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Agroclimatic Indicators for Grapevines in the Zielona Góra Wine Region (Poland) in the Era of Advancing Global Warming

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Abstract: Grapevine is a highly climate-sensitive plant. In the last few decades, an increase in the number and area of vineyards has been observed in the country, with the Zielona Góra region pioneering this revival. A comprehensive analysis of climatic and agroclimatic indicators for grapevines was conducted to assess the possibilities and limitations in this region. Based on data obtained from the Institute of Meteorology and Water Management—National Research Institute (IMGW-PIB) for stations in Zielona Góra, nine key indicators were identified. The analysis of agroclimatic conditions for the Zielona Góra winegrowing region from 1951 to 2022 revealed significant changes in air temperature, length of the vegetative period, and number of frosts. The average annual air temperature increased, while the number of days with temperatures below 8 °C decreased. The extension of the vegetative period (starting earlier and ending later) favours grapevine cultivation. The increase in temperature during the vegetative period and the lengthening of the frost-free period have a beneficial effect on grape production in the Zielona Góra region.

Keywords: grapevine; agroclimatic indicators; climate change; wine; Zielona Góra

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1. Introduction

Grapevine cultivation worldwide occurs at various latitudes; however, the majority of vineyards are established between the 30th and 50th parallels north and the 30th and 40th parallels south [1], primarily due to favourable climatic conditions. In the Northern Hemisphere, the main concentration of viticulture is noted between the 30th and 40th parallels, such as in countries bordering the Mediterranean Sea or in California in the USA. Poland is a country situated on the northern edge of intensive grape cultivation (that is over the 50th parallel in the north) [2]; however, this does not disqualify it from wine production development. Grape cultivation has been documented since medieval times, initially in the southern parts of the country [3] and later in the west [4]. Initially, grapes were grown solely for the needs of the clergy, near monasteries or churches, but over time, townspeople also began establishing their vineyards. In the 16th century, wine-producing regions in Poland were popular; however, in the 17th and 18th centuries, the wine industry experienced a crisis due to climatic and political conditions. Periods of increased or decreased grape cultivation were associated with thermal and precipitation conditions, as well as political situations and historical events. Based on vineyard records dating back to the medieval period, five wine-producing regions were identified: Podkarpackie, Małopolska, Małopolski Przełom Wisły, Sandomierz, and Zielona Góra [5].

The Zielona Góra region proved to be particularly attractive, becoming the northeasternmost winegrowing area in Europe in which grape cultivation took place on an industrial scale [4]. Winemaking traditions probably date back to AD 1150, when Flemish settlers brought the first grapevines. However, this date lacks confirmation in historical sources. The first documented mention of grape cultivation in the Zielona Góra region

dates back to AD 1314 [6]. Thus, it can be concluded that the winemaking tradition in this region has gone on intermittently since the Middle Ages [7].

Currently, interest in wine and vineyard management is increasing in Poland. Each year sees a growing number of farms cultivating grapevines and an increase in cultivation area [8–10] primarily due to climate warming. However, it is essential to remember that, alongside climatic conditions, habitat conditions play an incredibly significant role in vineyard management [5], and the quality and quantity of wine produced are influenced by the "terroir" [11]. Moreover, non-natural factors such as increased knowledge among growers, greater accessibility to vineyard management knowledge, the introduction of pest- and disease-resistant varieties, the growing trend in wine consumption, and relevant legal regulations significantly contribute to the noticeable upward trend in the number of vineyards [12].

Nevertheless, it should be emphasised that natural conditions primarily influence the possibility of reviving winemaking traditions in Poland. The impact of climate change concerning grapevines (particularly its effect on wine quality) [13,14], the shifting boundaries of grape cultivation [13], potential new cultivation areas [15,16], analyses of climate indicators [17], and changes in phenology and frosts [18] are frequently discussed in the literature. Few studies are focusing on Poland in this regard, addressing enotourism possibilities in wine-producing regions [19–22]; grape cultivation prospects in Poland [23,24], including the identification of existing winemaking problems [25]; and the influence of weather conditions [26,27] climatic [28–31], and agroclimatic [32] conditions on grape cultivation and their specific varieties and on wine quality [33].

One of the aforementioned studies [28] concentrates on analysing precipitation in the western part of Poland concerning grapevine requirements. However, there has not yet been a comprehensive assessment of the thermal conditions in the Zielona Góra winegrowing region. Such an analysis is crucial for proper cultivation, particularly considering the exceptional sensitivity of grapevines to climatic conditions [34].

This research aimed to determine the agroclimatic conditions from 1951 to 2022 for grapevines in the Zielona Góra region and the directions of their changes. Such a study was justified by the lack of previous investigations of the agroclimate of the Zielona Góra winegrowing area, which is particularly crucial in the era of rapid climate warming. This research utilised selected agroclimatic indicators to assess conditions from the grapevine perspective.

2. Research Area

The Zielona Góra winegrowing region is located in western Poland, in the southern part of the Lubusz Voivodeship. The boundaries of the area stretch from 51°44′ N in Bytom Odrzański to 52°16′ N at the height of Świebodzin and from 15°05′ E in Krosno Odrzańskie to 15°55′ E in the village of Kopanica [35]. The city of Zielona Góra and a meteorological research station are located in the centre of the region. This area is surrounded by natural boundaries of rivers: the Oder and its tributaries to the north and east, the Śląska Ochla and Czarna Struga to the south, and the Bóbr to the west (Figure 1). The central part of the winegrowing area belongs to the Zielonogórski Escarpment (terminal moraine from the Vistula glaciation), the northern part belongs to the Czerwieńska Upland, and the southern part is located in the Nowosolskie Depression [36]. The surface of the delineated region is varied and hilly, with numerous kames occurring between Krosno Odrzańskie and Zielona Góra in the NE–SW direction, which creates extremely favourable conditions for grape cultivation due to their shape, slope exposure, and substrate material [37]. The research area lies at the junction of two climatic regions: Region 13 Lubusz and Region 23 Lower Silesian West, although the significantly larger part belongs to the Lubusz region [38]. In terms of the average annual air temperature and the meteorological spring air temperature, this area is one of the warmest in the country. According to Matuszko and Bartoszek [39], an average of 1700–1800 h of sunshine was recorded in the research area in the years 1991–2020. The average annual air temperature was ~9 °C, with an average for January

of ~−0.5 °C and for July ~19 °C [40]. On the other hand, the average annual precipitation ranged from 550 to 600 mm [41].

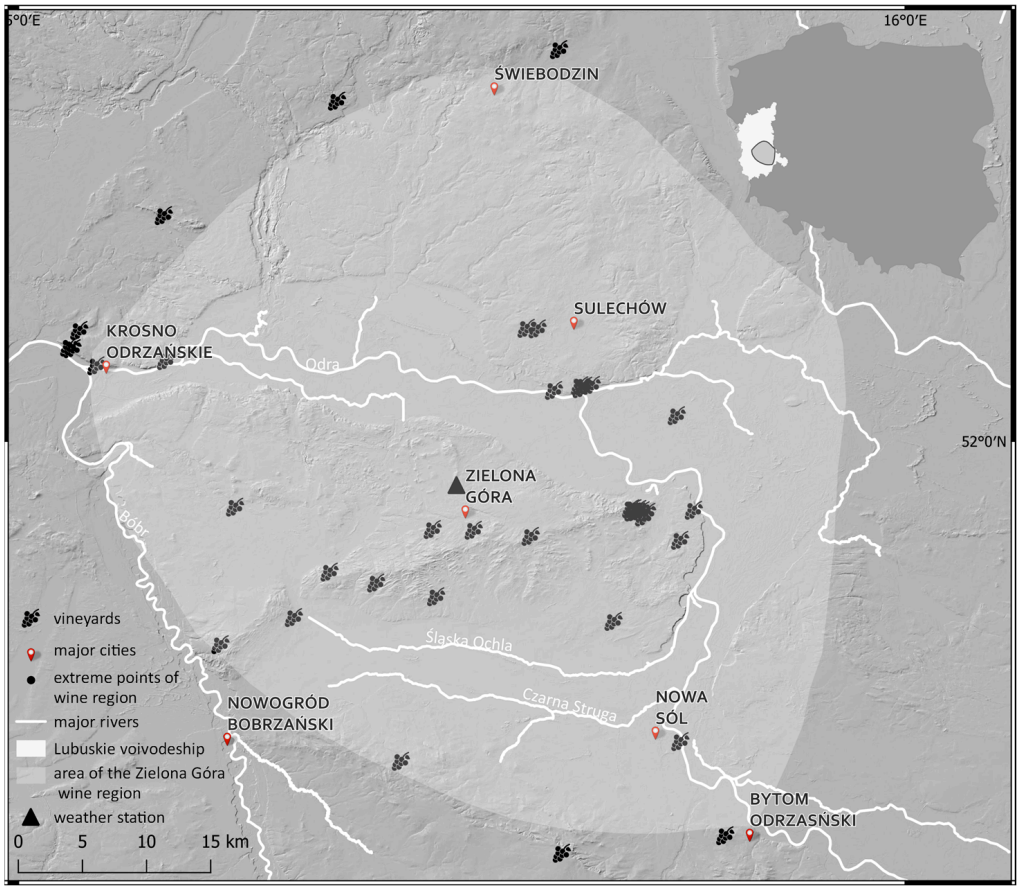


Figure 1. Location of the Zielona Góra wine region showing currently existing vineyards.

3. Materials and Methods

This research was conducted based on data obtained from the resources of the Institute of Meteorology and Water Management—National Research Institute (IMGW-PIB) for the Zielona Góra station from the multi-year period 1951–2022. The station was chosen due to its location in the centre of the Zielona Góra winegrowing region and the length of the measurement series. The analysis covered over 70 years, so it was divided and analysed in seven decades. Daily average, maximum, and minimum air temperatures, as well as daily and monthly precipitation totals, were used to calculate agroclimatic indicators.

Agroclimatic indicators described in the Polish literature were included in the analysis. Table 1 lists the applied agroclimatic indicators along with their characteristics and significance for grape cultivation, referencing the literature.

Based on the acquired data, the monthly and annual average air temperatures were calculated for each year, and then the average values for each decade and the entire multi-year period were determined. The warmest month was identified based on the calculations. Similar calculations were carried out for the minimum temperature in January. Absolute minimum air temperature values for the year and January were determined based on daily minimum air temperature values, and characteristic days with air temperatures ranging from −15 °C to −35 °C were identified. Additionally, days with air temperatures above 35 °C were determined based on maximum daily air temperatures.

Frost days were defined as days when the minimum temperature is below 0 °C and the maximum temperature is above 0 °C ($t_{min} < 0$ °C and $t_{max} > 0$ °C) [42]. Based on the literature, a classification of frost intensity for grapevines was proposed:

1. Mild frost: from 0 to −2 °C.
2. Frost damaging to leaves: from −2 °C to −3 °C.
3. Frost damaging to buds: from −3 °C to −5 °C.
4. Frost damaging to the entire plant: below −5 °C.

SAT was calculated from the sum of average daily temperatures equal to or higher than 10 °C from the period 1 April to 31 October (Dawitaj's method) [43]. It was calculated using the following formula:

$$SAT = \sum_{01.04}^{31.10} Td$$

where $Td \geq 10$ °C

GDD (Winkler method) was calculated using the following formula:

$$GDD = \sum_{01.04}^{31.10} Td - Tbase$$

where *Tbase* is 10 °C.

To determine the beginning and end dates of the growing season, the mathematical method proposed by Gumiński [44] was employed, with the following assumptions: the average monthly temperature occurs on the 15th day of the month, each month consists of 30 days, and temperature changes from month to month are uniform. Two formulas were utilised in the calculations:

For temperature increase:

$$x = 30 \times ((tp - t1)/(t2 - t1))$$

For temperature decrease:

$$x = 30 \times ((t1 - tp)/(t1 - t2))$$

where the variables are as follows:

tp is the threshold temperature;

t1 is the average temperature in the month preceding the threshold temperature;

t2 is the average temperature in the month following the threshold temperature;

x is the number of days between the day with the threshold temperature and the 15th day of the preceding month.

The result obtained (the number of days) is added to the 15th day of the preceding month with respect to the threshold temperature. The determined date serves as the beginning or end of the growing season. In this article, the threshold temperature was considered as ≥8 °C.

Based on daily precipitation sums, the total precipitation for each month of the growing season and their cumulative values were calculated, divided into decades and for the entire multi-year period.

For the calculated indicators, average values for the entire multi-year period and decades were determined. Additionally, the rate and direction of changes in the aforementioned indicators over the considered multi-year period were determined using linear regression analysis, and statistical significance was assessed based on Student's *t*-test at a significance level of $p < 0.05$.

Table 1. Climatic and agroclimatic indicators for viticulture with their significance.

No.	Climatic/Agroclimatic Indicator	Importance/Methods of Analysis	References
1.	average annual air temperature	Areas favourable for grape cultivation are those where the average annual air temperature is ≥8 °C.	[45]
2.	average monthly air temperature of the warmest month of the year	Areas favourable for grape cultivation are those where the average monthly air temperature of the warmest month is ≥17 °C.	[45]
3	the dates of the first and last frosts and the length of the frost-free period in days	The occurrence of frost poses a threat to the profitability of grape cultivation. Frosts occurring in April and May are particularly dangerous. Temperature drops below −2 °C negatively affect fruiting, while frosts around −4 °C can lead to the loss of the entire yield. Frosts after October 15, around −3 °C, damage leaves and interrupt ripening, which is significant for varieties ripening in October.	[45,46]
4.	absolute values of minimum air temperature	Different grape varieties have different frost tolerance. Depending on the variety, temperatures can range from −15 °C to −35 °C. Temperatures below −25 °C are a particular threat to the vines and break the winter dormancy phase.	[45,47]
5.	sum of active temperatures (SAT) and Growing Degree Days (GDD)	The SAT, which stands for the sum of active temperatures, indicates the accumulated amount of warmth during the growing season. For very early varieties, it ranges from 2000 to 2200 °C, early varieties from 2200 to 2500 °C, early–medium varieties from 2500 to 2700 °C, medium–late varieties from 2700 to 2900 °C, and late varieties above 2900 °C. The value of the SAT may vary depending on the slope inclination, exposure, soil type, or wind protection. Ideally, this indicator should not fall below 2000 °C. The higher the SAT value, the later grapevine varieties can be cultivated in a given area. The GDD index is otherwise known as the Winkler index and describes the heat energy received by the crop maturity over a given time period to progress in development or growth processes. Winkler divided 5 viticulture zones according to the value of the GDD: I—values equal to or below 1371 °C, II—1372–1648 °C, III—1649–1927 °C, IV—1928–2204 °C, V—greater than or equal to 2204 °C.	[34,43,45,47]
6.	the average monthly temperature in January, the minimum temperature in January, and the lowest values of minimum temperatures in January	The January temperature is representative for analysing the threat of severe frost. A monthly average January temperature below −1 °C is an indication for additional protective measures to prevent frost damage. Far better, exceeding the threshold of −1 °C indicates the monthly average minimum January temperature, and analysis of the lowest minimum temperature in January and the year allows one to assess the frost resistance of varieties and possible protective measures.	[48]
7.	average number of hot days	Temperatures above 35 °C lead to the onset of heat acclimation, while temperatures above 40 °C negatively affect photosynthesis. They are particularly dangerous when they occur over periods of several days and are accompanied by a lack of water.	[49,50]
8.	average length of the growing season	This is one of the most important climatic criteria used to assess the feasibility of growing grapevines. Vines begin and end the growing season at 8–10 °C and the season should not be shorter than 160 days. In this study, the growing season is defined as a period with an average daily air temperature of at least 8 °C.	[5,44,45]
9.	precipitation during the growing season	Grapes require significant amounts of water, with its delivery during the growing season being particularly crucial. The greatest amounts of water are needed by the plant during intense growth and berry development, typically from mid-May to mid-August. Drought as well as excessive rainfall can contribute to poor flowering. Excessive rainfall during fruit ripening, in September for example, can cause fruit cracking and rotting.	[5,45]

4. Results

4.1. Characteristics of Climatic Conditions

The average annual air temperature over the multi-year period from 1951 to 2022 in Zielona Góra was 8.8 °C. In individual years, it ranged from 6.6 °C in 1956 to 11 °C in 2019. The highest values were reached in the 21st century and the lowest in the 20th century (Table 2). The lowest average value was recorded in the decades 1961–1970 and 1991–2000 (8.1 °C), while the highest was in the decade 2011–2020 (10 °C). In the 21st century, in most cases, the average annual air temperature exceeded the multi-year average. The research showed a statistically significant increase in the average annual air temperature, which amounted to 0.29 °C per decade (Figure 2). As mentioned earlier, thermal conditions favourable for grapevines are those with an average annual air temperature $\geq$ 8 °C. In the analysed period, the temperature was below this threshold 19 times (which is 26.7% of all years), broken down by decade as follows: 1951–1960—4 times, 1961–1970—5 times, 1971–1980—4 times, 1981–1990—4 times, 1991–2000—1 time, 2001–2010—1 time, 2011–2020—0 times, and in the last two years—0 times.

Table 2. Five highest and lowest values of average air temperature in Zielona Gora from 1951 to 2022.

N°	Highest Value of Air Temp.	Year	Lowest Value of Air Temp.	Year
1	11.0 °C	2019	6.6 °C	1956
2	10.7 °C	2018, 2020	6.8 °C	1996
3	10.6 °C	2022	7.0 °C	1980, 1987
4	10.4 °C	2014, 2015	7.2 °C	1985
5	10.1 °C	2000	7.5 °C	1969

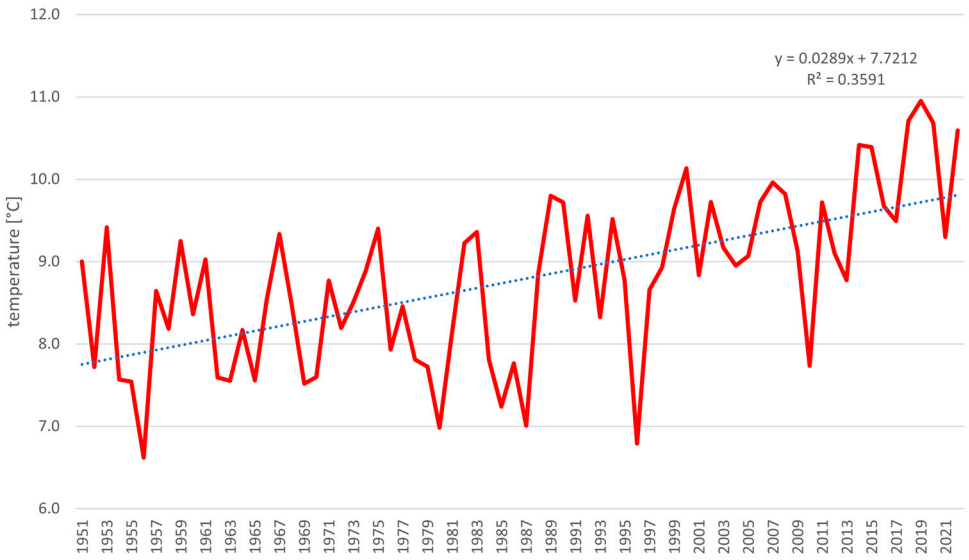


Figure 2. Average annual air temperature in Zielona Góra from 1951 to 2022.

The warmest month during the considered period was July, with an average monthly air temperature of 18.6 °C. In individual years, the average value ranged from 15 °C in 1979 to 24.2 °C in 2006. The research indicated an increase in the average air temperature in this month, with changes of 0.32 °C per decade. The lowest average value for July was recorded in the decade 1971–1980 (17.5 °C), while the highest was in the decade 2001–2010 (19.8 °C). In the analysed years, July was the warmest month of the year in 34 cases (48%). In the remaining years, the highest average monthly air temperature was recorded in August (26 times—37%) or June (10 times—14%). An average monthly temperature below 17 °C for the warmest month was recorded six times (8%): in 1962 (August, 16.4 °C), 1965 (June, 16.6 °C), 1978 (July, 16.3 °C), 1980 (August, 16.4 °C), 1981 (July, 16.7 °C), and 1993 (July, 16.4 °C). The highest temperature for the warmest month was recorded in 2006, i.e.,

24.2 °C. For the entire multi-year period, the average air temperature for the warmest month was 19.2 °C, and by decade it was as follows: 1951–1960—18.6 °C, 1961–1970—18.4 °C, 1971–1980—18.5 °C, 1981–1990—18.4 °C, 1991–2000—19.6 °C, 2001–2010—20.4 °C, 2011–2020—20.6 °C. A significant increase in the temperature of the warmest month has been observed since the 1990s (Figure 3).

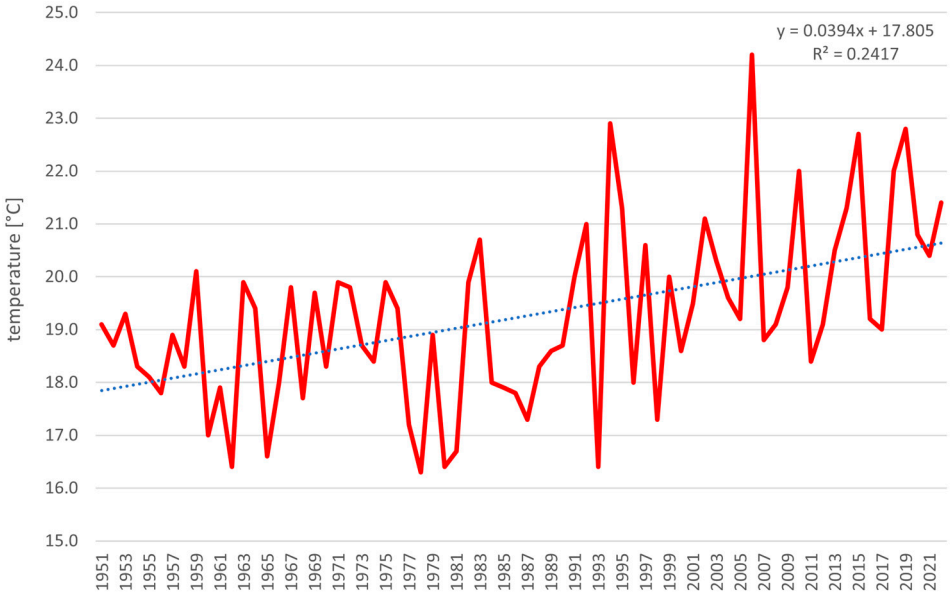


Figure 3. Average air temperature of the warmest month in Zielona Góra from 1951 to 2022.

The coldest month annually was January, with a multi-year average of −1.1 °C, and in individual years, it ranged from −9.1 °C in 1963 to 4.2 °C in 2007. The lowest average value was recorded in the decade 1961–1970 (−2.8 °C), while the highest was in the decade 2011–2020 (0.1 °C). The last decade covered in the analysis was the only one where the average air temperature in January was positive (Figure 4). A more accurate indicator in terms of grapevine development is the average minimum temperature in January. The lowest values of the average minimum temperature in January were as follows: −12.3 °C in 1963, −11.5 °C in 1987, −9.7 °C in 1985, −9.2 °C in 1954. The highest values were as follows: 2 °C in 1975, 1.7 °C in 2007, 1.4 °C in 1983, 0.8 °C in 2020. Similar to the average air temperature in January, the minimum air temperature in January showed an increase, which amounted to 0.4 °C per decade and was statistically significant.

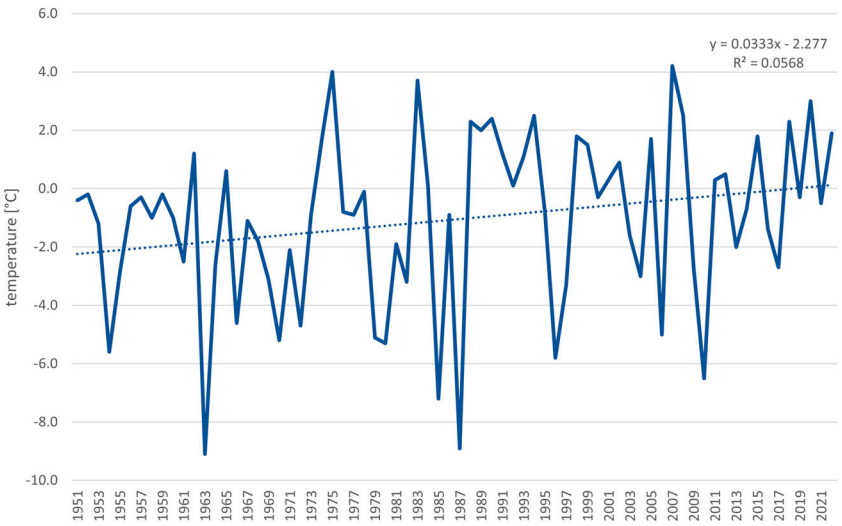


Figure 4. Average January temperature in Zielona Gora from 1951 to 2022.

To assess the resistance of grapevines to frost, it is important to observe the absolute minimum air temperatures. For the coldest month (January), the multi-year average of these values was −12.8 °C. It is worth noting that the absolute minimum air temperature values occurred from November to March. In total, in January, the absolute minimum temperature was recorded 36 times—14 times in February, 6 times in March, 2 times in November, and 14 times in December. The average of the lowest minimum temperatures in a year was lower than those in January and amounted to −15.1 °C. A comparison of the average lowest temperatures in January and the year is presented in Table 3.

Table 3. Comparison of average lowest January and year minimum temperatures by decade.

Average of Lowest Minimum Temperatures	1951–1960	1961–1970	1971–1980	1981–1990	1991–2000	2001–2010	2011–2020
in January	−14.7 °C	−14.9 °C	−12.3 °C	−11.5 °C	−13.3 °C	−14.6 °C	−10.1 °C
during the year	−16.3 °C	−16.6 °C	−15.0 °C	−14.8 °C	−15.3 °C	−15.7 °C	−12.7 °C

The average annual precipitation sum in Zielona Góra during the growing season over the multi-year period was 389.7 mm. In individual years, it ranged from 196.1 mm in 1992 to 517.7 mm in 2017. Particularly dry growing seasons were observed in the years 1982, 1992, and 2018. The research showed a statistically insignificant decrease in the precipitation sum from April to October, which amounted to 5.4 mm per decade (Figure 5). The changes were not statistically significant. The decade with the highest precipitation sum was the decade 1961–1970 (426.4 mm), while the lowest was the decade 1981–1990 (361.5 mm) (Table 4).

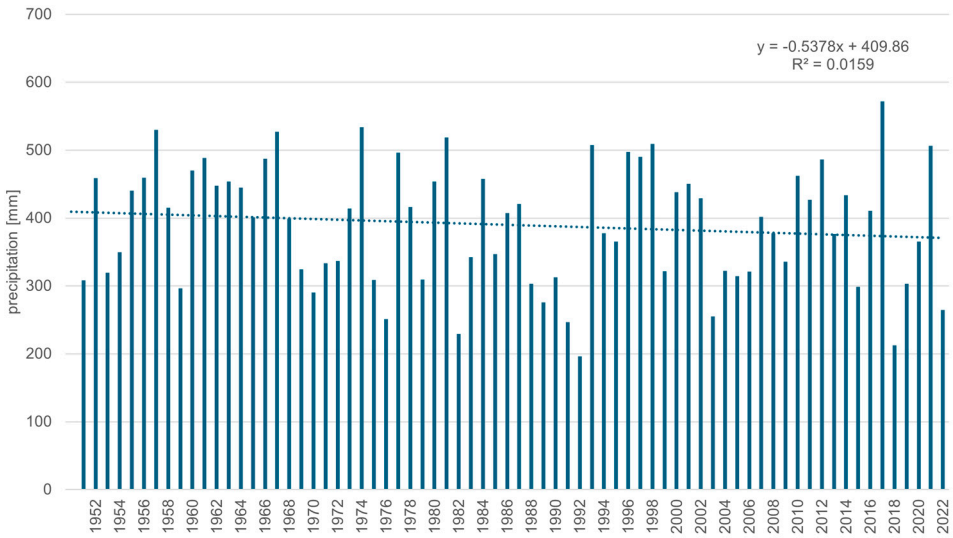


Figure 5. Total precipitation from April to October in Zielona Góra from 1951 to 2022.

Table 4. Average precipitation in the months of the growing season by decade in Zielona Góra.

	April	May	June	July	August	September	October	Sum
1951–1960	45.2	48.6	61.7	94.0	70.3	45.6	39.5	404.8
1961–1970	42.25	77.58	67.15	60.39	81.56	49.75	47.75	426.43
1971–1980	43.27	51.40	56.90	65.66	61.11	54.18	52.84	385.36
1981–1990	41.69	49.67	62.69	75.96	70.23	29.89	31.36	361.49
1991–2000	39.36	52.18	58.12	90.68	73.34	44.97	36.36	395.01
2001–2010	27.24	56.45	46.59	79.54	64.31	53.17	39.67	366.97
2011–2020	25.18	49.44	62.36	100.05	58.10	46.64	46.82	388.59

4.2. Characteristics of Agroclimatic Conditions

4.2.1. Growing Season

The growing season is one of the most important factors influencing plant development. The average start date of the growing season for the considered multi-year period fell on 13 April, and the average end date was 21 October. The earliest start of the growing season occurred on 18 March (in 2014), while the latest was on 5 May (in 1994). On the other hand, the earliest last day of the growing season was recorded as 6 October (in 1952) and the latest was 6 November (in 2000 and 2006). From the above data, it can be inferred that the potential duration of the start of the growing season was 49 days, and the end was 32 days. Analysing the start and end dates of the growing season by decade, it was noticed that the earliest start occurred in the years 2011–2020, i.e., 5 April, while the latest was in 1971–1980, i.e., 20 April. Meanwhile, the earliest end occurred in 1971–1980, on October 16, and the latest in the last decade, i.e., 25 October. There is a noticeable trend of earlier starts (by 1.3 days/10 years) and later ends (0.6 days/10 years) of the vegetative period. Changes in the start of the vegetative period are statistically significant, whereas they are not statistically significant for the end of the growing season.

The average length of the growing season for the entire multi-year period was 191 days. The shortest period was recorded in 1994 (160 days), while the longest was in 2014 (230 days). It is worth noting that for each calendar year, this period did not last less than the minimum number of days of the thermal period of grapevine vegetation (i.e., 160 days). The shortest average growing season was recorded for the decade 1971–80 (179 days), while the longest was for the decade 2011–2022 (203 days). The research showed an increase in the length of the grapevine vegetative period of 1.9 days/10 years (Table 5). The observed changes were statistically significant. In the analysed period, changes at the outset had a greater impact on its prolongation.

Table 5. Average start, end, and length of growing season for grapevines by decade.

Decade	Average Start	Average End	Average Length
1951–1960	16 April	20 October	187 days
1961–1970	12 April	24 October	195 days
1971–1980	20 April	16 October	179 days
1981–1990	13 April	22 October	192 days
1991–2000	14 April	19 October	188 days
2001–2010	6 April	20 October	197 days
2011–2020	5 April	25 October	203 days

4.2.2. Spring and Autumn Frosts and Frost-Free Period

Spring and autumn frosts have a significant impact on vegetation, including grapevine fruiting and harvest. On average, over the multi-year period, the last spring frost occurred on 16 April, while the first autumn frost occurred on 29 October, after the end of the vegetative period. Throughout the analysed period, the earliest last spring frost was recorded on16 March 2010, and the latest on 22 May 1952, while for autumn frosts, the dates were 3 October 1979 and 23 November 2021. Analysing frost dates in spring and autumn by decade, the earliest last spring frost was noted in the years 2001–2010 as 3 April, while the latest was in 1951–1960 on 28 April. Conversely, autumn frosts began earliest in the 1991–2000 decade—on 23 October—and latest in the years 2011–2020—on 5 November (Table 6). The analysis indicates that the last spring frost occurred three days earlier every ten years, while the first autumn frost occurred one day later every ten years (Figure 6).

Table 6. Average onset of spring and autumn frost and length of frost-free period for grapevines by decade.

Decade	Spring Frost	Autumn Frost	Average Length of the Frost-Free Period
1951–1960	28 April	25 October	180 days
1961–1970	14 April	1 November	201 days
1971–1980	25 April	26 October	184 days
1981–1990	21 April	1 November	194 days
1991–2000	11 April	23 October	195 days
2001–2010	3 April	27 October	207 days
2011–2020	11 April	5 November	208 days

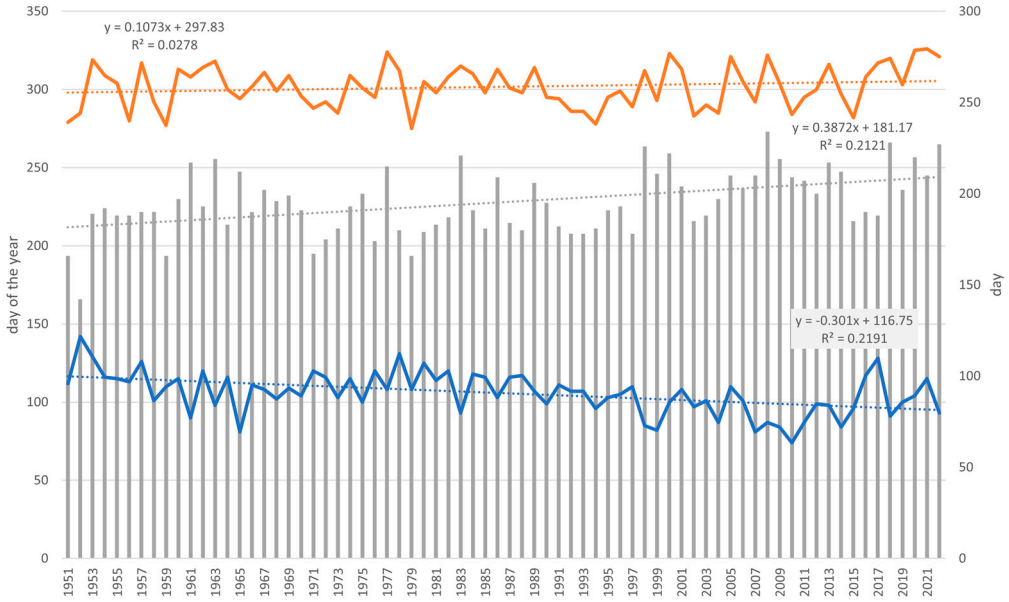


Figure 6. Date of first spring frost (blue line) and first autumn frost (orange line) and length of frost-free period (grey bars) for Zielona Góra station in 1951–2022.

The frost-free period for the entire multi-year period averaged 195 days. In the considered multi-year period, its length ranged from 142 days in 1952 to 234 days in 2008. In individual decades, the shortest period was recorded in 1971–1980 (184 days), while the longest was in 2011–2020 (208 days). There was an increase in the length of the frost-free period of 3.8 days/10 years (Figure 6). The changes were statistically significant.

The number of frosts during the grapevine growing season (from April to October) each year was characterised by considerable variability. The most frosts in the analysed period were recorded in April—a total of 288. The highest number of frosty days in this month was recorded in 1958 and 1997 (11 days each). Frosts in May were infrequent, with a total of 11 occurrences from 1951 to 2022, whereas in October there were 114 occurrences. Although May frosts occur sporadically, it should be noted that they are the most dangerous for plants. They occurred in the following years: 1952, 1957, 1962, 1978, 1980, 1982, 2017 (Figure 7). The trend for the number of spring frosts (April and May) is decreasing, but for autumn frosts (October) it is increasing, albeit at a slight level of 0.08 days/10 years. Among April frosts, the majority (almost 200) were mild, while those damaging leaves and buds occurred almost equally frequently. For each type of spring frost, there was a decrease in frequency (Figure 8). The situation is different in autumn. Mild frosts also dominate, occurring almost 90 times. However, their number is increasing the fastest (0.05 days/10 years), while the number of frosts damaging leaves and buds is increasing much more slowly. Frosts with a minimum air temperature below −5 °C were not recorded in October (Figure 9).

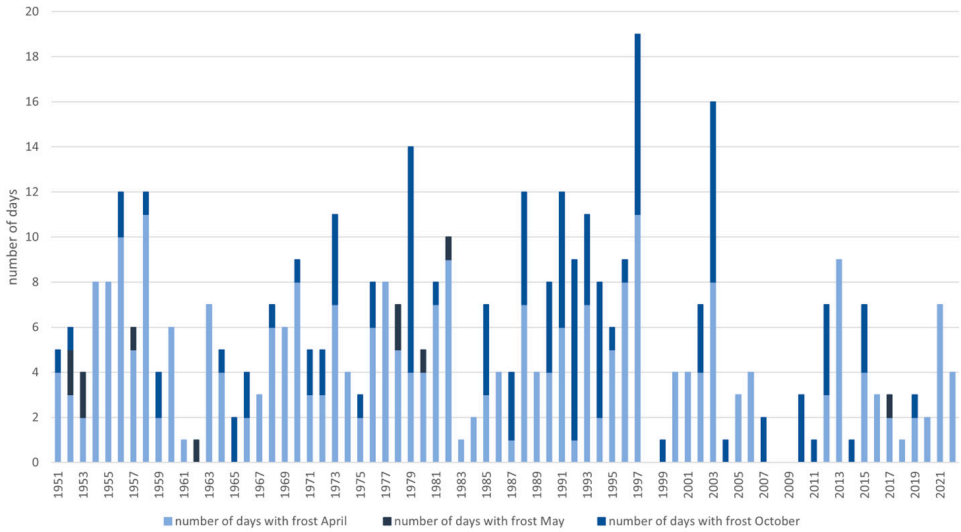


Figure 7. Number of days with frost by month in Zielona Góra from 1951 to 2022.

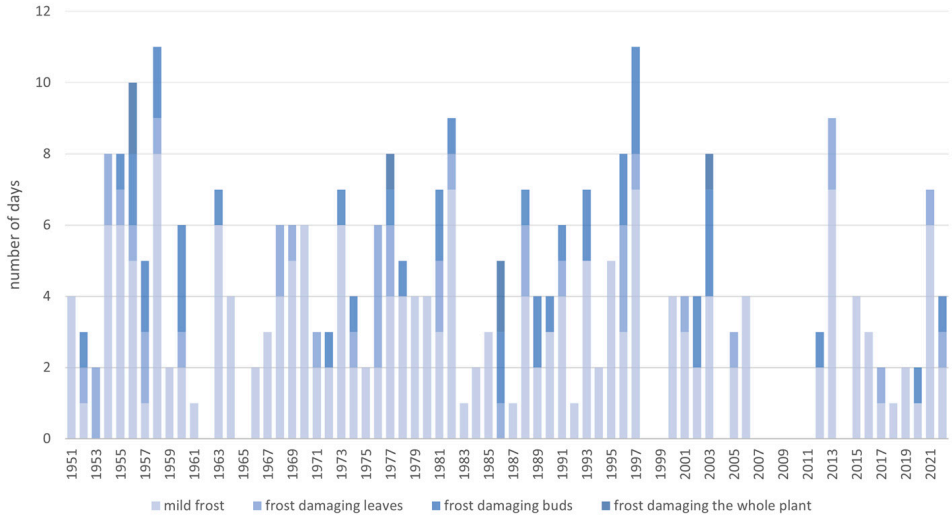


Figure 8. Intensity of frost in April in Zielona Góra from 1951 to 2022.

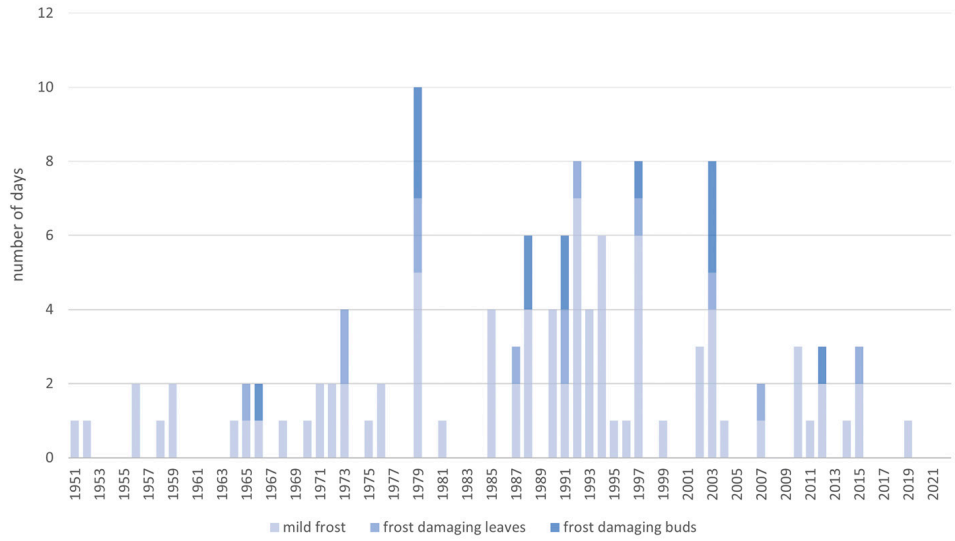


Figure 9. Intensity of frost in October in Zielona Góra from 1951 to 2022.

4.2.3. Sum of Active Temperatures and Growing Degree Days

An important indicator is the sum of active temperatures (SAT), which allows for the analysis of the accumulated amount of heat during the grapevine growing season. It also enables the matching of grapevine varieties to the prevailing conditions. The SAT indicator was calculated using Dawitaj's method [43,48] and ranged from 2404 °C in 1980 to 3630 °C in 2018, with a multi-year average of 2940 °C. The decade with the lowest values of this indicator was 1971–1980 (2679 °C), while the highest decade was 2011–2020 (3256 °C) (Figure 10). The GDD indicator was calculated using the Winkler method [34], with a multi-year average of 968 °C, ranging from 640 °C in 1962 to 1150 °C in 2018. Both the SAT and GDD indicators show an increase of 69 °C/10 years and 50 °C/10 years, respectively. These changes are statistically significant (Figure 10).

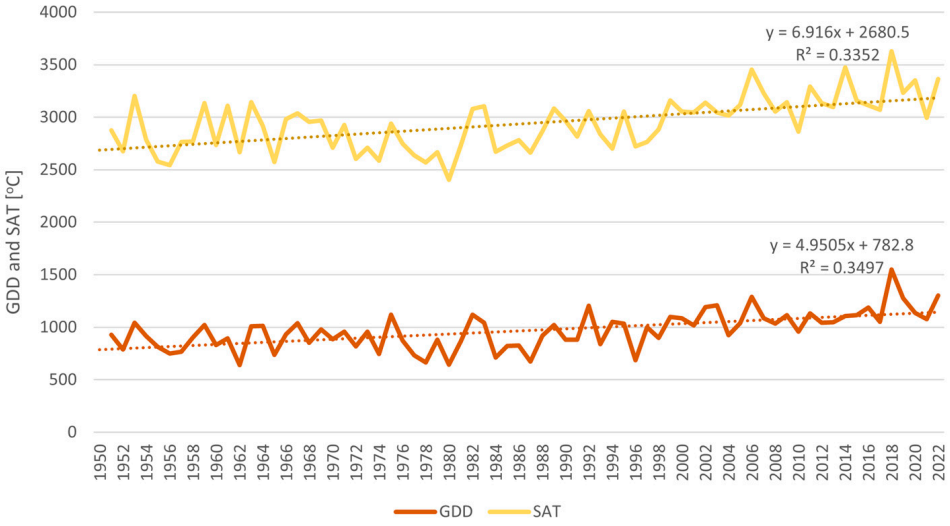


Figure 10. Comparison of SAT and GDD values in Zielona Góra between 1951 and 2022.

4.2.4. Characteristic Days

For the development of grapevines, winter temperatures are also extremely important. Each grapevine variety exhibits different frost resistance, with the accepted temperature range being from −15 to −35 °C (see Table 1). In the analysed multi-year period, such characteristic days most frequently occurred in January (75 times), followed by February (56 times), December (22 times), and 1 time in March. The highest number of such occurrences in a single month (February) was recorded in February 1954, with a total of 13 times. The research showed a statistically significant decrease in these days in the analysed multi-year period at a rate of 0.4 days/10 years. Their highest sum occurred in the years 1951–1960 (38 times), while the lowest was in 2011–2020 (12 times) (Table 7).

Table 7. Number of days with absolute minimum air temperature between −15 °C and −35 °C.

Decade	January	February	March	December	Sum
1951–1960	10	27	0	1	38
1961–1970	18	6	1	9	34
1971–1980	10	0	0	3	13
1981–1990	14	7	0	1	22
1991–2000	7	6	0	4	17
2001–2010	14	0	0	4	18
2011–2020	2	10	0	0	12

Equally dangerous for the process of photosynthesis are extremely high air temperatures, i.e., above 35 °C (see Table 1). In the studied period, the average daily air temperature never exceeded this threshold, while the maximum daily air temperature occurred 18 times throughout the multi-year period, ranging from 35.1 °C on 19 June 2022 to 36.9 °C on 26 June 2019. It was first recorded on 11 July 1984, at 35.3 °C. Subsequent occurrences were noted in 1992 (two times), 1994 (four times), 1998 (one time), 2000 (one time), 2007 (one time), 2015 (three times), 2018 (one time), 2019 (two times), and 2022 (two times). It is worth noting that these are sporadic occurrences.

5. Discussion

The ongoing climate changes significantly influence the distribution of grapevines worldwide [13]. The increasing average air temperature necessitates the adaptation of grapevines to climate change in current winegrowing regions or the relocation of cultivation zones to areas not traditionally associated with vineyards, such as further north [51,52]. This study focuses on the characterising climatic and agroclimatic conditions regarding grapevines in one of the revitalising wine regions in western Poland (the Zielona Góra region). The conducted research confirms that the Zielona Góra region is becoming increasingly suitable climatically for grapevine cultivation. The studies have shown a statistically significant increase in the average annual air temperature at a rate of 0.29 °C/10 years. The obtained results are consistent with earlier studies conducted in the country [53–57]. Furthermore, the documented changes align with those occurring in other regions of Europe [58] and worldwide [59]. The prevailing thermal conditions are suitable for the cultivation of selected grapevine species, such as Riesling, Rondo, Regent, Aurora, Pinot Noir, and Solaris. Research by Koźmiński et al. [30] indicates that 60% of the country's area is conducive to intensive grapevine cultivation.

The average annual air temperature, as well as the average temperature of the warmest month, exceeds the threshold of 8 °C and 17 °C, respectively, and since the 1990s, sporadic years with lower values have occurred. Urban [60] presented very similar results of a thermal conditions analysis in Zielona Góra at the turn of the 21st century in a climatological study covering the years 1961–2016. Similar results were obtained in the areas of the Wieliczka Foothills in the vineyards of Gaik-Brzezowa and Łazy for the years 1988–2007 [32]. The main difference between vineyards in western and southern Poland lies in the air temperature values in January. The average monthly value for January (0.1 °C), the average minimum monthly temperature for January (−2.3 °C), and the average of the lowest minimum temperatures in January (−14.5 °C) during the period 1988–2007 were about 1–1.5 °C lower in southern Poland, particularly at the Gaik-Brzezowa station. Comparing the results with the Łazy station, the difference in these values is even greater [32]).

The observed warming has also led to an earlier start and a later end of the vegetative period. Consequently, the period has extended, but the change in the start date had the greatest impact. Comparing the obtained results with those from other regions in Poland, it can be concluded that the Zielona Góra region experienced an earlier start and earlier end of the period. The difference between the analysed region and other regions in southern Poland [32] was about (or over) two weeks for the start of the period and less than a week for the end. The prolongation of the vegetative period, its earlier start, and later end for Poland were confirmed by Tomczyk and Szyga-Pluta [61] and Żmudzka [62] in their research. Tomczyk and Szyga-Pluta [61] note that the end of the vegetative period occurs earlier in the Wieliczka Foothills than in the Lubuskie region. Żmudzka [62] indicates that the extension of the growing season and intensive vegetation create opportunities for introducing plants with higher thermal requirements, including grapevines, to Poland. It is forecasted that the vegetative season will significantly lengthen, with the longest vegetative period expected in southwestern Poland, reaching over 290 days under the RCP8.5 scenario (a scenario created for the business as usual formula that says that by the end of the century CO_2 concentrations are assumed to reach about 940 ppm and a radiative forcing of 8.5 [W/m^2] and the Earth's average temperature will rise by 4.5 °C compared to

the pre-industrial era) by the end of the 21st century [63]. In this work, the growing season temperature threshold is 5 °C.

The observed warming has also influenced the length of the frost-free period in the analysed area. Similarly to the vegetative period, differences in the length of the frost-free period between the Zielona Góra region and regions in southern Poland were noted. This period was four days longer in western Poland than in Gaik-Brzezowa, while in Łazy it was as much as 22 days longer. This discrepancy in the duration of the frost-free period is likely due to the location of Gaik-Brzezowa above the Dobczyce Reservoir, which has a moderating effect on the climate and increases the minimum air temperature [32].

The ongoing warming and the lengthening vegetative period do not eliminate the occurrence of spring and autumn frosts [64]. Spring frosts are particularly perilous not only for grapevines cultivated in the west but also in other wine regions in Poland.

The year September 2008 was especially perilous for cultivation in central Poland, as on January 6, a minimum temperature of around −23 °C was recorded. Different varieties exhibited varying frost resistance, with 'Riesling' varieties coping best with low temperatures, while Polish varieties 'Rondo' and 'Regent' were highly susceptible to occasional freezing winters occurring every few years [26]. It is worth noting that in that year, the air temperature in Zielona Góra was higher than in central Poland, which did not result in such numerous vineyard frosts. However, there are years when the air temperature drops below −20 °C, posing a risk of plant damage. As historical records indicate, frosts damaged vineyards in the Zielona Góra wine region in 1997, when temperatures dropped to −10 °C from April 11 to 13, accompanied by snowfall, and frosts with temperatures between −7 and −5 °C also occurred between May and June [4]. In addition to frosts, extremely low winter air temperatures are also extremely dangerous. In 1956, due to February frosts, young seedlings were damaged, sub-surface roots froze, and even older bushes perished. The severe frosts that year resulted in a lack of a grape harvest. Moreover, frosts affected wine quality and yields in 1963 and 1971 [4].

The increasing air temperature also contributes to raising the SAT values. Since the beginning of the 21st century, the sum of active temperatures has exceeded 3000 °C, allowing for the cultivation of even late grapevine varieties. Similar results were obtained by Kryza et al. [31], who examined SAT values for the transboundary area of Germany, Poland, and the Czech Republic. In their studies, the Zielona Góra wine region performed very favourably. For the years 1970–2010, the SAT in the area examined by the authors ranged between 2500 and 3000 °C, depending on the location, with a rising and statistically significant trend of change. Additionally, Kryza et al. [31] used the Growing Degree Days (GDD) indicator, which in the discussed area ranged from 1000 to 1200 °C, indicating suitable and good climatic suitability for late grapevine ripening. The GDD index is estimated as the sum of daily average temperature values from 01.04 to 31.10 (greater than or equal to 10 °C) minus a constant value of 10 °C. Favourable conditions for grapevine cultivation are present not only in the Zielona Góra wine region but also in eastern Germany [31]. In southwestern Poland, in Wrocław, SAT values have consistently exceeded 3000 °C since 2013, confirming the suitability of southwestern Poland for the cultivation of late grapevine varieties [30].

Although grapevines are considered to be drought-resistant plants [65], they require monitoring in the face of decreasing precipitation during the growing season to achieve an adequate quantity and quality of yields. Precipitation conducive to grapevine cultivation should range from 500 to 800 mm, and in most places in the country, this sum is fulfilled [5]. However, in addition to the annual precipitation sum, the appropriate distribution of precipitation during the growing season is crucial. Jagosz et al. [28] analysed the water requirements for grapevines in the West Pomeranian, Lubusz, and Lower Silesian Voivodeships. The research found that Lubusz Voivodeship has the greatest variability in water needs for grapevines. In the era of climate change, the water demand for grapevines in the Lubusz Voivodeship is increasing by 9.1 mm/10 years. There is a need for additional irrigation of vineyards in very dry years during the June–August period [28].

Research on the adaptation of grapevines to changing climates at similar and higher latitudes to Poland was conducted by Dunn et al. [15] in Scotland. Interestingly, thermal analyses conducted for the whole year revealed numerous areas in Scotland suitable for grapevine cultivation. However, limiting the analysis to thermal conditions in summer alone revealed a small area suitable for growing this plant. Furthermore, adding lithological, topographic, or rainfall conditions to the analysis showed that despite favourable thermal conditions, Scotland is not be suitable for grapevine cultivation on an industrial scale. The results of the aforementioned studies are a basis for further analysis of the habitat conditions in the Zielona Góra wine region. It is important to consider the entirety of 'terroir' in the context of grapevine cultivation, not just selected parameters.

Future climate forecasts suggest significant changes that may profoundly impact grapevine cultivation and existing wine regions. The increasing average minimum and maximum air temperatures, the number of hot days, the decrease in the number of frost days in Poland [56], and the lengthening of the vegetative period [63] are revealing new areas suitable for grapevine cultivation, especially in southern and southwestern Poland, and are positively affecting yields and wine quality in current vineyards. In the future, wine regions in Southern Europe and the Mediterranean Basin will likely be vulnerable to reduced productivity, mainly due to droughts and water scarcity [16,66,67]. Over the next 50 years, with the current increase in air temperature, the northern limit of grapevine cultivation in Europe may shift to around the 60th parallel of latitude [68]. Therefore, it will be essential to relocate current grapevine cultivation from known wine regions to areas with cooler climates.

6. Conclusions

The analysis of agroclimatic conditions for grapevines in Zielona Góra from 1951 to 2022 showed the following:

- There were statistically significant increases in the average annual air temperature of 0.29 °C/10 years, the temperature of the warmest month of 0.32 °C/10 years, and the minimum temperature of January of 0.4 °C/10 years.
- Average annual precipitation during the growing season has shown a slight, statistically insignificant downward trend in recent decades, at 5.4 mm per decade.
- The frost-free period is extending by 3.8 days/10 years, with the last spring frost occurring earlier by 3 days/10 years and the first autumn frost occurring later by 1 day/10 years.
- The SAT value in the 21st century exceeded 3000 °C, allowing for the cultivation of late grapevine varieties.
- Frosts present a major threat to grapevines, especially spring frosts, but in recent years they have been recorded less frequently, and in the last five years not a single case of May frost has been recorded.
- Current and future thermal conditions make the Zielona Góra region extremely attractive for growing grapes.

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References

1. Schultz, H.R.; Jones, G.V. Climate Induced Historic and Future Changes in Viticulture. *J. Wine Res.* **2010**, *21*, 137–145. [CrossRef]
2. Kapłan, M.; Suszyna, J. Uprawa winorośli w Polsce. *Wieś I Doradztwo. Pismo Małopolskiego Stowarzyszenia Doradz. Rol.* **2015**, *1–2*, 37–41.
3. Włodarczyk, W. Janowiec i winnice Środkowej Wisły. *Not. Janowiecki* **2018**, *15*, 31–53.
4. Kuleba, M. *Enographia Thalloris*; Wydawnictwo Fundacja Gloria Monte Verde: Zielona Góra, Poland, 2013.
5. Myśliwiec, R. *Uprawa Winorośli*; Państwowe Wydawnictwo Rolnicze i Leśne: Kraków, Poland, 2009.
6. Schmidt, H. *Geschichte der Stadt Grünberg, Schlesien*; Levysohn: Grünberg, Germany, 1922.
7. Kopczyńska, E. Stare i nowe smaki lokalnego wina: O lubuskiej winorośli, winnicach i winiarzach. In *Terytoria Smaku. Studia z Antropologii i Socjologii Jedzenia*; Jarecka, U., Wieczorkiewicz, A., Eds.; IFiS PAN: Warszawa, Poland, 2014; pp. 133–152.
8. Brodnicka, E. Rozwój polskiego winiarstwa w latach 2000–2017. *Zesz. Nauk. Szkoły Głównej Gospod. Wiej. Ekon. I Organ. Gospod. Żywnościowej* **2019**, *126*, 5–16. [CrossRef]
9. Maciejczak, M. Korzyści zewnętrzne prowadzenia zrównoważonych winnic w Polsce w warunkach zmian klimatu. *Rocz. Nauk. Ekon. Rol. I Rozowju Obsz. Wiej.* **2019**, *106*, 97–109. [CrossRef]
10. Olewnicki, D. Uprawa winorośli w Polsce w świetle danych statystycznych. *Rocz. Nauk. Stowarzyszenia Ekon. Rol. I Agrobiznesu* **2018**, *20*, 139–145. [CrossRef]
11. Gladstones, J. *Viticulture and Environment*; Winetitles: Underdale, Australia, 1992.
12. Wilk, K. Polski rynek win w świetle zmian w krajowych i wspólnotowych uregulowaniach prawnych. *Stud. I Pr. Wydziału Nauk. Ekon. I Zarządzania* **2011**, *22*, 135–148.
13. Jones, G.V.; White, M.A.; Coper, O.R.; Storchmann, K. Climate change and global wine quality. *Clim. Change* **2005**, *73*, 319–343. [CrossRef]
14. Vršič, S.; Vodovnik, T. Reactions of grape varieties to climate changes in North East Slovenia. *Plant Soil Environ.* **2012**, *58*, 34–41. [CrossRef]
15. Dunn, M.; Rounsevell, M.D.A.; Boberg, F.; Clark, E.; Christensen, J.; Madsen, M.S. The future potential for wine production in Scotland under high-end climate change. *Reg Environ Change* **2019**, *19*, 723–732. [CrossRef]
16. Fraga, H.; Malheiro, A.C.; Moutinho-Pereira, J.; Santos, J.A. Future scenarios for viticultural zoning in Europe: Ensemble projections and uncertainties. *Int. J. Biometeorol.* **2013**, *57*, 909–925. [CrossRef] [PubMed]
17. Heydari, H.; Movaghari, A. Analysis of changes in viticultural climatic indices in northwestern and western Iran. *Vitis-J. Grapevine Res.* **2021**, *60*, 179–187. [CrossRef]
18. Kartschall, T.; Wodinski, M.; von Bloh, W.; Oesterle, H.; Rachimow, C.; Hoppmann, D. Changes in phenology and frost risks of Vitis vinifera (cv Riesling). *Meteorol. Z.* **2015**, *24*, 189–200. [CrossRef]
19. Makowski, J.; Miętkiewska-Brydna, J. Turystyka winiarska w Polsce. *Zesz. Naukowe. Tur. I Rekreac.* **2015**, *1*, 163–172.
20. Rogowski, M.; Kasianchuk, A. Atrakcyjność turystyczna winnic Lubuskiego Szlaku wina i miodu. *Zesz. Naukowe. Tur. I Rekreac.* **2016**, *2*, 101–118. [CrossRef]
21. Smogór, J. Wpływ autostrady Warszawa-Berlin na rozwój turystyki w województwie lubuskim. *Zesz. Nauk. Wielkop. Wyższej Szkoły Tur. I Zarządzania* **2012**, *7*, 121–130.
22. Charzyński, P.; Nowak, A.; Podgórski, Z. Turystyka winiarska na Ziemi Lubuskiej- historyczne uwarunkowania czy nowatorskie rozwiązanie? *J. Health Sci.* **2013**, *3*, 189–216.
23. Maciejczak, M.; Mikiciuk, J. Climate change impact on viticulture in Poland. *Int. J. Clim. Change Strateg. Manag.* **2019**, *11*, 254–264. [CrossRef]
24. Krochmal-Marczak, B.; Sawicka, B.; Bienia, B.; Kiełtyka-Dadasiewicz, A. The possibilities of growing common grape vine (*Vitis vinifera* L.) in the conditions of the Lower Beskids area. *J. Agric. Appl. Econ.* **2018**, *30*, 1–15.
25. Pink, M.; Ligenzowska, J. The problems of winemaking in Poland: The case study of winemakers from Malopolska wine route. In Proceedings of the Conference: International Scientific Days 2016 The Agri-Food Value Chain: Challenges for Natural Resources Management and Society, Nitra, Slovakia, 19–20 May 2016; pp. 213–223. [CrossRef]
26. Lisek, J. Frost damage of buds on one-year-old shoots of wine and table grapevine cultivars in central Poland following the winter of 2008/2009. *J. Fruit Ornam. Plant Res.* **2019**, *17*, 149–161.
27. Wojciechowska, E.; Sitarek, M.; Stań, A. Ocena agronomiczna wybranych odmian winorośli deserowej w warunkach glebowo-klimatycznych Polski Centralnej. *Zagadnienia Doradz. Rol.* **2023**, *3*, 68–87.
28. Jagosz, B.; Rolbiecki, S.; Stachowski, P.; Ptach, W.; Łangowski, A.; Kasperska-Wołowicz, W.; Sadan, H.A.; Rolbiecki, R.; Prus, P.; Kazula, M.J. Assessment of Water Needs of Grapevines in Western Poland from the Perspective of Climate Change. *Agriculture* **2020**, *10*, 477. [CrossRef]
29. Jagosz, B.; Rolbiecki, S.; Rolbiecki, R.; Łangowski, A.; Sadan, H.A.; Ptach, W.; Stachowski, P.; Kasperska-Wołowicz, W.; Pal-Fam, F.; Liberacki, D. The Water Needs of Grapevines in Central Poland. *Agronomy* **2021**, *11*, 416. [CrossRef]
30. Koźmiński, C.; Mąkosza, A.; Michalska, B.; Nidzgorska-Lencewicz, J. Thermal Conditions for Viticulture in Poland. *Sustainability* **2020**, *12*, 5665. [CrossRef]

31. Kryza, M.; Szymanowski, M.; Błaś, M.; Migała, K.; Werner, M.; Sobik, M. Observed changes in SAT and GDD and the climatological suitability of the Poland-Germany-Czech Republic transboundary region for wine grapes cultivation. *Theor. Appl. Climatol.* **2014**, *122*, 207–208. [CrossRef]
32. Bokwa, A.; Klimek, M. Warunki klimatyczne Pogórza Wielickiego dla potrzeb uprawy winorośli. In *Człowiek i rolnictwo: Profesorowi Czesławowi Guzikowi w 70. Rocznicę Urodzin*; Zborowski, A., Górska, Z., Eds.; Instytut Geografii i Gospodarki Przestrzennej Uniwersytetu Jagiellońskiego: Kraków, Poland, 2009; pp. 103–111.
33. Dobrowolska-Iwanek, J.; Gąstoł, M.; Wanat, A.; Krośniak, M.; Jancik, M.; Zagrodzki, P. Wine of Cool-climate Areas in South Poland. *S. Afr. J. Enol. Vitic.* **2013**, *35*, 1–9. [CrossRef]
34. Winkler, A.J.; Cook, J.A.; Kliwer, W.M.; Lider, L.A. *General Viticulture*; University of California Press: Berkeley, CA, USA, 1974.
35. Kuleba, M. *Ampelografia Zielonej Góry*; Wydawnictwo "Pro Libris": Zielona Góra, Poland, 2015.
36. Solon, J.; Borzyszkowski, J.; Bidłasik, M.; Richling, A.; Badora, K.; Balon, J.; Brzezińska-Wójcik, T.; Chabudziński, Ł.; Dobrowolski, R.; Grzegorczyk, I.; et al. Physico-geographical mesoregions of Poland: Verification and adjustment of boundaries on the basis of contemporary spatial data. *Geogr. Pol.* **2018**, *91*, 143–170. [CrossRef]
37. Urbański, K. *Objaśnienia do Szczegółowej Mapy Geologicznej Polski w Skali 1:50,000 Arkusz Zielona Góra (575)*; Państwowy Instytut Geologiczny, Państwowy Instytut Badawczy: Warszawa, Poland, 2003.
38. Woś, A. *Klimat Polski w Drugiej Połowie XX Wieku*; Wydawnictwo Naukowe UAM: Poznań, Poland, 2010.
39. Matuszko, D.; Bartoszek, K. Zachmurzenie. In *Atlas Klimatu Polski*; Tomczyk, A.M., Bednorz, E., Eds.; Bogucki Wydawnictwo Naukowe: Poznań, Poland, 2022.
40. Tomczyk, A.M. Temperatura powietrze. In *Atlas Klimatu Polski (1991–2020)*; Tomczyk, A.M., Bednorz, E., Eds.; Bogucki Wydawnictwo Naukowe: Poznań, Poland, 2022.
41. Bedorz, E. Opady atmosferyczne. In *Atlas Klimatu Polski (1991–2020)*; Tomczyk, A.M., Bednorz, E., Eds.; Bogucki Wydawnictwo Naukowe: Poznań, Poland, 2022.
42. Niedźwiedź, T. Słownik meteorologiczny. In *Polskie Towarzystwo Geofizyczne*; IMGW: Warszawa, Poland, 2003.
43. Jones, G.V.; Davis, R.E. Climate influences on grapevine phenology, grape composition, and wine production and quality for Bordeaux, France., American. *J. Enol. Vitic.* **2000**, *51*, 249–261. [CrossRef]
44. Gumiński, R. *Próba Wydzielenia Dzielnic Rolniczo-Klimatycznych w Polsce*; Przegląd Meteorologiczno-Hydrologiczny: Warszawa, Poland, 1948.
45. Bosak, W. *Uprawa Winorośli i Winiarstwo w Małym Gospodarstwie na Podkarpaciu*; Polski Instytut Winorośli i Wina: Jasło, Poland, 2004.
46. Ostrowski, S.; Kaszuba, M.; Gajewski, K. *Uprawa Winorośli i Amatorskie Przetwórstwo Winogron*; Lubuskie Stow. Winiarskie: Zielona Góra, Poland, 2004.
47. Myśliwiec, R. *Nowoczesna Winnica*; Państwowe Wydawnictwo Rolnicze i Leśne: Warszawa, Poland, 1992.
48. Bosak, W. *Winorośl i Wino w Małym Gospodarstwie w Małopolsce*; Małopolska Agencja Rozwoju Regionalnego S.A.: Kraków, Poland, 2006.
49. Bernardo, S.; Dinis, L.T.; Machado, N.; Moutinho-Pereira, J. Grapevine abiotic stress assessment and search for sustainable adaptation strategies in Mediterranean-like climates. A review. *Agron. Sustain. Dev.* **2018**, *38*, 66. [CrossRef]
50. Ferrandino, A.; Lovisolo, C. Abiotic stress effects on grapevine (*Vitis vinifera* L.): Focus on abscisic acid-mediated consequences on secondary metabolism and berry quality. *Environ. Exp. Bot.* **2014**, *103*, 138–147. [CrossRef]
51. Malheiro, A.C.; Santos, J.A.; Fraga, H.; Pinto, J.G. Climate change scenarios applied to viticultural zoning in Europe. *Clim. Res.* **2010**, *43*, 163–177. [CrossRef]
52. Sanos, A.J.; Malheiro, C.A.; Pinto, G.J.; Jones, V.G. Macroclimate and viticultural zoning in Europe: Observed trends and atmospheric forcing. *Clim. Res.* **2012**, *51*, 89–103. [CrossRef]
53. Marosz, M.; Wójcik, R.; Biernacik, D.; Jakusik, E.; Pilarski, M.; Owczarek, M.; Miętus, M. Zmienność klimatu Polski od połowy XX wieku. Rezultaty projektu klimat. *Pr. I Stud. Geogr.* **2011**, *47*, 51–66.
54. Marosz, M.; Miętus, M.; Biernacik, D. Features of Multiannual Air Temperature Variability in Poland (1951–2021). *Atmosphere* **2023**, *14*, 282. [CrossRef]
55. Owczarek, M.; Filipiak, J. Contemporary changes of thermal conditions in Poland, 1951–2015. *Bull. Geogr. Phys. Geogr. Ser.* **2016**, *10*, 31–50.
56. Ustrnul, Z.; Wypych, A.; Czekierda, D. *Climate Change in Poland. Past, Present, Future*; Springer: Cham, Switzerland, 2021; pp. 275–330. [CrossRef]
57. Wójcik, R.; Miętus, M. Niektóre cechy wieloletniej zmienności temperatury powietrza w Polsce (1951–2010). *Przegląd Geogr.* **2014**, *86*, 339–364. [CrossRef]
58. World Meteorologicl Organisation. *State of the Climate in Europe 2022 (WMO-No. 1320)*; WMO: Geneva, Switzerland, 2023.
59. IPPC. Climate change 2021: The Physical Science Basis. In *Contrubution od Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2021.
60. Urban, G. *Klimat Zielonej Góry*; Instytut Meteorologii i Gospodarki Wodnej-Państwowy Instytut Badawczy: Warszawa, Poland, 2020.
61. Tomczyk, A.M.; Szyga-Pluta, K. Okres wegetacyjny w Polsce w latach 1971–2010. *Przegląd Geogr.* **2016**, *88*, 75–86. [CrossRef]

62. Żmudzka, E. Wieloletnie zmiany zasobów termicznych w okresie wegetacyjnym i aktywnego wzrostu roślin w Polsce. *Woda-Sr. Obsz. Wiej.* **2012**, *12*, 377–389.
63. Szyga-Pluta, K.; Tomczyk, A.M.; Piniewski, M.; Reza Eini, M. Past and future changes in the start, end, and duration of the growing season in Poland. *Acta Geophys.* **2023**, *71*, 3041–3055. [CrossRef]
64. Wieteska, S. Ryzyko występowania przymrozkówa. w Polskiej strefie klimatycznej. *Acta Univ. Lodz. Folia Oeconomica* **2011**, *259*, 143–157.
65. Serra, I.; Strever, A.; Myburgh, P.; Deloire, A. Review: The interaction between rootstocks and cultivars (*Vitis vinifera* L.) to enhance drought tolerance in grapevine. *Ausralian. J. Grape Wine Res.* **2014**, *20*, 1–14. [CrossRef]
66. Giupponi, C.; Shechter, M. *Climate Change in the Mediterranean*; Edvard Elgar Publishing Limited: Cheltenham, UK, 2003.
67. Kenny, G.J.; Harrison, P.A. The effects of climate variability and change on grape suitability in Europe. *J. Wine Res.* **1992**, *3*, 163–183. [CrossRef]
68. Schernewski, G. Adaptation to Climate Change: Viniculture and Tourism at the Baltic Coast. In *Global Change and Baltic Coastal Zones*; Schernewski, G., Hofstede, J., Neumann, T., Eds.; Coastal Research Library; Springer: Dordrecht, The Netherlands, 2011; Volume 1. [CrossRef]

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