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ANALYZING VINEYARD VULNERABILITY: INVESTIGATING THE CLIMATE IMPACT ON GRAPEVINE CULTURE IN MADEIRA, PORTUGAL

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Abstract: Grapevines, belonging to the Vitaceae family, are of paramount significance in the world of viticulture. This family encompasses a diverse array of species, predominantly tropical or subtropical, spanning across 14 to 16 genera and comprising over 900 species. Within the Vitis genus, we encounter a notable diversity of 80 species classified into two subgenera: Muscadinia and Euvitis. The Euvitis subgenus, particularly, garners attention as it encompasses three distinct groups—American, Asian, and Eurasian. The Eurasian group, dwelling in the Mediterranean basin, holds global prominence in viticulture, with widespread distribution in temperate regions of Europe, North America, and Asia. These grapevines undergo an annual developmental cycle, encompassing nine distinct growth stages, commencing from bud break and culminating in leaf fall, heralding winter dormancy. The productivity of grapevines hinges on the interplay of genetic attributes specific to vine varieties and the influence of agroecological factors on the phenological phases of development. This paper delves into the intricate world of grapevines, their taxaonomic diversity, and annual growth cycle, shedding light on the pivotal factors that shape their productivity.
Keywords: Grapevine, Vitaceae family, Eurasian group, phenological stages, agroecological conditions

1. Introduction

The grapevine belongs to the Vitaceae family. This family joins predominantly tropical or subtropical species, with 14 to 16 genera and more than 900 species (Jackson, 2008; Wen *et al*., 2018). The *Vitis* genus includes 80 species organized in *Muscadinia* and *Euvitis* subgenus. The *Euvitis* subgenus grouping *Vitis* species is composed of 3 groups, namely American group, with 20 species, some used as rootstock; Asian group, with around 50 species and limited importance to viticulture; and Eurasian group that includes only one species *Vitis vinifera* L. and 2 subspecies, *sylvestris* (wild) and *vinifera* (cultivated forms). This last group includes most of the world vine varieties (Focus OIV, 2017). Nowadays, the Eurasian grapevine, which is indigenous from the Mediterranean basin, shows a world distribution mostly in temperate zones of Europe, North America, and Asia (Magalhães, 2011).

Although the grapevine is a perennial species, the plant has an annual development, including nine growth stages starting with bud break and ending with leaf fall before the winter dormancy (Zhu *et al*., 2020). The grapevine productivity depends on genetic characteristics of vine varieties (Inês, 2011) and the influence of agroecological conditions on the phenological stages of development.

The main grapevine producing areas are located between the 20º North and 50º South, where 4 climatic seasons are well defined (González *et al*., 2015). The climate is one of the main factors influencing grapevine productivity, and temperature, insolation, and water availability are the major variables (Rosenzweig& Hillel, 2008). The sensitivity of grapevine to temperature and precipitation depends on the specific growth stage. The heat required by the grapevine is necessary above all for vegetative development and fruit maturation (Hidalgo, 1980). Temperatures suitable for cultivation should not be less than 9ºC, and the optimal range is between 11 and 18ºC. Temperatures around 10ºC are considered as the base temperature for the annual development and growth of the grapevine varieties (Hidalgo, 1999; Gladstones, 2011).

The upper temperature limit can reach 40ºC, but many crop varieties show high sensitivity to the rise of temperatures (Guisado, 2016). The vine can resist low temperatures, such as -1ºC, during the vegetative period, and to -15ºC, specifically -12ºC for the buds, during the fallow period (Andrades, 1991). In most wine regions, the budding occurs on the sixth day, when it provided an average daily temperature exceeding 10 ºC, during 5 successive days (Amerine and Berg, 1980).

Viticulture and wine production have a high impact on the world economy, based on this, a better understanding of the culture development in the most different places and climates is required. The crop adaptation to environmental conditions comes from the grapevine genetic characteristics, which in turn enables a good or bad optimization of the quality of the wines produced in certain regions (Inês, 2011).

Monteiro *et al*. (2012) claims that climatic conditions have a considerable influence on the development and productivity of the vine. The same effect was noticed during all phenological stages of the grapevine, starting from vegetative dormancy during winter, passing through the bud break, flowering, veraison, until the grapes maturation and leaves fall in late autumn (Maia, 2013; Zhu *et al*., 2020). The increase of temperature promotes highest levels of nutrient absorption, allowing the bud cells to reach tumescent, creating a cover break that is protected, at the start of the budding season (Valduga, 2005). Temperature variations have a detrimental influence on yield traits when higher than 32 ºC before the vineyard reaches the 50% flowering stage (Zhu *et al*., 2020). The variation of temperature and water on grapevine can be detrimental or benefit yield and quality, depending on the phenological stage and its phase of development (Chaves *et al*., 2007; Jones and Alves, 2011; Zhu *et al*., 2020).

Tonietto and Carbonneau (1999) have formulated a world classification system for viticulture, assessing the influence of climate on culture. This system known as Multicriteria Climatic Classification System (Géoviticulture MCC System), allowing to define the climate of the wine regions, and is recognized and supported by the World Meteorological Organization (WMO). This system aims to combine and synthesize climatic information, enabling the identification of ideal locations for the development of vineyards (Machado, 2010).

The determination of the viticultural capacity from a scalable point of view allows a regional or local characterization of the environment. This scaled characterization can be carried out by generating or distinct elements of the climate, which integrate and influence the valorization of the wine-growing potential (Tonietto, 1999).

The first step in determining the wine-growing capacity of a given region is to determine the climatic and bioclimatic index, which it classifies as zones and evaluates the general possibilities it performs of performance for the development of different vine crops (González *et al*., 2015). The indexes establish relationships between one or more climatic parameters to characterize the productive capacity of cultivation in a region, as well as the maturation possibilities, aptitude of varieties, vocation for obtaining quality wines, and the risk of pests and diseases (Tonietto, 2001).

The System MCC recovers the calculation of three complementary bioclimatic indexes, applied according to the main stages of development of the vegetative cycle of the vine (Tonietto and Carbonneau, 1999). These indexes are Heliothermal Index (HI), Night Cold Index (CI), and Dryness Index (DI). In addition to the presented index, the Winkler Index (WI) was also determined.

The present work aimed to determine the bioclimatic indexes for the main viticultural zones of Madeira Island, for the current period and for two other simulated climatic scenarios simulated, to understand the future potentials and limits that will be imposed for to the development of the vine culture.

2. Material and Methods

The archipelago of Madeira belongs to the sub-region of Macaronesia, is in the subtropical region of the Atlantic Ocean. This archipelago consists of two main populated islands, Madeira (742 km^2) and Porto Santo (43 km^2) (Figure 1).

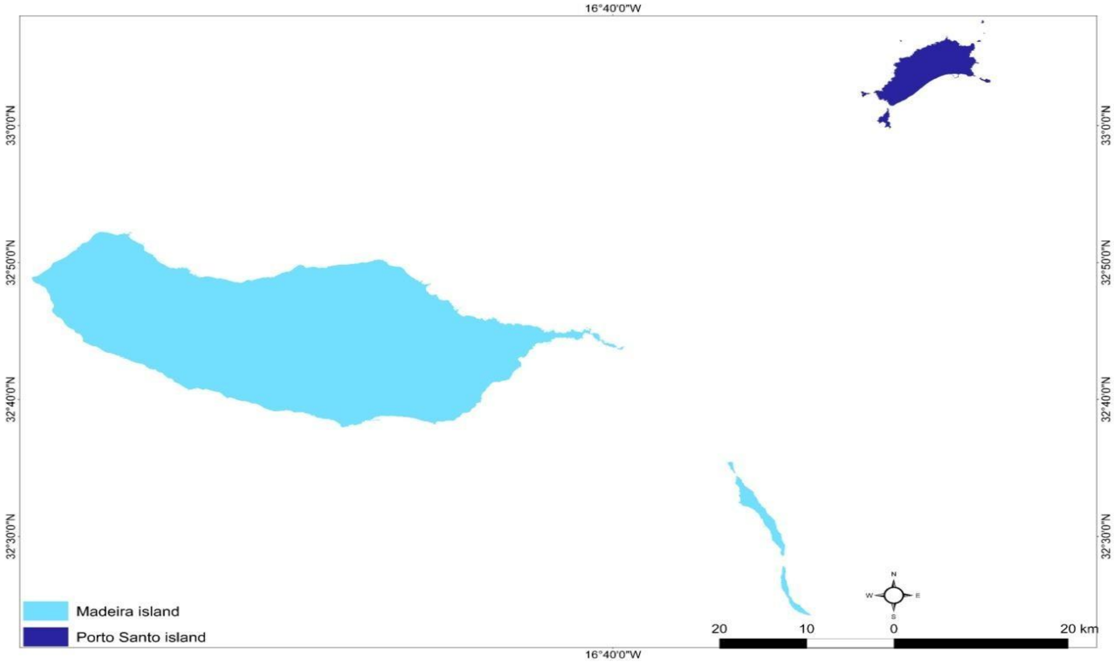

Figure 1. Madeira Island and Porto Santo Island

The Madeira island from a climatic point of view can be classified as being of the Mediterranean and Temperate type (Rivas-Martínez, *et al*., 2011) or even Mediterranean Temperate, according to the Köppen-Geiger climate classification (Peel *et al*., 2007). Higher volumes of precipitation occur in the winter and almost zero rainfall is expected in the summer; mild temperatures below 18°C are common in winter, however, they are always above -3°C, at the highest points on the island; summers are usually hot and dry, with temperatures between 10 and 22°C (Pinheiro de Carvalho *et al*., 2019).

2.1 Database

Data from the last 10 years of 6 climatic stations (Quinta Grande, São Vicente, Santana, Observatório, Calheta / P. do Pargo and Porto Moniz) were used (Figure 2). These stations were chosen because they are located close to the centers that produce the culture of the vine. The data were obtained from the Instituto Português do Mar e da Atmosfera (IPMA) (Table 1). The following figure shows the locations of all climatic seasons in Madeira island.

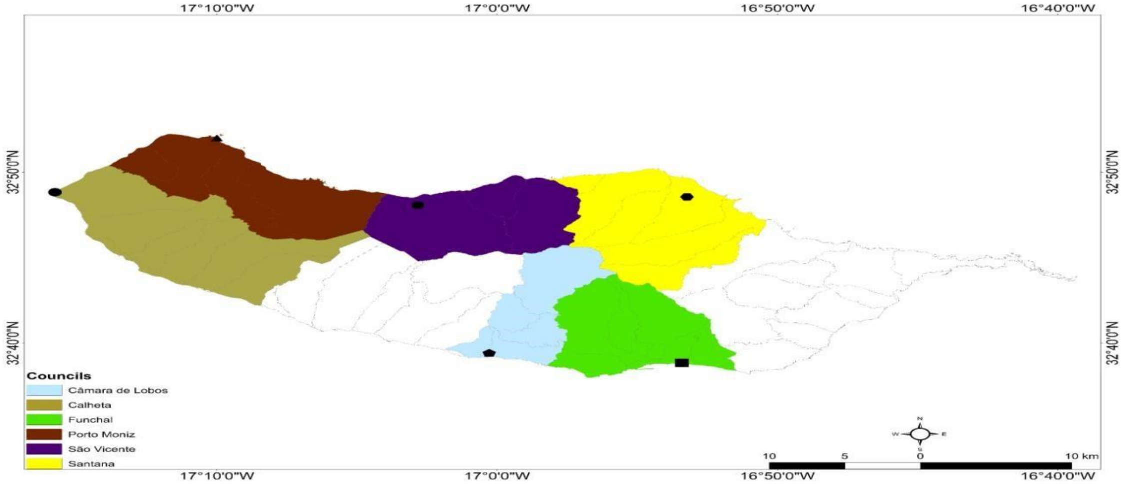

Figure 2. Main producing areas of Vitis vinífera L. and distribution of Meteorological Stations used in the present study

The use of data related to the last 10 years, aimed to verify the current climatic situation with the needs of the vine culture. Likewise, data from the Adaptation Strategy for Climate Changes in Madeira Region (Gomes *et al*., 2015) was used (Table 1), to understand what will happen to the culture, given the increase and decrease of precipitation in Madeira described in the document. According to the document, two scenarios called ∆A2 and ∆B2 will happen between 2070-2099, where:

Table 1. Increase temperature (ºC) and decrease precipitation (mm) proposed by Madeira Climate Strategy for 2070-2099

	Scenario ∆A2 (ºC)	Scenario ∆A2 (mm)	Scenario ∆B2 (ºC)	Scenario ∆B2 (mm)
January	2.4	0.34	1.5	0.4
February	2.8	0.50	1.8	0.34
March	2.5	0.33	1.6	0.32
April	2.7	0.39	1.6	0.3
May	2.8	0.61	1.7	0.48
June	2.7	1.09	1.8	1.23
July	2.6	1.92	1.7	1.33
August	2.3	1.94	1.5	1.34
September	2.3	0.33	1.6	0.37
October	2.3	0.56	1.4	0.25
November	2.5	0.53	1.5	0.4
December	2.3	0.34	1.2	0.3

2.2 Bioclimatic index

To estimate the different climatic indexes of viticultural interest, on Madeira island, monthly records of the different meteorological variables were used. The determinations of these indexes for the grapevine follow the recommendations proposed by Tonietto and Carbonneau (2004).

2.3 Heliothermal index (HI)

The HI was developed by Huglin (1978) (eq. 1), it aims to characterize areas, considering the accumulation of heat throughout the life cycle of plant species. In the case of vines, HI is calculated for the months in which the growth and development of the crop occur (April to September in the Northern Hemisphere). The results obtained by this index are expressed in degree-days (°C day or GD), making it possible to understand the times of the year that are most favorable to planting and harvesting agricultural species (Machado, 2010).

$$HI = \sum_{1\ April}^{30\ September}\left((T-10)+\left(\frac{Tmax-10}{2}\right)\right)*k \qquad \textbf{eq.1}$$

T = average air temperature (ºC)

Tmax = maximum air temperature (ºC) k = day length coefficient, ranging from 1.02 to 1.06 between 40 and 50º latitude

2.4 Night Cold Index (CI)

The Night Cold Index (CI) (eq. 2) has the function of analyzing the nighttime thermal conditions during the stage of ripening of the grapes (Tonietto and Carbonneau, 2004). Tonietto (1999) proposed the calculation of this index using only average minimum air temperatures, providing the results for this index.

The CI is calculated only for September, this month corresponds to the stage of maturation of the grapes (Maia, 2013). September is the determining month to obtain color and aroma before the harvest begins (Tonietto and

Carbonneau, 2004). According to Machado (2010), if the minimum temperature values are above 10ºC in September, the ripening of the grapes will also tend to continue during the night. The CI is achieved according to the following equation:

$$CI = Tn_9 \qquad \textbf{eq.2}$$

2.5 Dryness Index (DI)

The Dryness Index (DI) (eq. 3) aims to characterize the water component of a region, closely linked to the qualitative characteristics of wine and grapes (Guisado, 2016). This index was adapted by Tonietto, 1999; Tonietto and Carbonneau, 2004, through the potential soil water balance carried out by Riou (Riou, 1994). The result of this index conveys the potential water availability of the soil, considering the climatic requirement of a standard vineyard, evaporation in bare soil, rainfall without reducing runoff or infiltrated water (Guisado, 2016).

$$DI = Wo + P - Tv - Es \qquad \textbf{eq.3}$$

IS = soil water reserve
Wo = useful initial soil water reserve
P = rainfall
Tv = potential transpiration from the vineyard Es = direct evaporation from the soil

2.6 Winkler Index (WI)

It is an index that accounts for the accumulation of heat units, being used to describe the suitability of growing crops in different climates. This index (eq. 4) corresponds to the number of degree-days, considering the effective temperatures during the active vegetation period (Amerine and Winkler, 1944). It was originally designed for California, being extremely simple to obtain, since only the sum of average daily temperatures above 10ºC (temperature considered as zero vegetation for the cultivation of the vine) is considered from April 1 to October 31st. Through the results of this index, it is possible to establish five zones according to the amplitude obtained with its calculation.

$$WI = \sum_{1\ April}^{31\ October} \left(\frac{Tmax + Tmin}{2}\right) - 10 \qquad \textbf{eq.4}$$

2.7 Classes for Bioclimatic Indexes

Tonietto and Carbonneau (2004) defined some intervals for the 3 indexes, these intervals are known as climate classes. These climate classes are related to what each class represents, not only in climatic differences but also in the answers about grapes, vines, and their products as the climatic factors defined by the index considered, thus allowing a grouping of homogeneous viticultural regions. The index developed by Winkler was also used (Amerine and Winkler, 1944) (Table 2).

Table 2. Classes of viticultural climate for Heliothermal Index, Night Cold Index, Dryness index, and Winkler Index of grape-growing regions

Index	**Class of Viticultural Climate**	**Acronym**	**Climate Classes**
Heliothermal Index (HI)	Very Cool	HI_1	≤ 1500
	Cool	HI_2	> 1500 ≤ 1800
	Temperate	HI_3	> 1800 ≤ 2100
	Temperate Warm	HI_4	> 2100 ≤ 2400
	Warm	HI_5	> 2400 ≤ 3000
	VeryWarm	HI_6	> 3000
Night Cold Index (CI, °C)	Warm Nights	CI_1	> 18
	Temperate Nights	CI_2	> 14 ≤ 18
	Cool Nights	CI_3	> 12 ≤ 14

	Very Cool Nights	CI_4	≤ 12
Dryness Index (DI, mm)	Humid	DI_{00}	> 150
	Sub-Humid	DI_0	≤ 150 > 50
	Moderate Dry	DI_1	≤ 50 > -100
	Strong Dry	DI_2	≤ -100 > -200
	Very Strong Dry	DI_3	≤ -200
Winkler Index (WI)	Zone 1	i	< 1390
	Zone 2	ii	1391 – 1670
	Zone 3	iii	1671 – 1950
	Zone 4	iv	1951 – 2220
	Zone 5	v	> 2220

3. Results and discussion

3.1 Heliothermal Index (HI)

After tabulating the meteorological data applied to equation 1, a general average was obtained for the last 10 years. With these averages, a modelling of the index was done to verify its behaviour in Madeira (Figure 3), and two more maps were extrapolated and generated that contemplate the changes proposed by the Climate-Madeira Strategy.

Analyzing the present scenario, it was possible to observe that currently the island can be classified into 3 climatic classes: Temperate warm located in the northern part of the island, Warm in the central part of the island, and Very Warm both in the southern and western part of the island. With the modelling according to the ΔA2 (red lines) scenario parameters, it can be seen that the 3 climatic classes currently present no longer exist, and the island as a whole is now classified as Very Warm. A similar fact happens to the ΔB2 (blue lines) scenario, however, the same region that is currently classified as Temperate warm will change to Warm.

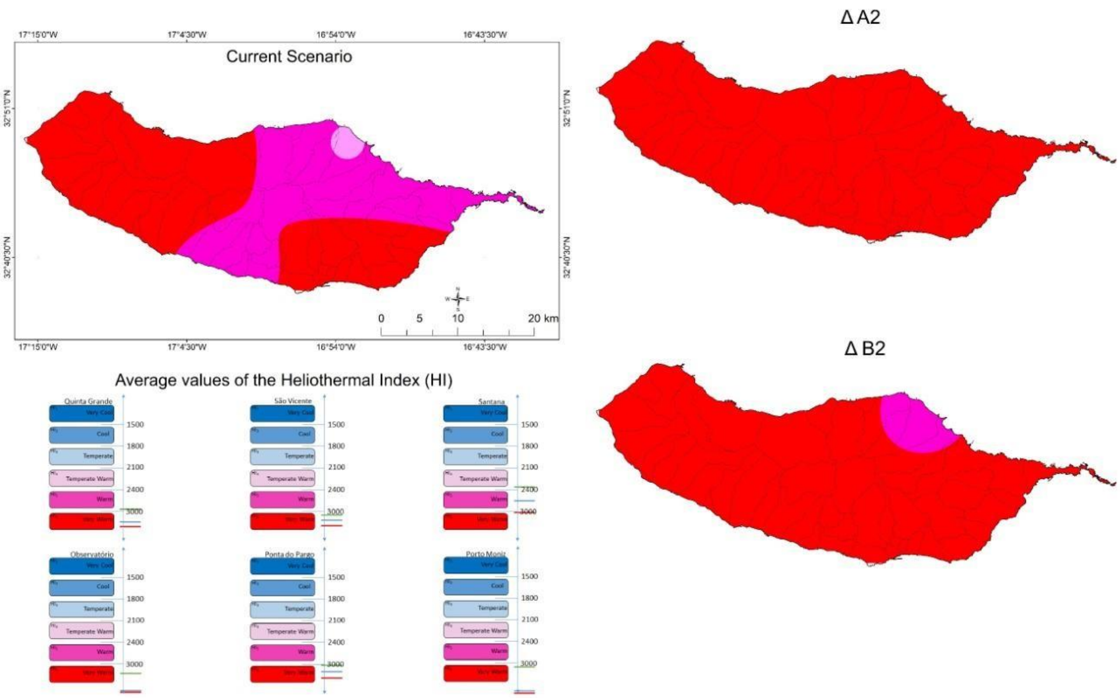

Figure 3. Interpolation of the Heliothermal Index (HI), for the current scenario and for the ΔA2 and ΔB2 scenarios proposed by Madeira Climate Strategy for 2070-2099

The values were also obtained for each of the 6 stations near the main producing localities of the vine culture. São Vicente, Observatório, Ponta do Pago, and Porto Moniz, presently the accumulation for this index in these areas is above 3000 GD (green lines), a fact that, even with the temperature increase proposed by the Strategy scenarios, it will tend to increase, even more, however, the classification for these areas will remain unchanged. Based on this, it is possible to affirm that, the varieties that are currently being cultivated in these locations, will not suffer serious consequences due to the temperature increase processes.

However, for the other two areas analyzed Quinta Grande and Santana currently classified as Warm and Temperate warm respectively (Figure 4), will change due to the climatic increases proposed by the document. However, this change from Warm to Very Warm in the Quinta Grande area should not impede the development of the vineyard. Santana will undergo more significant changes, since the zone is currently classified as Temperate Warm, and in the first scenario it will change to Warm and in the second to Very Warm.

3.2 Night Cold Index (CI)

Different from the results obtained for HI, the Night Cold Index (CI) has been causing a decrease in the quality of wines, since this index has the main role of evaluating the stage of maturation of the vine. Looking at the recent graphic data and Figure 4, it was noted that only Quinta Grande, São Vicente, and Santana have lower minimum night-time temperatures (green lines, between 16 and 18ºC), an ideal factor for this index. The other regions analyzed have presented, in recent years, minimum night temperatures above the 20ºC factor. It's interesting to into that in Porto Moniz in the last 2 years, the minimum average temperature has dropped by practically 2ºC. According to Guisado (2016), regardless of the vine variety used in the area, maturation is favourable thanks to the low night-time temperatures obtained in these areas.

However, with the simulation of the 2 scenarios, this classification will change from Temperate Nights to Warm Nights for all analyzed areas, these changes should make the farmer more careful and he should perform a more careful evaluation of the quality of his final product.

The areas near the stations (Observatório, Ponta do Pargo, and Porto Moniz), currently and in the two proposed scenarios, will not change, since they are classified as Warm Nights, and this will continue into the possible future.

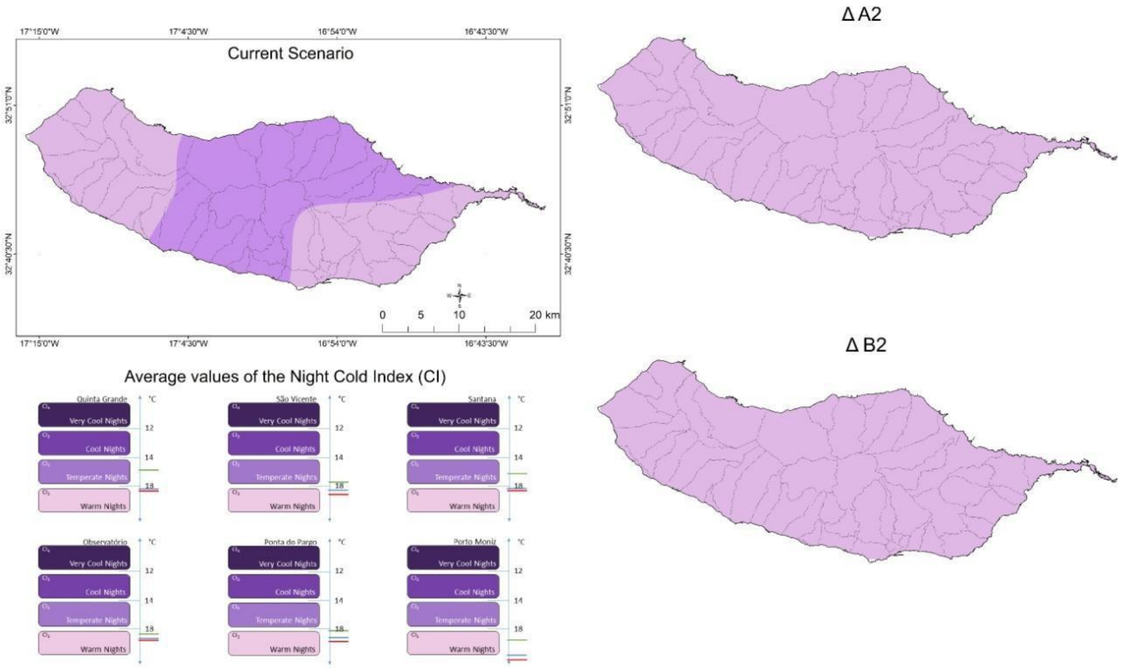

Figure 4. Interpolation of the Night Cold Index (CI), for the current scenario and for the ΔA2 and ΔB2 scenarios proposed by Madeira Climate Strategy for 2070-2099

3.3 Dryness Index (DI)

Analyzing the results obtained for the Dryness Index, it was verified that none of the sites analyzed in the last 10 years presented hydric restrictions for the development of the vine culture (Figure 5). The six production zones are classified as Humid range above 150 mm. According to Guisado (2016), this wine class corresponds to the absence of drought, with a high level of water availability according to the water balance. This factor, even with the simulation of the scenarios proposed by the Climate-Madeira Strategy, will not have drastic changes, continuing to be in the class classified as humid (Figure 5).

3.4 Winkler Index (WI)

The results obtained for this index show that there are similarities for the regions near the climate stations of Quinta Grande, São Vicente, and Ponta do Pargo, which are currently classified as region 4 (Figure 6), which enables the production of naturally sweet wines, however, in warmer years the most acceptable varieties tend to have low acidity. Wines are satisfactory if they are produced from grape varieties with high acidity (Gonzalez, 2005). However, with the simulation of the 2 scenarios, these areas will tend to be changed to region 5, where, according to the author cited above, wine production should have high acidity. This same classification applies to areas near the Observatório and Porto Moniz stations, that even after the simulation of the scenarios, these areas will not change.

The region that will tend to suffer more drastic changes concerning this index is located near the Santana station. Currently, this area is classified as Region 2, which according to Winkler's classification usually corresponds to the valleys and vineyards planted on the hillsides. The valleys can produce the best wines. However, less productive vineyards on the hillsides, despite their low expertise, can produce excellent quality wines. However, as mentioned above, this area according to the simulated scenarios will encompass region 4 for scenario 2 and region 5 in scenario 1.

These changes, if they materialize, will make it impossible to produce wine of the current quality, since the climatic requirements will not be the most possible to choose from.
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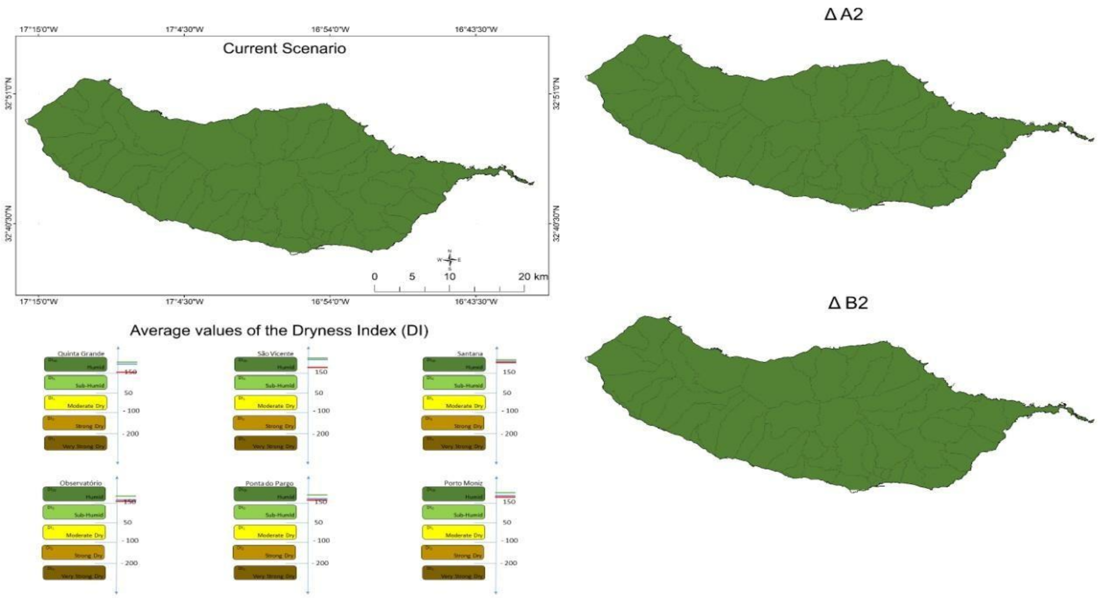

Figure 5. Interpolation of the Dryness Index (DI), for the current scenario and for the ΔA2 and ΔB2 scenarios proposed by Madeira Climate Strategy for 2070-2099

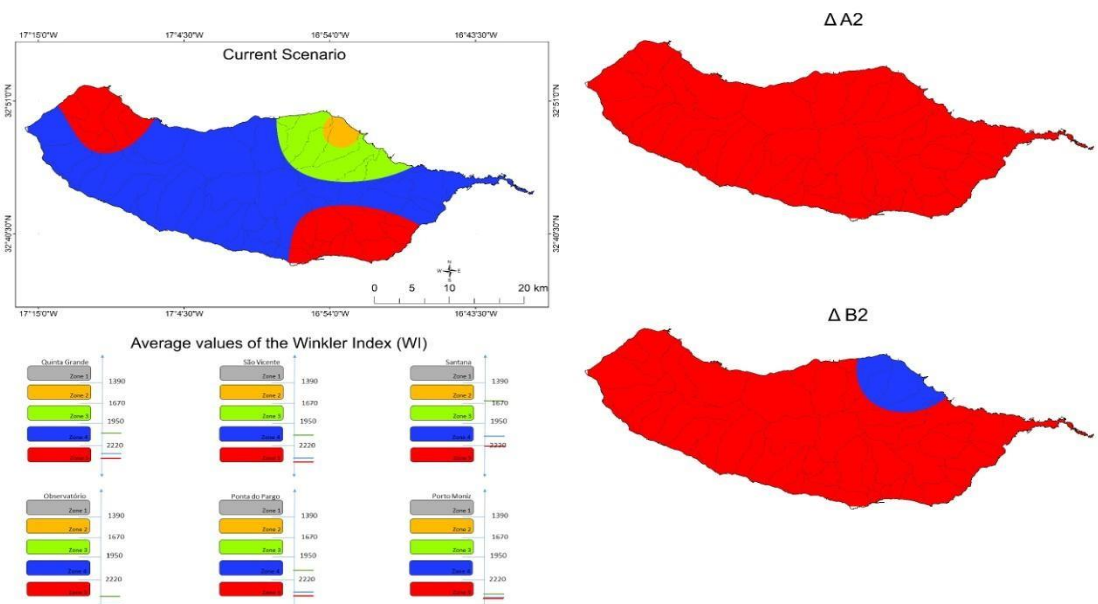

Figure 6. Interpolation of the Winkler Index (WI), for the current scenario and for the ΔA2 and ΔB2 scenarios proposed by Madeira Climate Strategy for 2070-2099

4. Conclusion

The results concerning the Heliothermal Index (HI) in general, showed that the regions analyzed will not change in terms of heat accumulation, except the region of Quinta Grande that is currently classified as Warm, in the future, if the simulations become reality, will change to Very Warm and the Santana region that is currently classified as Temperate Warm will suffer a change in ΔB2 to Warm and ΔA2 to Very Warm.

For the Night Cold Index (CI), the regions of Quinta Grande, São Vicente, and Santana currently have minimum ideal temperatures for a good maturation of the vineyards. However, with the simulation of the 2 scenarios (ΔA2 and ΔB2), this classification will change from Temperate Nights to Warm Nights for all analyzed areas, these changes should make the farmer more careful and he should perform a more careful evaluation of the quality of his final product.

The Dryness Index (DI) showed that currently and in the simulated scenarios, all regions have not suffered from drastic water restrictions.

In the regions of Quinta Grande, São Vicente, Ponta do Pargo, and Santana according to the Winkler Index (WI), the quality of the wines will change if the results of the simulations come true. The three regions are currently classified as zone 4 according to the Winkler Index, which comprises naturally sweet wines; they moved to zone 5 classified as wines with high acidity. The region of Santana, currently classified as zone 2, where good quality wines are produced, will move to zone 4 (ΔB2) or zone 5 (ΔA2).

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There is no conflict of interest in this work.

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