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The Spatiotemporal Evolution of the Growing Degree Days Agroclimatic Index for Viticulture over the Northern Mediterranean Basin

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Abstract: The agricultural sector faces significant challenges worldwide due to climate change. The pressure exerted by altered thermal conditions drives the zonal shift for various cultivations. This study aims to analyze and present the spatiotemporal evolution of the growing degree days (GDD) index in the northern Mediterranean Basin (NMB). More specifically, this research presents the multiyear analysis of the GDD index, which is focused on a high-value vine cultivation derived from the E-OBS dataset. The investigated time period spans from 1969 to 2018, and the performed analysis indicates a broad shift/expansion in areas with GDDs exceeding 2000 heat units. This is present in traditional winemaker countries such as France and Italy. Still, it is also evident that there is a high positive change in countries such as Serbia, Bulgaria, and other Balkans countries. The findings may be helpful in the strategic planning of the agricultural sector in these countries or on a vinery scale.

Keywords: climate change; agroclimate; agroclimatic indices; viticulture; viticultural zoning

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1. Introduction

A great number of surveys have extensively explored the relationship between agriculture and climate, given that atmospheric conditions are crucial factors influencing crop growth and development [1–5]. Variations in atmospheric conditions such as temperature, relative humidity, and precipitation may limit crop growth and productivity in the future. Latest-generation crop and climate models project markedly more pessimistic yield responses for major crops (e.g., maize, soybean, and rice), considering the climate impacts expected to occur before 2040 [6]. Therefore, the diverse spatial variability in climatic parameters [7,8] necessitates regionally focused and crop-specific research.

Viticulture, in particular, represents an integral constituent of the Mediterranean agricultural sector in direct financial terms and as a cultural factor [9,10]. Globally, vineyards are distributed among a total of 34 countries, and Europe accounts for 53% of the total viticultural area, concentrated in Spain, France, Italy, and Portugal [11].

Temperature is the predominant driver of grapevine development and growth as it principally controls the evolution of fundamental phenophases (e.g., bud break, flowering, veraison, and maturity) [12–15] and determines, therefore, viticultural production in terms of quality and quantity [10,16–18]. In addition, temperature plays a leading role in constraining the spatial/geographical distribution of grapevines, which may be overturned by the year 2100, as has been widely documented in projection investigations [10,18–20].

Although the vine is one of the crops most resilient to climate change (CC) [21], the latter is expected to form more xerothermic conditions over specific areas of the northern Mediterranean Basin (henceforth defined as NMB), such as in southeastern and central Europe, Adriatic coastal countries, and the Balkans [22–25]. Temperature records emphasizing viticultural areas reveal that, from 1950 to 2000, the mean growing season temperature had already increased by approximately 1.6–1.8 °C in Europe and 1.2–1.4 °C globally [26,27].

Most recent CC projections by Sgubin et al., in 2023 [28], revealed a northward shift up to 3° and 8° of latitude of suitable viticultural regions under the RCP4.5 and RCP8.5 emission scenarios, respectively. These shifts may result in a net expansion of the total suitable areas of 33% under the RCP4.5 and 45% under the RCP8.5, with a concomitant area loss of traditional wine regions of approximately 20% and 55% for the respective scenarios. The authors concluded that viticultural production is majorly threatened by suitability loss over typical, traditional wine-growing regions, the reduction in which appears to be non-linear.

Parallel to CC, extreme meteorological events (e.g., heatwaves, high-temperature incidents, droughts, and floods) are becoming more frequent (significant probability increase) and severe [29], negatively impacting the main European viticultural regions (e.g., yield reduction due to heatwaves and frost events during the growing period) [30,31] and also threatening their future [32]. Thus, it is of utmost importance to investigate and model the changing agroclimatic conditions that have been projected to affect the NMB viticultural sector's productivity in terms of quality and quantity, the phenological timings of the vine, and the viticultural areas' geographical distribution [18].

Given that viticultural production is directly affected by the consequences of CC, it is imperative for the research community to develop and share accurate and user-friendly information and tools. A group of essential research studies has already been published, taking advantage of datasets such as Agri4Cast, ERA, E-OBS, and other big atmospheric datasets [33–36].

Additionally, a wide range of agroclimatic indices have been developed to establish a connection between atmospheric and agricultural environments on a climatic timescale [37–40]. These indices often quantify the thermal environment during crop growth, making them vital for applications in various agricultural aspects such as the evaluation of agrometeorological conditions and the related trends for staple crops [41–44], the estimation of the agrometeorological requirements for a plant phenology's principal stages [45], the assessment and projection of agroclimatic suitability with respect to the evolution of viticultural zoning [46–49], the prediction of abiotic and biotic hazards in fruit production [50], yield-production predictions [51,52], and also for policy and decision making and the implementation of adaptation strategies [53–55].

One of the most performant, uncomplicated, and commonly utilized agroclimatic indices is the growing degree days (GDD) index, which is related to the growth cycle of plants since it incorporates air temperature, which constitutes a widely available and highly effective atmospheric parameter [56–58]. Reaumur introduced the concept of heat units or thermal time in 1730, when he recognized the significance of accumulated heat as a critical ecophysiological factor for plants and an important determinant of crop productivity [59,60]. The GDD index is based on the idea that the plant will develop if the air temperature exceeds a specific base value for a certain time period (number of days). Thus, each plant type best develops over its own specific base temperature (T_{base}) [50].

For over 30 years, numerous agroclimatic studies have been based on the GDD requirements specified for a wide variety of crops, considering physiological characteristics, phenological observations, and growth stages [61–67], while variations in the GDD values have been exploited as significant indications of CC effects on plants [68–71]. Therefore, the GDD index may be regarded as a classic, well-established, and applicable agroclimatic index due to its widespread and long-term use and its undemanding calculations, based on accessible air temperature parameters.

Given the projected NMB's vulnerability to climate change [18,22,23,72], numerous surveys have been undertaken regarding the basin's traditional viticultural regions, based on the GDD index. The most common aspects of scientific interest, with matters of phenology and production quantity and quality playing a leading role, are the following: phenological behavior assessment, modeling, seasonal forecasting, future projections, and past–future trends [73–78]; the impact of the climate on harvest time; harvest variation and harvest period prediction [79,80]; and the description of growing-season weather conditions and thermal–climatic characterization.

To our knowledge, from the bibliographic review conducted, most researchers are concentrated on specific countries and regions. At the same time, no scientific work has been documented regarding the spatial shifting of viticultural zones, mainly over the entire northern Mediterranean territory, based on calculations of the GDD index during past timeframes. Thus, by focusing on the expected spatiotemporal alterations in the traditional viticultural regions over the NMB (Albania: AL; Bosnia–Herzegovina: BA; Bulgaria: BG; Croatia: HR; Cyprus: CY; France: FR; Greece: GR; Italy: IT; Montenegro: ME; N. Macedonia: MK; Portugal: PT; Romania: RO; Serbia: RS; Slovenia: SI; and Spain: ES) and considering present and future wine-growing climatic constraints owing to CC-induced thermal warming, we proceeded to conduct an examination attempt on the evolution of the entire area's agroclimatic trends for vine cultivation. Our investigation was performed over intervals of time, covering an extended and relatively recent, past timeframe (1969–2018), aiming to discover a probable shifting/expansion of the surveyed viticultural zones.

Following this objective, we estimated and visualized the distribution changes in the viticultural regions belonging to the NMB and corresponding to the crucial annual threshold (2000 heat units) of the critical and commonly applied GDD agroclimatic index. The GDD calculations derived from the highly accurate (high spatial resolution ~10 × 10 km) atmospheric E-OBS dataset for three 10-year intervals: 1969–1978 (P1: Period 1), 1989–1998 (P2: Period 2), and 2009–2018 (P3: Period 3). This study aimed to illustrate (1) the spatial distribution of the areas that meet GDD values greater than 2000 units over the entire NMB over P1, P2, and P3 and (2) the kilometric evolution of the same areas (with GDDs > 2000 units) per individual country during P1, P2, and P3.

2. Materials and Methods

The selected area is the NMB, which consists of 15 European countries (Albania: AL; Bosnia–Herzegovina: BA; Bulgaria: BG; Croatia: HR; Cyprus: CY; France: FR; Greece: GR; Italy: IT; Montenegro: ME; N. Macedonia: MK; Portugal: PT; Romania: RO; Serbia: RS; Slovenia: SI; and Spain: ES) and constitutes a major epicenter of the vine world.

For this study, a high-spatiotemporal-resolution (~10 × 10 km) dataset, the E-OBS (v19.0e), was utilized. Several comparison studies have revealed that the E-OBS is a considerably accurate and confident dataset [33,35], which has already been exploited in various related research works [36,47,81]. For the calculation of the GDD index, the following traditional/canonical formula [59] was applied based on daily data from the E-OBS. These high-resolution gridded datasets, considering the daily minimum temperature TN and daily maximum temperature TX, were processed covering the period 1 January 1950–31 December 2018, based on the E-OBS dataset (0.10° × 0.10°; v.19e) from the European Climate Assessment & Dataset [82]. Moreover, these datasets cover 25 N–71.5 N × 25 W–45 E, and the data files are in a NetCDF-4 format.

$$\text{GDDs} = \left[\frac{T_{max} + T_{min}}{2}\right] - T_{base} \quad (1)$$

The calculations involved the 1950–2018 timeframe, and the input parameters were the daily minimum (T_{min}) and maximum (T_{max}) air temperature. The base temperature (T_{base}) was set to 10 °C. The starting point of the growing period was set to April and its completion at the end of October. Equation (1) is utilized with the following adjustment: when $\left[\frac{T_{max}+T_{min}}{2}\right] < T_{base}$, the GDD index is equal to 0 [34].

For the facilitation of a large amount of data and the conduction of the calculations, an R-language script [83] was utilized along with the QGIS software (ver. 3.28.15) [84] to map the results (Figure 1).

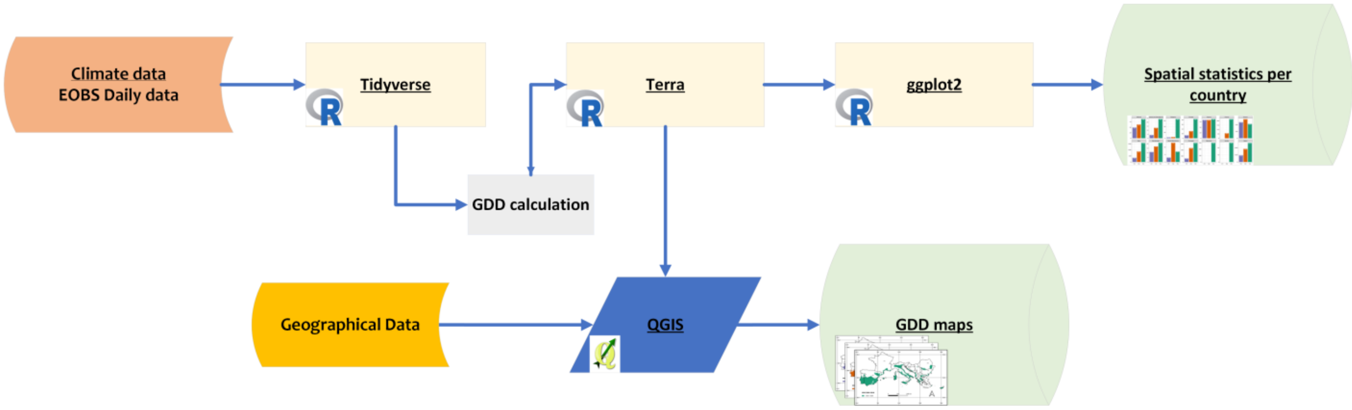

Figure 1. The analysis process performed.

3. Results and Discussion

The GDD index accumulates in the thermal environment, which is fundamental for the biological cycle of crops. The crucial threshold for the vines is defined as 2000 GDDs (annually), but there is also "cool–clixara mates" viticulture under agroclimatic conditions of less than 1000 GDDs [85]. In order to examine the spatial evolution of the zones with GDDs $\geq$ 2000 heat units, related maps (Figures 2–4) of the time periods (P1: 1969–1978; P2: 1989–1998; and P3: 2009–2018) were produced. In addition, multiple bar plots of the total surface area with GDDs $\geq$ 2000 for the individual countries in the NMB are presented in Figure 5. It is imperative to pinpoint that the GDD values are only one of the crucial factors of the atmospheric and environmental requirements for successful vine cultivation in terms of quantity and quality. So, the values of GDDs exceeding 2000 units are not evidence of environmental suitability for cultivation, given that farmers should also consider supplementary parameters, e.g., frost frequency, thermal stress, soil texture and fertility, and water availability in the area.

As depicted by the purple-colored surfaces in Figure 1, the areas fulfilling the GDDs $\geq$ 2000 criterion for P1, 1969–1978, occurred mainly in the southern part of the NMB. To the right, this part includes half of the southern coastline of the Italian peninsula (IT), the Adriatic shoreline of Albania (AL), Montenegro (ME), Croatia (HR), a significant surface area in mainland Greece (GR) and the country's islands, and almost the whole of Cyprus (CY). Moving to the right, the parts of the NMB with GDDs > 2000 over P1 involve the southern regions of Spain (ES) and Portugal (PT) (Iberic peninsula), with the majority concentrated in the former. It is worth mentioning that the E-OBS dataset for P1 did not detect the zones with GDDs $\geq$ 2000 in the traditional wine regions of northern France (FR) and Romania (RO).

The areas with GDDs $\geq$ 2000 during the subsequent timeframe (P2: 1989–1998) are illustrated by the brown-colored parts of the investigated territories (Figure 3), indicating an expansion towards higher altitudes and latitudes. More specifically, the results for this period indicate more extended areas over the northern part of Italy (IT) (the valley from Milan to Venice) and the entire peninsula's coastline, along with a wider occupation of the islands of Sicily and Sardinia. New areas fulfilling the GDD criterion appeared during P2, such as the Mediterranean shore of France (FR) and great parts of central and northeastern Spain (ES) (the Catalonia subregion), along with an extended area concentrated in the southern half of Portugal (PT).

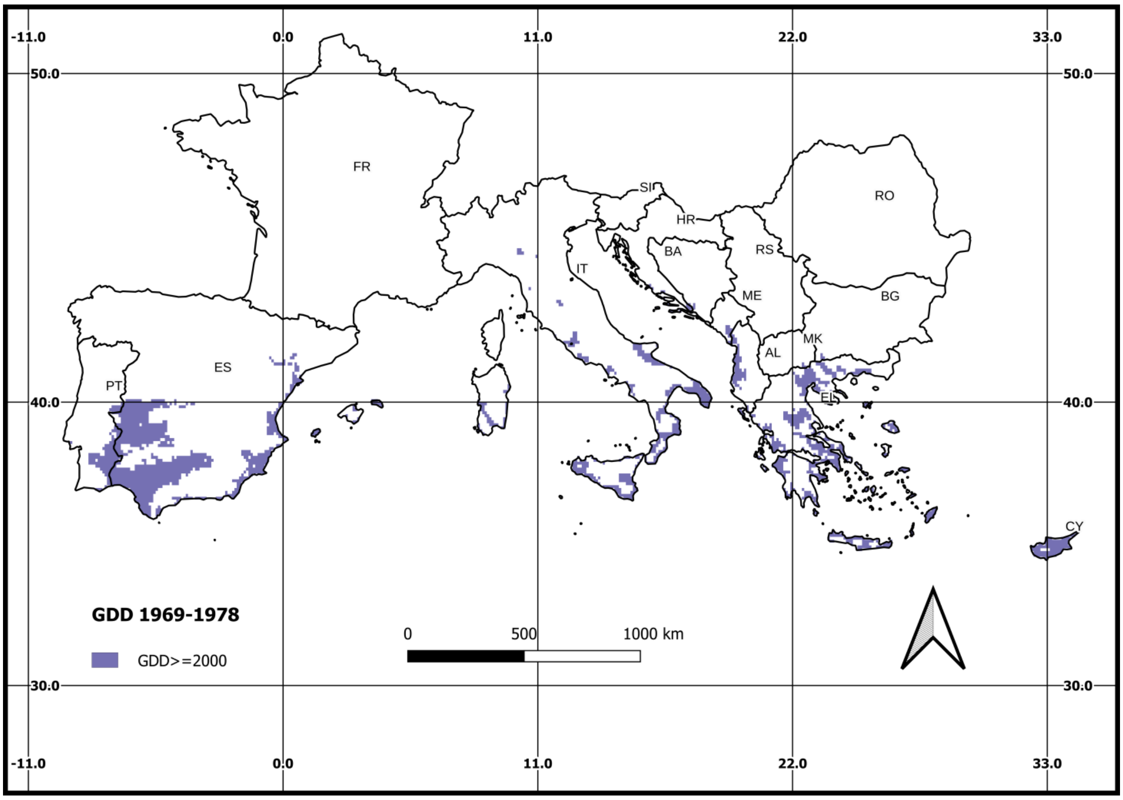

Figure 2. The areas with GDDs ≥ 2000 for the 1969–1978 (P1) time period.

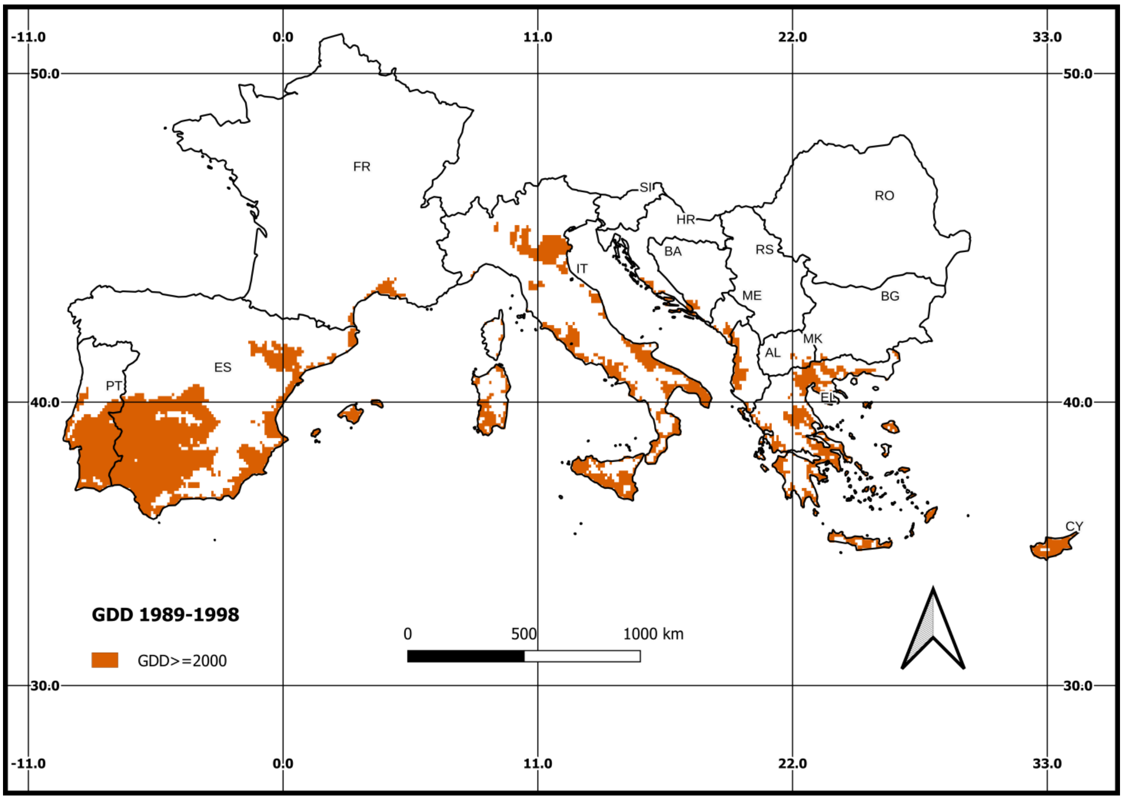

Figure 3. The areas with GDDs ≥ 2000 for the 1989–1998 (P2) time period.

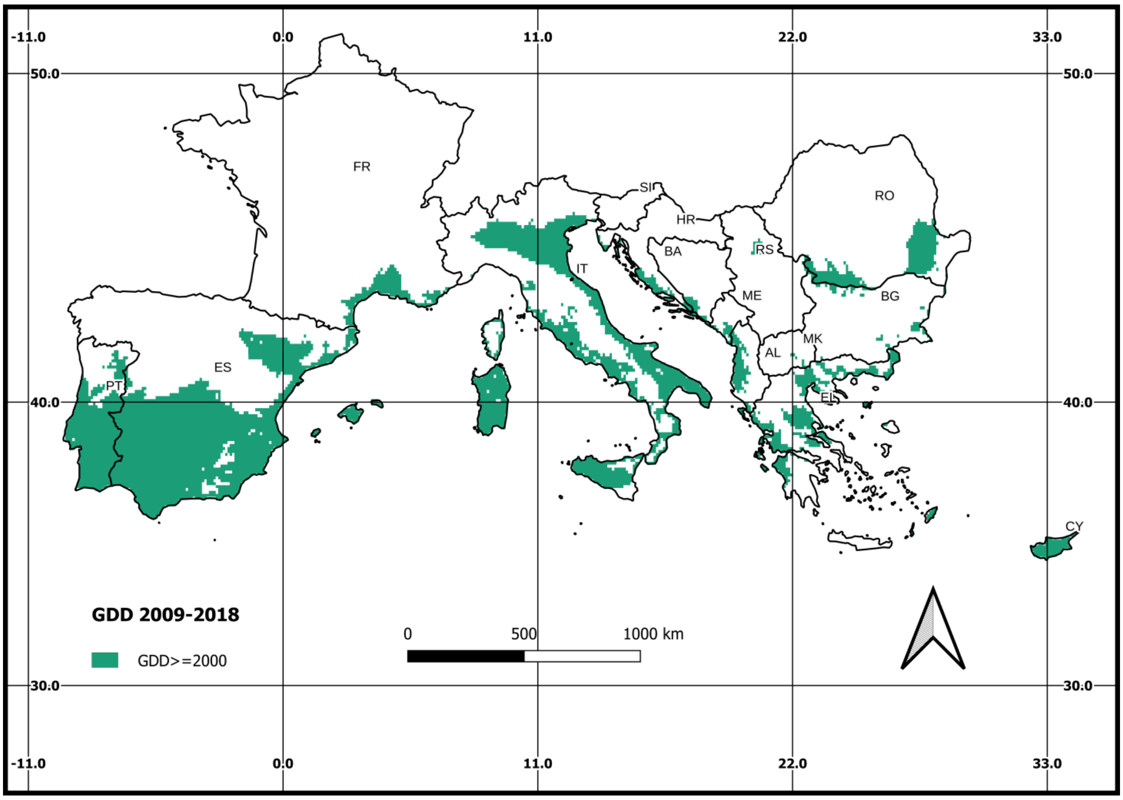

Figure 4. The areas with GDDs $\geq$ 2000 for the 2009–2018 (P3) time period.

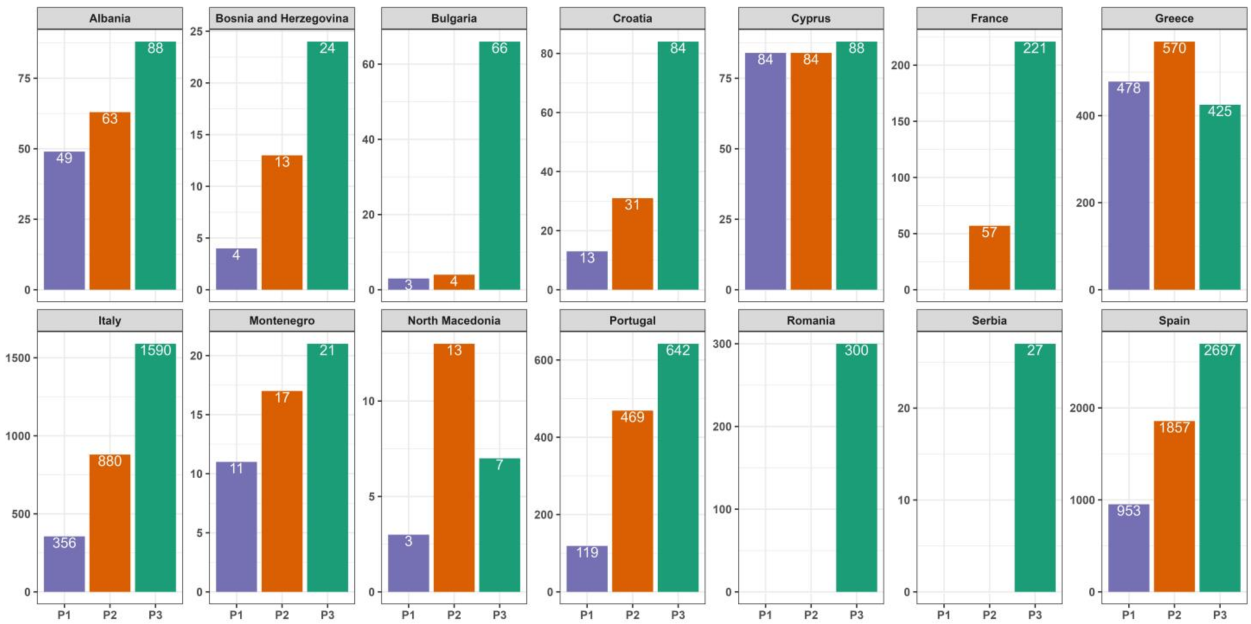

Figure 5. The temporal evolution of the areas with GDDs $\geq$ 2000 per country (displayed in alphabetical order). The value is $\times 100$ km^2 for the 1969–1978 (P1), 1989–1998 (P2), and 2009–2018 (P3) intervals.

The third period (P3: 2009–2018), involving the green-colored surfaces (Figure 4), indicates a significant expansion of the areas with GDDs $\geq$ 2000 towards the northern regions, such as the area over the Bulgaria (BG) and Romania (RO) borders and the parts of Romania (RO) neighboring the Black Sea. Areas with GDDs $\geq$ 2000 are also spread over some mountainous landscapes in Greece (GR), mainly in the western part of the country. It is also shown that, during P3, parts of Greece (GR) previously (P2, Figure 2) corresponding to the thermal units' criterion did not comply with the GDD threshold for grapevine cultivation (e.g., the entire island of Crete, the eastern Peloponnese, and Attica). The most significant advancements in regions with GDDs $\geq$ 2000 take place over the eastern and northern Italian territory (IT), with a significantly wider occupation of the latter, which is also the case for the southern shoreline of France (FR) and the southern and eastern parts of Spain (ES). It is also apparent that, in the 2009–2018 period, almost all of Sardinia appeared to be favorable for winegrape cultivation.

The areas (covered by GDDs $\geq$ 2000) for each country (Figure 4) reveal the phenomenon's evolution over time. It is very important to mention that the E-OBS dataset presents some gaps (empty cells), mainly in the perimeter, during the last 15 years of the studied timeframe. To avoid severe inaccuracies and false conclusions, removing pixels with a non-complete series of data was considered appropriate. This intervention justifies the reduction in the area covered from the second (P2) to the third period (P3). No climate cooling was recorded in North Macedonia (MK) and Greece (GR). The multiple bar plots in Figure 4 indicate a steady increase in the surface area under agroclimatic conditions of GDDs $\geq$ 2000 due to CC. All the above findings corroborated previous related research, indicating extensive shifting of the GDDs and vine areas to more northern (in Europe) and higher areas [10,34,54,86–88]. Albania (from 4900 to 8800 km^2), Montenegro (1100 to 2100 km^2), Croatia (from 1300 to 8400 km^2), and Bulgaria (from 300 to 6600 km^2) are among the countries demonstrating relatively significant surface increases with GDDs $\geq$ 2000, especially between the P1 and P3 intervals.

It has already been highlighted that there is a lack of scientific work on the spatiotemporal distribution of viticultural areas falling into the critical condition of GDDs $\geq$ 2000 for the entire NMB and, furthermore, on the evolution of viticultural zoning during past timeframes. Most studies have focused on demonstrating the index's (along with other thermal accumulating indices) past and future trends and, majorly, on a regional scale. However, the outcomes of such investigations have confirmed a future continuation of the northward- and higher-elevation-shifting trends of areas with GDDs $\geq$ 2000, which have been previously demonstrated over P2 and P3 (Figures 2 and 3, respectively), which were thus considered appropriate to be included in our discussion.

3.1. Europe

The aforementioned viticultural areas' expansion trends have demonstrated a temporal potential future continuation, considering the scientific outcomes of surveys involving the projected CC by the end of the century. In these surveys, CC appears to be a major modification factor in the present conditions in the current regions favorable for winemaking, resulting in the emergence of new potential wine-producing areas. Malheiro et al. (2010) [89] have analyzed the impact of the projected future climatic changes on European viticultural geography based on several bioclimatic indices, including the LGS (length of the growing season), calculated as the number of days with mean temperatures above 10 °C (GDDs). The researchers concluded that the projected future CC might demarcate new potential areas for viticulture in western and central Europe. Santos et al. (2012) [90] have computed the Winkler index (GDD in °C) over Europe using the E-OBS gridded daily temperature dataset for the years 1950 to 2009. The resulting figures depicting the mean pattern of the index in 1950–2009 and the differences in the medians of the index between 1980–2009 and 1950–1979 have revealed significant increasing trends for the index, particularly in the southwestern part of the continent and mainly over the Iberian peninsula, France (FR), and Italy (IT). Tóth and Végvári (2016) [91] have calculated the potential future area loss for the leading wine-producing countries in Europe, namely, Portugal (PT), Spain (ES), France (FR), and Italy (IT). Their predictions, using a pessimistic scenario (A1B) for 2050 and 2080, revealed an approximate loss of 2% to 48%, accompanied by the northward shifting of the Mediterranean wine-growing regions. Similarly, Cardell et al. (2019) [92] have studied the prospects of the future evolution of agroclimatic indices (including the GDD) linked to viticultural zoning across Europe based on observed data (daily max and min temperatures from the E-OBS dataset) and projected features (RCMs from the European CORDEX project under the RCP4.5 and RCP8.5 emission scenarios). The survey's outcomes suggested negative effects on winegrape growing in southern Europe but significant northward extensions of high-quality viticulture areas in the territory's western and central parts.

By exploiting the formulation of GDDs classed into the Winkler index, Moriondo et al. (2013) [93] have predicted the potential spatial expansion and/or shift of the possible grapevine-cultivated area in 2020 and 2050 under the A2 and B2 SRES scenarios over the European domain. The results exhibited progressive shifts in the current wine-growing areas to the north–northwest of their original ranges and the expansion or contraction of the viticultural regions owing to alterations in the regions' suitability for grapevine cultivation. The effect of climate warming was more evident in the southern areas of the NMB, which was attributed to the gradual disappearance, starting in 2020, of the combination of climatic factors that had benefited the formation of wine production suitability in these regions in the period during which the investigation was conducted. A significant number of grapevine regions over Spain (ES), Portugal (PT), and France (FR) were projected to lose suitability in their inland areas. Some of the wine regions demonstrated shifts to higher elevations typically associated with area limitations. Characteristic cases are those of the Chianti area (northwestern Italy (IT)), which, in 2020, was found to move from an average elevation of 211 m a.s.l. to 450 and 455 m a.s.l. (A2 and B2), with reductions of 83% and 77% in its areas, respectively. Similar shifts resulted in La Mancha (central Spain (ES)), where a progressive shift to higher elevations (e.g., northward shifting from 0.9° to 1.6° Lat N in A2) was found to be accompanied by a large decrease in area in both scenarios.

3.2. Balkans

In their survey on the spatiotemporal estimation of vine cultivations' GDDs in the Balkans' region, Charalampopoulos et al., in 2021 [34], mapped the suitable areas for viticulture in the year of 2020 based on the criterion of GDDs $\geq$ 2000. The respective regions corresponded to the entire southern part of the Balkans and, more precisely, the coastal zones of Albania (AL), Montenegro (ME), Croatia (HR), and Slovenia (SI), together with southern Romania (RO), also reflected in the present study's mapping results by the year 2018 for the same region (P3, Figure 4). Contrary to their findings, however, in the current investigation, the GDD criterion's fulfillment resulted in a far lesser area of North Macedonia (MK), Serbia (RS), and Bulgaria (BG).

3.3. Individual Countries

Jones et al. (2005) [27] have conducted a climatic analysis over a long timeseries of at least 50 years (from 1952 to 2004) on European wine-growing areas located in France (FR), Italy (IT), and Spain (ES) and have highlighted the increases in the heat accumulation indices. They evidenced an average warming of 1.7 °C during the growing season and an average increase in the GDDs by 245 units, e.g., for Colmar, Reims (northeastern France), Bordeaux (southwestern France), and Conegliano Veneto (northeastern Italy).

3.4. France (FR)

The calculations show a substantial GDD increase in France (from 5700 to 22100 km^2). Our results are in line with those of previously published research. So, temperature warming during the past decades (between 1960 and 2010) has been demonstrated by Neethling et al. (2012) [94] for the northwestern parts of France (FR) (Loire Valley). The authors denoted increases in the GDDs, which reached a maximum value of 360 units. Xu et al. (2012) have investigated the differences between projected (2030s) and recent past (the 1970s) growing season degree days (GDDs) in Burgundy (eastern France (FR)). The research findings indicated a systematic strong increase in the GDDs owing to the alterations in the growing season mean temperatures and spatial distribution. According to the authors, this trend allowed potential regions best suited for sustainable premium wine production to move northward and towards higher elevations. Kurtural and Gambetta (2021) [95] have shown the substantial warming of the Bordeaux region in southwestern France (FR) from 1950 to 2020, thus contributing to a positive evolution of the average wine quality. Although the annual growing degree days (GDD) evolution (from approximately below 1500 annual units in 1950 to over 2000 units in 2020) showed values markedly increasing in the early 1980s, the authors expressed concerns about ripening relationships (fruit-based metrics) that were "reaching a plateau" and may thus lead to a turning point in traditional viticultural regions. For the same region (Bordeaux, southwestern France), Baciocco et al. (2014) [96] computed the growing season GDD index from 1961 to 2009. Similar to P1 and P2 (Figures 1 and 2, respectively) the mean GDD index did not display values over 2000 units. Calculations of the GDDs have also been performed by Davis et al. (2019) [97] based on data recorded over the Dijon (Côte-d'Or department, eastern France) for the 1961–2015 period. The index's mean across all the years revealed a thermal accumulation of 1271 units (<2000), like that occurring for all the examined periods in this study (Figures 1–3).

3.5. Italy (IT)

Eccel et al. (2016) [98] have reported significant changes in the mean thermal conditions during the growing season (higher GDDs), which have led to substantial shifts in the traditional winegrape areas in Trentino (Italian Alps). A new climatic suitability has been projected (2006–2070 period under the RCP 4.5 and RCP 8.5) for the mountain areas above 450 m a.s.l., particularly for the white grapevine varieties (Müller Thurgau), while no winegrowing limitations have been projected for lower-altitude areas. Pallotti et al. (2022) [99] have characterized the seasonal (April to October) climate trends of the Matelica area (central Italy (IT)) for a period of almost thirty years (1989–2016). Based on the heat summation data (Winkler index; sum of GDDs), the highest value of 1814 units was registered for the decade of 1999–2008, with a mean value of 1748 units for the entire period (1989–2016), which exceeded the mean value recorded in the years from 1950 to 2000 by about 200 units. However, for the investigated area, the values never exceeded 2000 units, as depicted in the examined periods of Figures 1–3. As illustrated for northwestern Italy (Figure 3), GDD values <2000 units were also estimated by Rocchetti et al. (2021) [100] for the Piacenza viticultural region (northern Italy) throughout the 8-year period from 1998 to 2005, where the highest value reached 1975 thermal units. In their three-year survey (2017, 2018, and 2019), over four South Tyrol's locations (the northernmost point of Italy (IT)), Michelini et al. (2021) [101] reported ranges of GDDs from 1603.1 to 1972.5, as has also been demonstrated in this study for the same region by the year 2018 (Figure 3). Teslić et al., in 2017 [102], detected climate shifts in the periods of 1961–1990 and 1986–2015 over viticultural areas of the Emilia-Romagna region (northern Italy). A significant increase in the GDD value was detected for the entire region, with an exhibited total trend of 371.98 units (6.1 units per year). Gentilesco et al. (2023) [103] have estimated an increase in the mean GDD value (or Winkler index) across the Apulia region (southern Italy (IT)) from 2106 to 2368 units. This also applies to the present research, given the area's correspondence to the GDDs > 2000 threshold over all the investigated periods (Figures 2–4). The authors also denoted the potential existence of areas still suitable for quality viticulture by 2081–2100 (based on the Shared Socioeconomic Pathway SSP2–4.5), mainly in the higher altitudes of the Murgia plateau, the Gargano promontory, and the Pre-Apennine area. Using temperature observations from the E-OBS gridded dataset, Massano et al. (2023) [104] have estimated heat accumulation during the growing season (GDD index) at the regional scale over a past timescale of 39 years (1980–2019) in Italy (IT). In their results on the climate–productivity relationship, the authors mention that the GDD trend (units increase every year) reflects the country's general temperature increase, with the region of Sicilia displaying a significant decreasing trend in vineyard areas (-2.16×10^3 ha/year). Lanari et al. (2022) [105] have calculated heat accumulation over a period of 13 years (2007–2019) in eastern-central Italy's

Marche region in different periods of the grapevine annual cycle. The average GDDs were higher than 2000 (2036) for the April–October interval, as illustrated in Figure 4 for P3. Vigl et al. (2017) [106] have assessed the potential extent of grape cultivation in the South Tyrolean Alps (northern Italy (IT)) by exploiting the Winkler index (growing season's mean daily temperature sum) for the years 2001 to 2013. The average values of the index were lower than 2000 °C for all the examined locations, while the highest values were recorded for the southern part of the entire area.

3.6. Spain (ES)

Moral et al. (2016) [107] have analyzed the potential effects of CC on the Winkler index (based on the GDD), which was considered, in their study, over the 1980–2011 period for the Extremadura region located in southwestern Spain (ES). The researchers reported increasing trends of 16.12 units per year, summing up to a total of 484 units over 30 years. A few years later, the same researchers (Moral et al. (2022) [108])provided results on the temporal evolution of the GDDs for the historical period of 1971–2005 over the wine-growing areas of southwestern Spain (ES) (Extremadura) and showed an increase in the index's values from 1800 to almost 2200 units. Similarly, this part of Spain exceeded the thermal limitation for grapevine growth, like in all three of the periods examined in the current study (Figures 1–3). The authors also predicted that, depending on the considered index and the emission scenario, 65% to 92% and 80% to 98% of the Extremadura region will be potentially unsuitable (too hot) for viticulture by 2036–2065 and 2066–2095, respectively. Piña-Rey et al. (2020) [109] have documented a significant trend in terms of an increase in the Winkler index (for temperatures between 1 April and 30 September) from 2000 to 2015 in northwestern Spain (ES). More specifically, an analysis of the index's variations for 1950–2015 showed higher values in the Euro-Siberian area (approximately 1500 in the Ribeiro DO transition bioclimatic area and <1000 in the more Mediterranean areas) and a more pronounced increase of 420 units in the DO areas located in the eastern Mediterranean area during the more recent and smaller timeframe (2000–2015). This fact may be related to the expansion of the wine-growing areas in western Spain, as illustrated in Figure 3 when compared with Figures 1 and 2. Based on estimations of the annual evolution and long-term trends of the GDDs (Winkler index over the past few decades (1958–2005)) in Rías Baixas, Lorenzo et al. (2013) [110] have shown positive trends of 36 GDDs per decade in northwestern Spain (ES). This temporal evolution reveals the future viticultural exploitation of the northern parts of Spain, which appears more probable given the expansion of grapevines, which has already been shown for 2018 in the present study (Figure 3). Martínez de Toda and Ramos (2019) [111] have estimated the climatic conditions over six vineyards located in northern Spain (ES) and, more specifically, in Rioja Alta (RA1: Haro and Cenicero municipalities; and RA2: Sotés and Alesanco) and Rioja Oriental (RO), over the period of 2008–2018. The results of the mean GDDs during this period showed 1515, 1199, and 1800 values in RA1, RA2, and RO, respectively, all below 2000 units, as exhibited for the same spatiotemporal context in the present study (Figure 3). Intrigliolo et al. (2014) [112] have described the climatic conditions in the viticultural area of Valencia (southeastern Spain (ES)) during three consecutive seasons (2009, 2010, and 2011). The area's temperature conditions were described as "typical for warm viticulture climates", with GDDs from April to October exceeding 2290 °C in all years, as presented in our study for P3 (Figure 4).

3.7. Portugal (PT)

According to our findings in Portugal, in the western part of the study area, a high spatial expansion of areas with GDDs $\geq$ 2000 has been recorded (from 119000 to 64200 km^2). Since the country is one of the most renowned wine producers, there are many published studies on the topic. More specifically, utilizing a high-resolution climatic dataset (<1 km), Fraga et al. (2016) [113] have demonstrated the present and future optimal climatic zones for the cultivation of specific varieties in Portugal (PT). Calculations of the GDDs for recent, past periods (1950–2000) over 12 Portuguese mainland viticultural regions exhibited mean values ranging from 1309 to 2116 units, while an intense future warming trend (years 2041–2060) was projected (RCP4.5 and 8.5 scenarios), involving the northward shifting and the movement of cultivations to higher elevations. Wunderlich et al., in 2023 [114], made predictions (by fitting suitability models of Vitis vinifera using environmental variables accounting for temperature, precipitation, soil properties, topography, and agricultural practice, specifically irrigation) on grapevine suitability in Portugal (PT) for a baseline period between the years of 1981 and 2010. A more extensive spatial distribution of high-suitability areas in the northern and central-western, mostly coastal, parts of the country, was displayed, and the result was far more limited under no-irrigation conditions. Our study's distribution of vine areas with GDDs > 2000 presents similarities with the respective results for the 1950–2000 period, in Portugal (PT), of Fraga et al. (2017) [115]. As in the present study, by the year 2000, the approximately lower half of the country was characterized by values of GDDs > 2000. This tendency for increasing accumulated temperatures appears to continue in the future, since projections for the years 2041–2070 under the IPCC A1B scenario suggest significant increases in the GDDs, especially in the innermost regions of Portugal (PT), with values exceeding 2700 thermal units.

3.8. Romania (RO)

As in the present study, the results from past climatic trends reveal that Romanian (in the northeastern part of the study area) viticulture will benefit from CC [116]. By conducting a comparative study on the influence of CC on southern Romanian's viticulture between a relatively extended period (1998–2018) and the reference period (1961–1997), Bucur et al. (2019) [117] have documented an increase in the Winkler index (based on the GDDs), among other temperature-dependent indices, of 173 units. Donici et al. (2021) [118] have concluded that, in Pietroasa (Bihor County, western Romania (RO)), the GDDs ranged from 1662 to 1825 in the years from 2010 to 2020, thus demonstrating GDD values < 2000 units, as during P3 in our study (Figure 3). Patriche and Irimia (2022) [87] have conducted more recent CC impact assessments on the country's viticultural potential and have revealed that, compared to the reference period (1961–1990), the areas suitable for viticulture have expanded over the last few decades (1991–2013). More precisely, the shifting of new regions in the plateau, hilly, and lower mountain areas from restrictive to suitable for winegrape cultivation (25245 km^2, 10.6% of the country) is documented, along with a rise in the upper altitude limit for vine growing from 612 m to 860 m. These expansion trends align with the present study, given an increase in the areas with GDDs > 2000 units by 30000 km^2 over P3. According to the authors, there has been an increase in the suitability for winegrape production in about one-third of the country (76833 km^2, 32.2%), with the potential for red wine production having significantly increased at lower elevations and the potential for white wines having migrated to higher elevations and latitudes.

3.9. Serbia (RS)

For the period of 1981–2007, Ruml et al. (2016) [119] have shown significant increases in the historical temperature parameters for the region of Sremski Karlovci (Vojvodina province, northern Serbia (RS)), relative to the rise in the estimated GDDs by 12.0 units per year, thus depicting significant temperature warming trends in northern Serbia (RS). According to Vujadinović Mandić et al. (2022) [120], the distribution of areas suitable for viticulture in Serbia (RS) for the years 1998–2017 was in the central and mostly northern parts of the country, where the values of the Winkler index spanned from 1944 to 2700 °C, reflecting a warmer climate compared to the reference period of 1961–1990. The appearance of suitable areas in northern Serbia (RS) is coherent with our findings, given that a small area emerging with GDDs > 2000 was exhibited for P3 (Figure 3). The researchers also documented an average change shift of approximately 200 m towards higher elevations. Ruml et al. (2012) [119] have performed climate projections and revealed Serbia's (SR) tendency towards warmer conditions by the year 2100. Comparisons between the 1961–1990 reference period and the years 2001–2030 (SRES A1B scenario) and 2071–2100 (SRES A2 scenario) showed that the mountainous region of Zlatibor (western Serbia (SR)), presently having an average heat accumulation of 700 GDDs, will probably reach approximately 1600 GDDs by the end of the century. Furthermore, non-traditional viticultural regions (e.g., Pozega in western Serbia (SR) and Kursumlija and Dimitrovgrad in southern Serbia (SR)), presently averaging nearly 1200 GDDs, are predicted to become more favorable for viticulture in the future, with an estimated value of almost 2000 GDDs. In the authors' opinion, these alterations open up the possibility for the transformation of previously unsuitable (too cool) marginal and elevated areas to climatically friendly regions for viticulture. Stefanovic et al. (2021) [121] have estimated the GDD index in the Negotinska Krajina wine region (eastern Serbia (RS)) over three consecutive experimental years (2011–2013). The values of the index were 1784, 1976, and 1686, respectively, for 2011, 2012, and 2013, demonstrating agreement with the GDDs < 2000 units shown in eastern Serbia (RS) during P3 (Figure 4). Marković et al. (2016) [77] have reported warmer trends in relation to the reference period (1981–2010) in Oplenac (central Serbia (RS)) during the years 2010 and 2011. The GDDs, however, did not exceed 2000 units (e.g., GDDs of 1562 and 1737, respectively, for 2010 and 2011), as found in our study, for the same area, during P3 (Figure 4).

3.10. Bosnia and Herzegovina (BA)

Most surveys on the impact of CC on grapevine cultivation in Bosnia and Herzegovina (BA) are based on other indices (Tebic et al., 2021) [122], the results of which are not in the scope of this study. However, Jovanović-Cvetković et al. (2023) [123] have estimated the GDD values in two viticultural regions in Herzegovina from 2000 to 2019. Similar to the distribution of the GDDs > 2000 displayed in Figure 4, the results exceeded 2000 units in the Trebinje (2372.7 °C) and Mostar (2555.3 °C) southern localities.

3.11. Bulgaria (BG)

Tzanova et al. (2020) [124] have reported the average GDDs for the period 2017–2019 in three viticultural districts of Bulgaria. The Danubian plain in northern Bulgaria (BG) (town of Pleven, 116 m a.s.l.) was characterized by a GDD value of 3911 °C. In the Thracian lowland in southern Bulgaria and, more specifically, the village of Mogilovo (Chirpan municipality, 312 m a.s.l.) and the village of Mezek (Svilengrad municipality, 168 m a.s.l.), the GDDs amounted to 3820 °C and 4346 °C, respectively. The values exceeded 2000 units, which is also the case in our study for new areas in northern Bulgaria and the area of Svilengrad by 2018, as shown in Figure 4.

3.12. Montenegro (ME)

In their effort for the phenolic assessment of the Montenegrin wines produced in the Podgorica region (southern Montenegro (ME)) during the years 2015 and 2016, Pajović Šćepanović et al. (2019) [125] have given a "warm" characterization to the area, owing to GDDs exceeding 2000 units (GDDs $\geq$ 2200), as shown for the southern part of the country in Figure 3.

3.13. Croatia

According to the results of Omazić et al. in their 2020 work [86] on the spatial distribution of the GDDs over Croatia (HR) for the historical period of 1971–2000, similarities are evident given that values of the index $\geq$2000 units (1944–2222) correspond to the country's southernmost Adriatic shoreline, which is almost the case for P2 (Figure 2). Leder et al. (2021) [126], in their research on the geographical discrimination of Croatian wines, mention low values in the calculated GDDs in both western and eastern continental Croatian regions, which ranged from 1323.9 to 1652.5 GDDs for the investigated climatologic period (1988–2017). On the contrary, for the same period, coastal Croatia (HR) reached 2483.5 GDD units, which is in agreement with coastal areas with GDDs > 2000 during P2 and P3 (Figures 2 and 3). Similarly, Karoglan et al. (2018) [127] have documented increases in the GDDs from the reference period of 1961–1990 to the examined 1988–2017 timeframe over major Croatian wine-growing regions. Increases were displayed for both continental and coastal areas, with the latter demonstrating values over the 2000-units threshold (e.g., Dalmacija in SW coastal Croatia (HR), with 2483 units, and Hrvatsko Primorje and Istra in NW coastal Croatia (HR), with 2036 and 2095 units, respectively), as illustrated in Figure 3. Omazić et al., in 2023 [128], concluded that, over the last 30 years, all wine-growing areas in Croatia (HR) have changed at least one wine-growing zone. Considering that this outcome also involves areas where winegrapes have never been cultivated, it becomes apparent that new regions are becoming suitable for the exploitation of some vine varieties.

3.14. Slovenia

Over an extended period between 1950 and 2009, heat accumulation indices (GDDs) started displaying significant increases in 1980, attributed by Vršič et al. (2014) [129] to growing season warming in Styria (northeastern Slovenia (SI). The authors concluded, with the hypothesis that the warming trends will continue to the same extent as what had been estimated in the 1980–2009 period, that major changes shall be anticipated. Wine-growing areas where vineyards are located on steep slopes have been proven to be more functional to customizing the style of wine according to those trends. Potisek et al. (2023) [130]'s calculations of the GDD index for the growing season period in western Slovenia (SI) during the 2015 and 2017 vintages have resulted in values <2000 units, as demonstrated in Figure 3 for P3. Similarly, calculations conducted by Šuklje et al. (2022) [131] for Litmerk (northeastern Slovenia) resulted in GDDs of 1674, 1876, and 1553 for the 2017, 2018, and 2019 vintages, respectively, thus exhibiting values below the threshold of 2000 thermal units, as in Figure 3.

3.15. Albania

Kopali et al. (2021) [132] have assessed the agroclimatic suitability zones of Tirana's vineyards (central Albania) based on the Winkler index calculated from historical climate data (1966–1990). The researchers demonstrated a variation in the index from <1200 °C to >2200 °C, indicative of an extensive suitability range for grapevines. It was concluded that a substantial part (approximately 60% to 70%) of the examined area was characterized as being suitable for viticulture, as is also depicted for central Albania in Figures 2 and 3.

3.16. Greece

Most viticultural areas in Greece (GR) are currently experiencing warm-to-very warm agroclimatic conditions. In their attempt to identify climate characteristics in wine regions in Greece (GR), Koufos et al. (2014) [133] demonstrated increasing temperature trends, which have led to significantly higher GDDs over the 1950–2000 time period. Owing to the country's complex physical geography, the results have shown a 200 GDD increase, ranging from 103 GDDs in Anchialos (northern Greece (GR), Central Macedonia) to 362 GDDs in Samos (southeastern Greece (GR), Aegean Islands). Anderson et al. (2014) [134] have utilized average monthly maximum and minimum temperature grids for the calculation of the GDDs (represented with the Winkler index) in Greece (GR) over the same period (1950 to 2000). The authors denoted increasing trends in the GDDs owing to warmer growing seasons, more evident in the island regions than in the mainland areas. From 1981 to 2010, significant shifts in regional classifications resulted in warmer and drier climate types, and increasing temperature trends were identified [135]. Xyrafis et al. (2022) [136] have estimated the trends in the GDDs (over March–August) between the years 1974 and 2019 for the island of Santorini, located in the South Aegean administrative region of Greece (GR). They commented on a significant annual index increase of 10.4 per year. For the period from March to August, the average GDD index was 1741 units from 1974 to 1982, 1951 units from 1982 to 2006, and 2162 units from 2006 to 2019. Lazoglou al. (2018) [137] have investigated the impacts of CC on Greek viticulture, using nine bioclimatic indices (including the GDD index) for the years 1981–2100, with a control period from 1981 to

2000). The values of the GDD index for the latter period fell into the range of 1940–2220 or exceeded 2220 units, particularly in the eastern and southern parts of the country, relative to the areas illustrated in Figures 2 and 3 for P2 and P3, respectively. The hottest GDD category (>2220) applied to the majority of the islands but was also found to extend over the mainland. On the contrary, the Greek mountainous regions (Pindos Mountain ridge) were characterized by values lower than 1390 units. Along with most of the indices investigated, the GDD index demonstrated positive spatiotemporal trends in terms of its projections for the 2041–2060 period, highlighting the extension of values >2220 to coastal areas and the entire Greek region by the end of the studied period. Petropoulos et al. (2018) [138] have conducted a survey in representative wine regions of Nemea (northeastern Peloponnese, Greece (GR)). Similar values of GDDs resulted between the years, all exceeding 2000 units (2475, 2350, and 2282, respectively, for 2012, 2013, and 2014), as also shown in our work for the same region in P3 (Figure 4). The investigations of Anastasiou et al. (2023) [139] on growing season thermal conditions over the winegrape area of Corinth (southern Greece (GR)) for three successive years (2015, 2016, and 2017) have depicted GDD values below 2000 units (1974.2, 1966.5, and 1826.9), which is in line with our results in Figure 3 for the same region.

3.17. Cyprus

With the aim to investigate the performance of indigenous Cypriot winegrapes in Krasochoria (Lemesos, southern Cyprus (CY)), Copper et al. (2020) [140] have discussed the results for the long-term average GDD values over the 1955–2017 period and the studied years of 2017, 2018, and 2019. All three seasons along, with the long-term average GDD value, exhibited values >2400, nearing 2700 units. Similar to the aforementioned investigation, in our work, almost the entire country exhibits GDDs $\geq$ 2000 for P1, P2, and P3 (Figures 2–4).

4. Conclusions

The spatial and temporal distribution of additional atmospheric indicators and parameters (e.g., frost, precipitation, evapotranspiration, etc.) should also be examined to draw sound conclusions about atmospheric suitability. Despite the gaps in its spatial perimeter, the E-OBS dataset arises as an asset for the agroclimatic assessment of the Mediterranean area. The temporal resolution (daily temperature data) and the accuracy of the estimated dataset parameters are fundamental. Spatial resolution is a limiting factor for investigations of this nature, since a 10 $\times$ 10 km resolution may hide several significant, narrow agricultural regions. However, the E-OBS dataset can be fine-scaled through the use of downscaling methods. Hence, the E-OBS dataset could be of service to extended bioclimatic modeling for essential cultivations, such as vines.

Based on the findings of the present investigation, it is evident that the rising temperatures over the northern Mediterranean Basin have led to an expansion of the areas suitable for viticulture according to the index selected for this study. This fact provides a perspective for viticultural development over higher-altitude (mountainous) and -longitude (northern) areas, thus allowing the fulfillment of vines' water and thermal demands. These results highlight direct climate impacts on viticultural zoning in the NMB over the last 50 years. Among the investigated countries, Croatia, Bulgaria, and Romania have demonstrated more significant expansionary tendencies, which probably indicate an emerging viticultural sector.

These outcomes are of paramount importance, since they may contribute knowledge on the prioritization, optimization, and assessment of adaptation strategies involved in the preservation of current and future winegrape production. Winemakers are facing challenges in mitigating the effects of CC due to the continuously warming conditions. Examining the spatial evolution of the GDD index in an significant area for viticulture is important, especially in a region which is one of the hot spots of climate change. The results of this review can provide important information for the modification of cultivation practices and winegrowers' strategies. In addition, spatial and statistical data by country can provide useful information for the formulation of agricultural policies. They can also be key input data for the investigation of climate suitability and zoning for a specific crop.

This study has attempted to improve the linkage between the evolution of the thermal climate and its effects on the temporal alteration of viticultural areas' surface distribution. The provision of quantitative knowledge may contribute to specialized and organized preparedness to deal with potentially imminent developments in the sustainability of viticulture under the more adverse climate regimes possibly occurring in the future. However, the GDD indicator alone cannot characterize a climatic area as being suitable or unsuitable for growing grapes but must be combined with other atmospheric, soil, biological, and geophysical parameters.

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