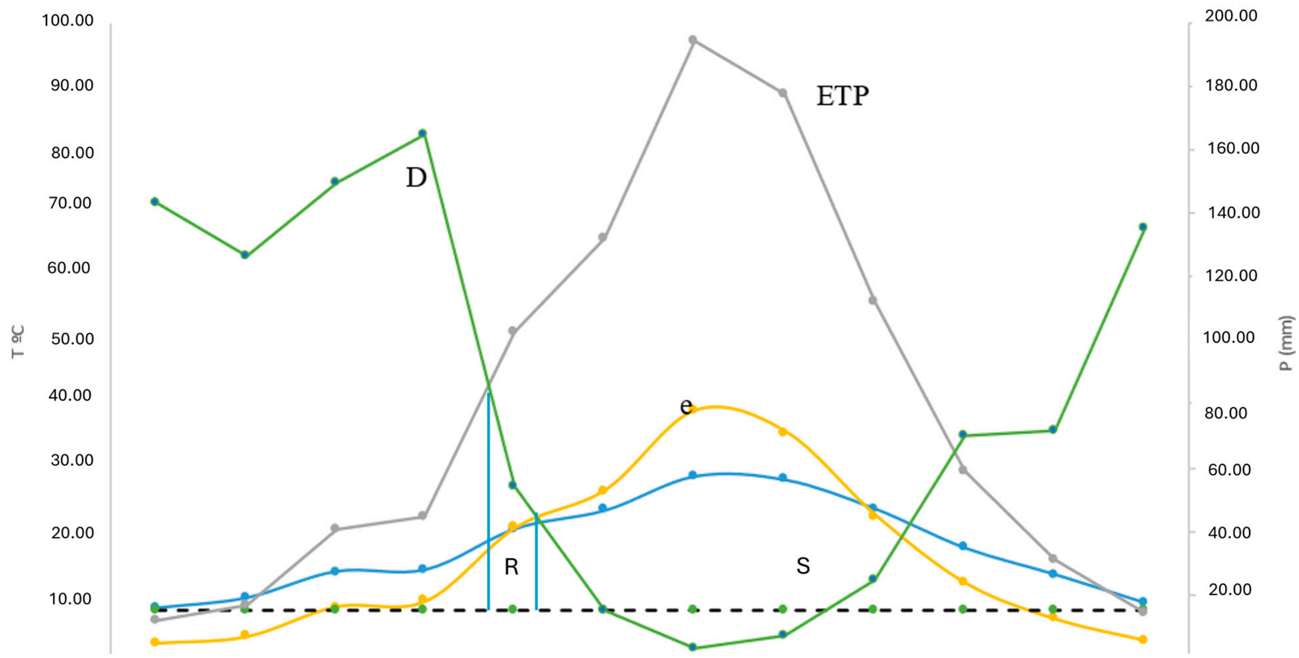

Figure 4. Bioclimatic diagram Jodar (Andalusia). D = Soil water availability. ETP = Potential evapotranspiration. e = Residual evapotranspiration. R = Regulation period. S = Period of water stress. Figure obtained and modified from Cano-Ortiz et al. [17].

This is a system to measure the period of stress suffered by the species, a period that will be greater or lesser depending on the climatic conditions of the territory and whether or not there is summer rainfall. It is also important to note that the months of stress suffered by the species can be reduced by maintaining the availability (D) of water in the soil with edaphic amendments, which is of great interest in agriculture.

The application of the bioclimatic diagrams to such disparate localities as Aracena, Jódar, and Tabernas yields significant differences in terms of the date on which water stress begins. This fact can be mitigated if the relationship between the summer ombrothermal indexes Ios3/Ios2 > 1, meaning that there is compensation for the June rains, the crop being productive when Io > 2.5.

3.3. Statistical Analysis

In the multiple linear regression analysis between the explanatory factors and the 10 species (Table 1), the *p*-value for Qfag, Joxy, Apins, and Sten is <0.05, which implies that the three independent variables Io, Ic, and Itc condition the presence and abundance of these three species, with an explanatory variability ranging between 62 and 74%. This high percentage of variability indicates that these three bioclimatic parameters—ombroclimate, continentality, and thermoclimate—condition the distribution of species.

Table 1. R-values^2 and *p*-value in multiple regression, percentage explanatory variability of the three variables.

Species	Qrot	Qsub	Qfag	Joxy	Osy	Phal	Aune	Apins	Sten	Qpyr
R^2	0.55684	0.39385	0.65870	0.61774	0.53728	0.50272	0.56527	0.74172	0.74327	0.28099
p-value	0.05 < 0.1	0.1 < 1	<0.05	<0.05	0.05 < 0.1	0.1 < 1	0.05 < 0.1	<0.01	<0.01	0.1 < 1
Var.	56	39	66	62	54	50	57	74	74	28

The same does not occur with the other species Qrot, Qsub, Osy, Phal, Aune, and Qpyr, which means that the explanatory variables are not as determinant. However, when applying simple regression analysis (Table 2), all *p*-values are less than 0.05, except for Qpyr, with all nine species being explained by one, two, or three independent parameters Io, Ic, Itc.

Table 2. R^2 and *p*-value in simple linear regression for each of the three explanatory variables.

Species	Qrot	Qsub	Qfag	Joxy	Osy	Phal	Aune	Apins	Sten	Qpyr
R^2-Io	0.368	0.387	0.630	0.406	0.322	0.151	0.554	0.429	0.121	0.270
R^2-Ic	0.521	0.298	0.493	0.585	0.509	0.342	0.404	0.088	0.441	0.163
R^2-Itc	0.414	0.236	0.370	0.474	0.529	0.234	0.315	0.082	0.561	0.148
Io-*p*-v	<0.05	<0.05	<0.01	<0.05	0.05 < 0.1	0.1 < 1	<0.01	<0.05	0.01 < 1	0.05 < 0.1
Ic-*p*-v	<0.01	0.05 < 0.1	<0.05	<0.01	<0.01	<0.05	<0.05	0.1 < 1	<0.05	0.1 < 1
Itc-*p*-v	<0.05	0.1 < 1	<0.05	<0.05	<0.01	0.1 < 1	0.05 < 0.1	0.1 < 1	<0.01	0.1 < 1

In the CCA analysis (Figure 5), the species located to the left of the Y axis, Apins, Qbro, Qpyr, Aune, and Qsub, are influenced by the ombrothermic index. The latter species, *Q. suber*, found in Aracena and Colmenar, is influenced in its distribution by low Ic values, being positioned below the X-axis. To the right of the Y axis are species typical of more xeric environments. In this case, low ombrothermal values and high values of the compensated thermicity index Itc condition the upper right quadrant of Figure 4, with these species classified ombrothermally between semi-arid and dry. The lower right quadrant reflects ombrothermic values ranging from dry to subhumid conditions.

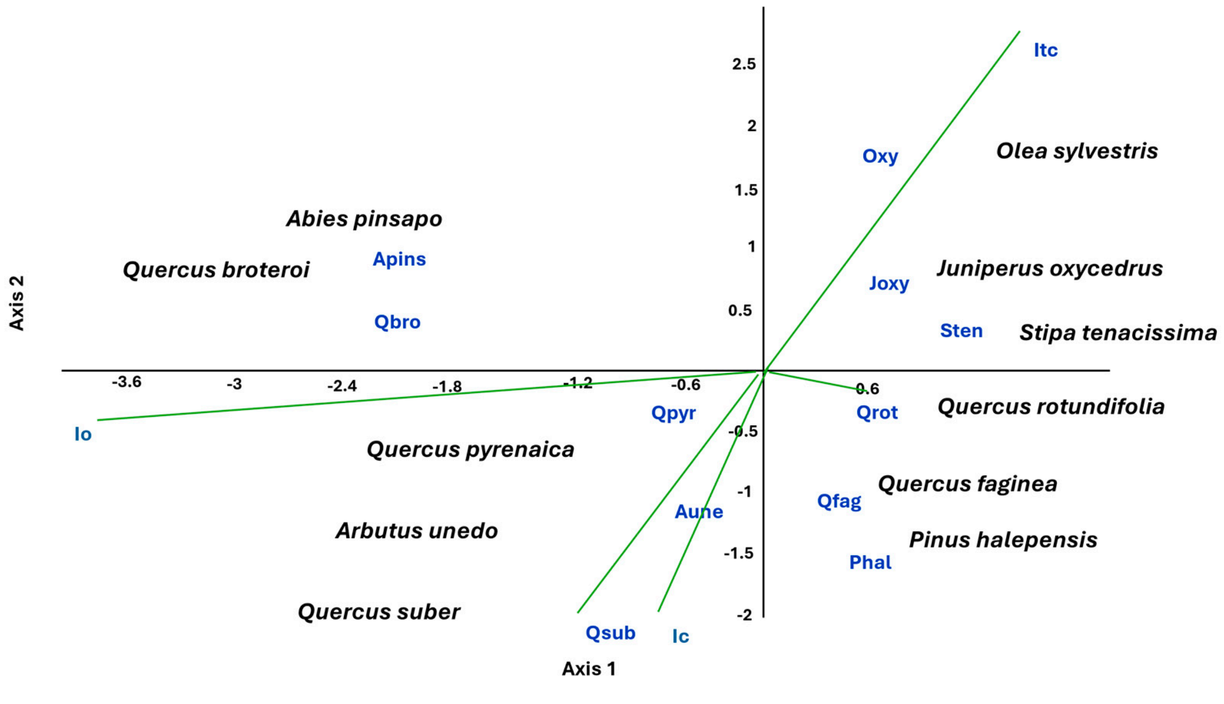

Figure 5. Canonical Correspondence Analysis (CCA). Influence of bioclimatic parameters Io, Ic, and Itc on the distribution of 11 species.

Due to the decrease in the ombrotype and the increase in the thermotype, the deciduous forests that have their optimum in the humid ombrotype, such as *Q. pyrenaica*, will be replaced by *Q. suber*, which has a subhumid optimum, while *A. pinsapo*, with a humid–hyperhumid optimum, will be replaced by *Q. broteroi*, which has lower humidity requirements. A similar situation occurs with *Q. rotundifolia* forests, which have a dry optimum and are replaced by wild olive trees (*O. sylvestris*) and junipers (*J. oxycedrus*). In general, it can be stated that, due to the decrease in the ombrotype, species with lower water requirements will predominate.

As a result of the increase in the thermotype, the meso-Mediterranean zone evolves into the thermo-Mediterranean, and the supra-Mediterranean into the meso-Mediterranean, which implies an expansion of thermophilic species, increasing their distribution area.

The thermotype of the study area ranges from lower thermo-Mediterranean to upper meso-Mediterranean, and the ombroclimatic horizons according to the I_o value range, from lower semi-arid to upper humid, with the stations of Alamillo, Málaga, Colmenar, Tabernas, Guadix, Nijar, and Jodar having the lowest ombroclimatic values, ranging between 1.1 and 2.7, these places being classified ombroclimatically from lower semi-arid to lower dry.

When applying the ombroedafoxeric index Ioex0.50 to explain the presence of edaphroxerophilic communities in rainy climatic environments, there is a high decrease, which is due to the nature of the substrate and the geomorphology of the terrain.

Edaphoxerophilic communities are those whose dependence on the substrate is much greater than the influence of the climate. Theoretically, the climate conditions the vegetation as long as the substrate allows it. Otherwise, this is the factor that conditions the presence of edaphoxerophilic vegetation.

As Ioex0.50 is the most representative index, we obtain values ranging from 0.01 to 0.98 for the 4 stations mentioned above, which are classified from ultrahyperarid to upper-arid.

The Grazalema, Cazorla, Aracena, and Jabugo stations also experience changes that explain the presence of *Q. rotundifolia* communities in the limestone-dolomitic ridges of Sierra de Grazalema and in the limestone ridges of Cazorla and the presence of *J. oxycedrus* and *J. badia* microforests. In this case, the values of the ombroedaphospheric index range between 1.18 and 4.55, with the ombric classification being between lower semi-arid and upper subhumid.

When the temperature is increased by 1.5 °C, which implies an increase in Tp of 18 °C, we obtain significant changes in the ombroid classification (Table 3). Although in all cases, the values of the index Io* remain close to Io, in the case of Jabugo, there is an ombric change from lower humid to upper subhumid.

Table 3. Bioclimatic indices of 11 weather stations in Andalusia (Spain). P = precipitation. ETP = potential evapotranspiration. e = residual evapotranspiration. Pp = positive precipitation. Tp = positive temperature. Io = ombrothermic index. Ios2 and Ios3 = bi-monthly summer index and quarterly summer index. Ic = continental index. Itc = compensated thermicity index. Ioex = ombroedafoxerophilic index (25, 50, 75, and 100% of CR). Tp + 18 °C. Io* = ombrothermic index for 2030–2035. Ioex0.50* index =ombroedafoxerophilic index for 2030–2035. Hs = upper humid. Shi = lower subhumid. Shs = upper subhumid. Ss = upper dry. Si = lower dry. Sai = lower semi-arid. Sas = upper semi-arid. As = upper-arid. Ai = lower arid. Ul = ultrahyperarid.

	P	ETP	e	Pp	Tp	Tp + 18	Io	Io*	Ios2	Ios3	Ios3/Ios2	Ombrotype	Ic	Itc	Alt	Ioex1	Ioex0.25	Ioex0.50	Ioex0.50*	Ioex0.75	Ombrotype
Grazalema	1971	1117.7	223.54	1971	191.8	209.8	10.2	9.39	2.14	3.16	1.47	Upper wet/Hs	17.7	304	825	10.2	2.27	4.55	4.16	6.83	Lower humid/Shi
Cazorla	602	1117.7	223.54	602	159.5	177.5	3.7	3.39	3.20	5.41	1.69	Lower subhumid/Shi	19.6	263	885	3.7	0.59	1.18	1.06	1.77	Lower semi-arid/Sai
Aracena	1030	1117.7	223.54	1030	195,2	213.2	5.2	4.83	1.9	3.46	1.82	Upper subhumid/Shs	17.6	276	731	5.2	1.03	2.06	1.89	3.09	Lower dry/Sas
Jabugo	1117	1117.7	223.54	1117.7	177	195	6.2	5.72	2.6	5.07	1.95	Lower wet/Shs	16.9	304	684	6.2	1.26	2.52	2.29	3.78	Lower dry/Si
Colmenar	602	1219.9	243.98	602	182.3	200.3	3.3	3.00	2.0	3.76	1.88	Dry top/Ss	19.9	295	731	3.3	0.49	0.98	0.89	1.47	Upper-arid/As
Alamillo	515	1219.9	243.98	515	189	197	2.7	2.61	2.0	4.73	2.36	Dry bottom/Yes	19.3	301	445	2.7	0.35	0.71	0.68	1.07	Upper-arid/As
Málaga	488	1331.8	263.9	488	212.2	230.2	2.2	2.11	1.4	2.22	1.58	Lower-semiarid/Yes	15.1	420	58	2.2	0.26	0.53	0.48	0.80	Lower arid/Ai
Tabernas	305	1331.8	266.36	305	204.3	222.3	1.4	1.37	2.3	3.02	1.31	Lower-semiarid/Sai	16.4	388	502	1.1	0.04	0.09	0.08	0.13	Ultrahyperarid/Ul
Guadix	549	1331.8	266.36	549	159.5	177.5	3.4	3.09	6.5	9.4	1.44	Dry top/Ss	18.9	263	905	3.4	0.44	0.88	0.79	1.32	Upper-arid/As
Nijar	271	1331.8	266.36	271	200.7	218.7	1.3	1.23	1.7	2.16	1.27	Lower-Semiarid/Sai	14.3	404	364	1.3	0.00	0.01	0.01	0.01	Ultrahyperarid/Ul
Jodar	610	1219.9	243.98	610	165.7	183.7	3.6	3.32	0.18	0.31	1.72	Dry bottom/Yes	20.9	243	647	3.6	0.34	1.10	0.99	1.02	Lower semi-arid/As

Given the need to preserve vulnerable species and habitats, the only solution is to apply bioclimatic classification to the territories and preserve those small bioclimatic zones that are maintained so that they act as reservoirs of species and habitats.

In the 11 stations the ratio Ios3 /Ios2 > 1, which means that there is compensation due to summer rainfall. These values range from 1.27 for Tabernas to 1.95 for Jabugo.

The analysis of data from 37 stations revealed high relative humidity values, with maximum values ranging from 55.5 to 100% with maximum values above 70% at all stations near the Mediterranean (Table 4). Linear regression analysis confirms that there is a close correlation between maximum and mean temperature and ambient relative humidity. In all cases, the R^2-value > 90 and the p-value < 0.001 (Table 5, Figure 6).

Table 4. Tmax = maximum temperature. Tmin = minimum temperature. T = average temperature. Hrmax = maximum relative humidity. Hrmin = minimum relative humidity. Hr = average relative humidity.

Meteorological Station	Altitude	Tmax	Tmin	T	P	Hrmax	Hrmin	Hr
Malaga (MA)	55	32	23.9	27.5	206.9	91.5	44.6	66.8
Almuñercar (GR)	29	30.5	22.9	26.7	338.2	100	53.8	83
Adra (AL)	2	35.7	23.9	29	221.8	89.3	29.4	63.2
La Mojonera (AL)	137	32.8	24.3	28.9	177.4	88.1	27.7	53.4
Almeria (AL)	5	34.1	25.6	29.5	104.7	58.2	36.3	46.4
Velez Malaga (MA)	33	32.2	22.9	27.3	381.2	88.8	45.1	67.1
IFAPA Churriana (MA)	17	31.5	24.3	27.7	250.4	84.2	49.1	68.4
Estepona (MA)	185	32	23.4	27	526	77.5	44.5	60.3
Conil de la Frontera (CA)	22	32.8	21.1	26.6	452.8	80.7	46.3	66.4
Salúcar de Barrameda (CA)	29	33.2	21.2	26.8	489.2	95.6	43.2	70.2
Moguer (Hu)	53	31.4	23.3	27.4	487	84.7	49.5	66.7
Jerez de la Frontera (CA)	17	32.9	22.8	27	529	90	43.9	65.2
Tabernas (AL)	502	30.1	21.8	25.1	154	90	43.2	59
Fiñana (AL)	958	30.7	18.2	23.6	211.7	87.2	35.1	60
Córdoba (CO)	94	36.4	24.3	29.8	590	68.3	31.4	52.4
Vejer de la Frontera (CA)	13	32.4	22.7	27.8	549.9	94.1	50.7	70.1
Sierra Yeguas (MA)	467	33	20.6	26.3	441.9	87.2	35.3	58.2
Jimena de la Frontera (CA)	50	32.2	22.8	27.2	487	85.9	47.8	69.1
Baena (CO)	310	36.2	22.9	29.2	411.4	71.4	31.2	51.5
Zafarraya (GR)	892	27.9	17	22.3	930.6	84.2	48.5	68.1
Mancha Real (JA)	407	35	23.4	28.9	350.9	58.6	28.5	42
Linares (JA)	432	27.1	12.6	20.2	586.2	75	31.4	50.9
Slate (MA)	71	34.3	23.7	28.4	215.9	80.3	37.8	58.9
Úbeda (JA)	343	37.5	20.6	28.2	442	74.7	25.5	46
Cártama (MA)	78	34.3	23.8	28.2	222.4	75.7	51	62
Ecija (SE)	109	35.4	23.8	29.1	509.3	71	31.4	51
Higuera de Arjona (JA)	257	36.1	23.1	29.3	472.9	62.1	29.4	44.7
La Rinconada (SE)	25	33.9	21.7	27.9	592.5	78.4	38.4	59.9
Osuna (SE)	198	34.6	22.1	28.1	412.6	73.8	34.1	54.5
Jaén (JA)	299	36.2	22.8	29.5	418.1	66.7	27.9	45.5
Puebla Cazalla (SE)	193	35.7	22.7	27.8	502.8	75	34.4	54.9
Torreperogil (JA)	535	35	21	27.8	463.5	77.1	25.8	45.6
IFAPA Cabra (CO)	543	33.5	21.5	27.1	506.7	81.1	33.5	57.4
IFAPA Camino del Purchil (GR)	630	34.5	19	26.4	307	95.3	30.4	63.6
Villacarrillo (JA)	649	34.4	20.5	26.2	496.2	69.1	21.1	47.8
IFAPA Center of Campanillas (MA)	63	34.1	23.9	28.6	209.8	86.3	37.3	64.5
Jodar (JA)	486	35.9	24.6	29.7	443.5	55.5	25.8	38.9

Table 5. Given the value of R^2 in all cases, the independent variables T = mean temperature and Tma = maximum temperature explain more than 93% of the variability of Hrmax = maximum relative humidity. Hrmin = minimum relative humidity, and Hr = mean relative humidity.

	T-Hrmax	T-Hrmin	T-Hr	% Explanatory
R^2	0.969	0.936	0.961	94–97%
p-value	0.001	0.001	0.001	
	Tmax-Hrmax	**Tmax-Hrmin**	**Tmax-Hr**	
R^2	0.968	0.924	0.957	93–97%
p-value	0.001	0.001	0.001	

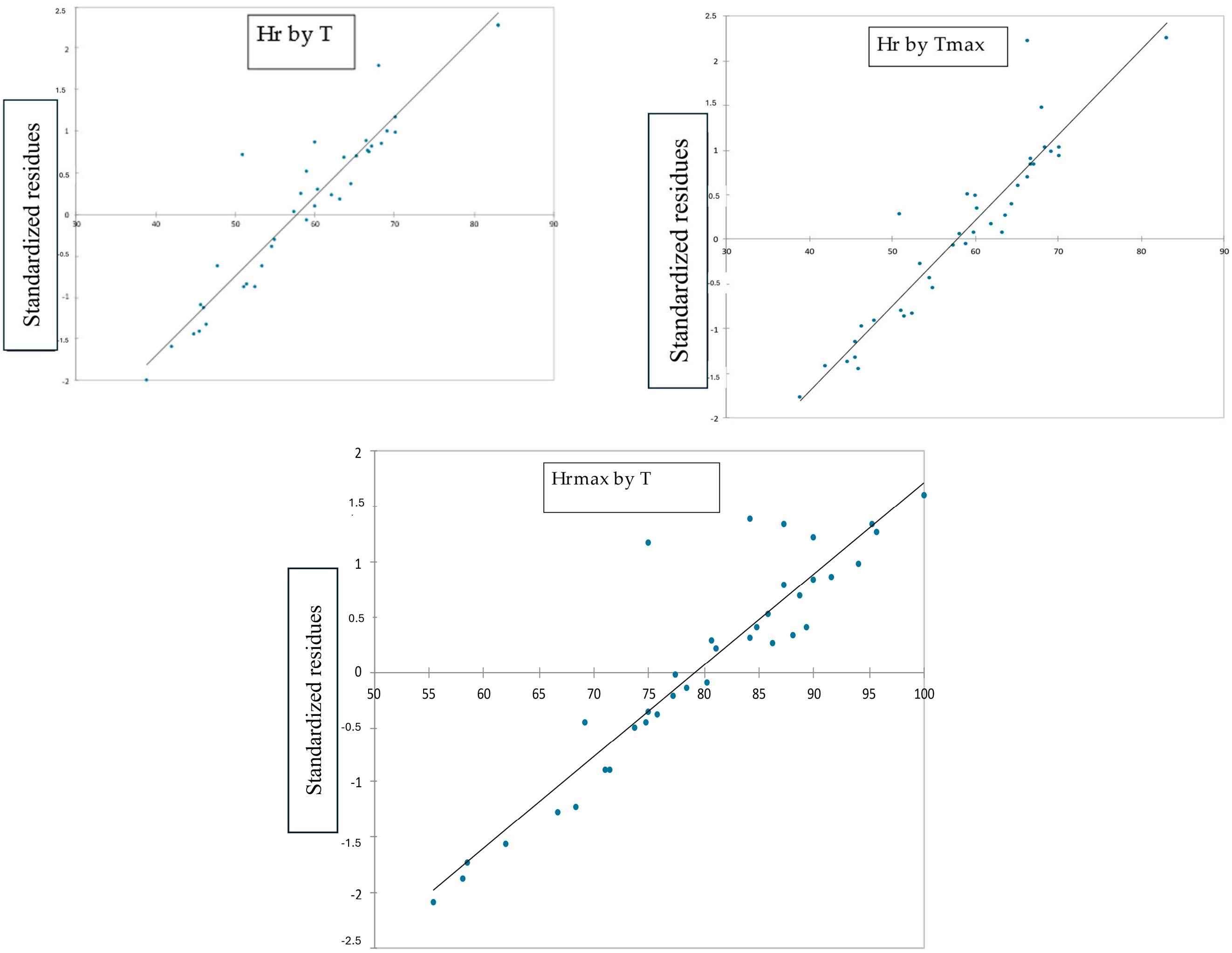

Figure 6. *Cont.*

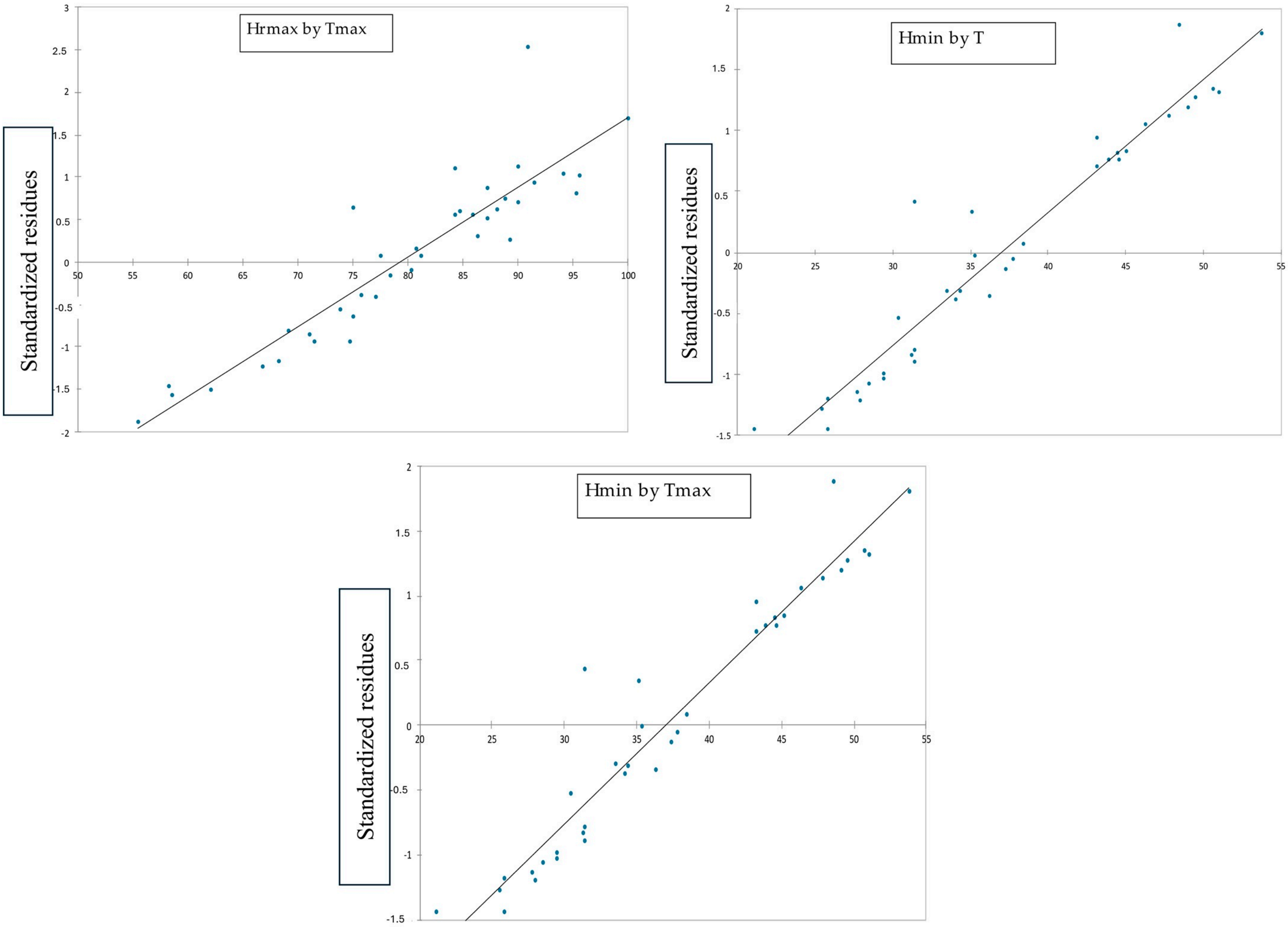

Figure 6. Linear regression analysis between temperatures and ambient relative humidity. T = mean temperature and Tmax = maximum temperature explain more than 93% of the variability of Hrmax = maximum relative humidity. Hrmin = minimum relative humidity, and Hr = mean relative humidity.

4. Discussion

The bioclimatic and vegetation analysis reveals a close relationship between bioclimate and species distribution, with each species responding to specific bioclimatic values. This relationship was already noted by Piñar et al. [31], who discussed the loss of nemoral species and the bioclimatic influence on *Q. pyrenaica*, *Acer opalus* subsp. *granatense*, and *Q. faginea*. Similarly, del Río et al. highlighted this phenomenon in the deciduous forests of northern Spain, focusing on *Fagus sylvatica*, *Q. robur*, *Q. petraea*, and *Betula celtiberica*. They estimate a decrease in forest mass due to climate change, which allows greater radiation to penetrate and, consequently, increases evapotranspiration. These microclimatic environments are being altered, leading to changes in microhabitats due to climate variability exacerbated by global change, which affects ecosystems.

In this sense, several studies on the vegetation in the southern Iberian Peninsula have shown that it is in a bioclimate that has not yet changed. In the predictive model that we present for several locations, assuming a temperature increase of 1.5 °C for 2030–2035, the bioclimatic trend points towards an ombroclimatic decrease.

Allen et al. [32] argue that greenhouse gas emissions result in prolonged droughts and thermal stress to vegetation, therefore altering the compositional structure and biogeography of forests. As a result, Alfaro-Saiz et al. [33] propose incorporating bioclimatic and biogeographic data to generate predictive models to identify potential habitats, particularly microclimatic environments that, in Mediterranean regions, are confined to small mountain areas with higher precipitation

Humid → Subhumid → Dry → Semi-arid → Arid → Hyperarid → Ultrahyperarid

This ombroclimatic change affects all species, particularly those adapted to a specific ombroclimatic type. The humid forests of the Betic mountain ranges, such as *Q. pyrenaica* and *Corylus avellana*, considered fragile habitats of interest, are affected by these bioclimatic changes [34–36], as well as the forests of the natural parks of Los Alcornocales (*Q. suber*) and Sierra de Grazalema (*Q. broteroi*, *A. pinsapo*) [37].

The ombroclimatic trend affects the structure of these forests, which will see a reduction in their extent and distribution as there is a decrease in the ombroclimatic index. The optimum conditions for these forests will no longer be sustained by the new bioclimatic regime that emerges.

The forests of *Q. pyrenaica*, *Q. suber*, *Q. faginea*, and *Q. broteroi*, which develop on siliceous substrates, have as a first dynamic stage a tall *Arbutus unedo* thicket, developed on cambisols, but with greater resilience to climate change. The northernmost Iberian deciduous forests, such as those of *Q. pyrenaica*, *F. sylvatica*, and *Castanea sativa*, have been studied by del Río et al. [6], who propose changes in their distribution as a consequence of climate change.

Rivas-Martínez et al. ([14], [19] pp. 433–922), in successive publications, establish a classification of vegetation for the Iberian Peninsula, including deciduous forests in the phytosociological class *Querco-Fagetea* and deciduous scrub in the class *Rhamno-Prunetea* [38]. Iberian forests, whose vulnerability to climate change is of concern [39,40], are undoubtedly affected and will continue to be affected, impacting biodiversity [41,42].

The *Querco-Fagetea* class is bioclimatically characterized by Rivas-Martínez et al. [19] as lower thermo-orotemperate, with its communities oscillating between subhumid and ultra-hyperhumid. Species such as *A. pinsapo* and *Q. pyrenaica* are included in the *Querco-Fagetea* class, located in Grazalema and Jabugo, respectively (Table 4). As the ombric values obtained are low, particularly in places with low RC (water retention capacity), the ombric value in Grazalema shifts from upper humid to lower subhumid and in Jabugo from lower humid to lower dry, placing these forests at risk of extinction.

The species *J. oxycedrus*, *O. sylvestris*, *Q. rotundifolia*, *P. halepensis*, *Q. faginea*, *Q. suber*, *Q. broteroi*, and *A. unedo* have been included in the class *Quercetea ilicis*, a class found in environments ranging from thermo-Mediterranean to supra-Mediterranean, with ombric values ranging from semi-arid to humid [19]. The optimum ombroclimate for *P. halepensis* is dry-semiarid, while the optimum for *Q. faginea*, *Q. broteroi*, and *Q. suber* is subhumid.

If the ombroclimatic decrease due to climate change continues, the *Q. pyrenaica* forests of Jabugo will be replaced by *Q. broteroi* and *Q. suber* forests. The forests of *P. halepensis*, whose optimum is dry lower-semiarid upper, are also at risk if the ombroclimatic change persists. They can only be maintained in Jódar and Guadix, where the ombroclimate ranges from dry lower to dry upper. They can also survive in limestone and dolomitic rocky areas with a dry-subhumid ombroclimate, as these places can behave from semi-arid to dry.

The increase in water temperature in the Mediterranean and the Atlantic due to climate change is the cause of an increase in relative humidity. Increased humidity on the Mediterranean and Atlantic coasts lasts for an average of 2–3 months (July, August, and September). The maximum relative humidity (Hrmax) during these 2–3 months exceeded 70% in 81% of the stations studied, despite a decrease in precipitation.

Relative humidity values in tropical climates typically range between 70 and 90%. In the specific case of Santo Domingo (Dominican Republic), according to ONAMET [43], the normal relative humidity data for the period 1971–2000 range between 79.4 and 84%. Consequently, we are witnessing a tendency towards tropicalization of the bi-xeric type during the summer months, as these are the seasons with a decrease or total lack of precipitation, particularly in winter and summer. This phenomenon is attributed to the increase in mean and maximum temperatures, with high spatial and temporal variability in climatic parameters [44,45].

Bioclimatology is intimately related to and connected with the management of plant ecosystems. Since the concept of bioclimate and bioclimatic floors (thermotype and ombrotype) are essential for planning, we must not forget that the objective is to achieve effective forest management (conservation and exploitation) with minimal environmental and economic cost. This cannot be accomplished without considering bioclimatology as a basic science in forest planning, and therefore, the use of bioindicators and bioclimatic indices must be incorporated. This is why it is necessary to conduct a bioclimatic territorial interpretation as an essential framework for management.

In view of the above, and incorporating another actor, humans, who alter nature through deforestation and fires, it is necessary to carry out massive reforestation to maintain these plant formations as CO_2 sinks. To achieve success in reforestation, we propose following the model of Cano et al. However, due to the degree of destruction of climaxes, it is essential to rely on plant dynamics, as shown in Figure 3. *Arbutus unedo* represents the first dynamic stage of cork oak (*Q. suber*) and oak (*Q. pyrenaica*). To implement the proposed model, education in sustainability is required, as expressed by Rivas et al. [46]. Sustainability should be based on ecosystem services [47], services that can be utilized within a sustainable exploitation model, which requires the use of climatic and bioclimatic data.

Environmental Factors → Bioclimatology and Biogeography → Vegetation Series → Forest Type

The current climate change, with extreme weather events, has a direct impact on agricultural production and food security and, consequently, on the economy and the health of the population. Faced with this serious situation, different mathematical and climatic-bioclimatic models have been published. All these models share a common objective: to mitigate the repercussions of climate change [48,49].

Although all models are positive and pursue the same purpose, it is necessary to promote research and teaching on climate change. Since all models aim toward the same goal, the fight against climate change, it is essential to incorporate not only predictive mathematical models but also climatology, bioclimatology, biogeography, and vegetation as fundamental pillars of education. This implies an analysis of the curricular content for teaching, as expressed by Salinas et al. [50]. In Chile, the study of climate change is integrated into the curricula on sustainability and biodiversity, but without delving deeply into the subject. Additionally, there is an imbalance in the teaching of this topic at different educational levels.

In the study we have conducted, the contents taught in universities and research centers are not usually related to bioclimatic knowledge. However, despite the population's limited application of sustainable development, it must be applied in response to the existing climate crisis. Since bioclimatology is the foundation of territorial sustainability, it must be taught in educational centers in order to be disseminated to society. In this case, we observe that the students' prior bioclimatic knowledge is scarce or non-existent but is effectively acquired during teaching.

In the study carried out, it was found that the student knowledge of bioclimatology and bioindicators (questions 2 and 3 in Figure 3) before teaching was low and even non-existent. However, after teaching there is a substantial improvement. Considering the importance of bioclimatology for territorial development in the face of climate change and seeing that students learn and are trained for management, it is appropriate to make a proposal on the incorporation of this subject in the curricular contents.

Although the educational system is a basic pillar for raising awareness and teaching about climate change, it is not the most influential. In fact, a situation similar to that in Chile occurs in Spain. Despite the significant research progress of recent decades, it has not resulted in a corresponding increase in societal knowledge, even though temperature and precipitation trends are well-known through predictive models [47,51]. Therefore, we propose to enhance research and teaching on climate change, facilitating a rapid transition to sustainability.

5. Conclusions

The main objective of this work is to highlight the importance of bioclimatology in land management. Both bioclimatic and agronomic studies related to cultivation techniques are indispensable for sustainable development that mitigates climate change. It is time for all countries to act together to generate economic models that maintain agricultural and forestry production in terms of both quantity and quality without further deteriorating the natural environment. Based on the studies that we are conducting in different territories, we can develop agricultural and forestry production models that help reverse climate change.

Bioclimatology, vegetation, and vegetation cover are terms that should be understood and applied with expertise, as proper management would mitigate climate change. This translates into a new world economic model based on sustainable development and the reasonable use of natural resources.

In the specific case of certain areas of the Earth, such as Andalusia, the consequences of climate change for ecosystems and agriculture are becoming catastrophic, as irregular temperatures and rainfall affect ecosystems, endangering species and phytocenosis. The bioclimatic framing of species is essential to establish sustainable management measures to mitigate climate change. Consequently, it is crucial to use management models based on the bioclimatic knowledge of the territory, as well as the use of vegetation covers, to mitigate sudden increases in temperature and reduce evapotranspiration, phenomena that can be addressed through sustainable development.

To succeed in reversing climate change, knowledge about sustainable development and ecosystem services must be enhanced, as this can save vulnerable forests from destruction. According to our results, there are positive and negative trends in temperature and rainfall irregularities in the south of the Iberian Peninsula. These scientific advances must be put into practice, and for this, it is necessary to strengthen education to train future managers of the natural environment. As education is a basic pillar for reversing the process, curricular content should be expanded within all degrees that are directly or indirectly related to the natural environment.

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