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Climate Vulnerability and Adaptation Challenges in Szekszárd Wine Region, Hungary

Attila Buzási

Department of Environmental Economics, Budapest University of Technology and Economics, H-1117 Budapest, Hungary; buzasi@eik.bme.hu

Abstract: Wine producers face several challenges regarding climate change, which will affect this industry both in the present and the future. Vulnerability assessments are at the forefront of current climate research, therefore, the present paper has two main aims. First, to assess two components of climate vulnerability regarding the Szekszárd wine region, Hungary; second, to collect and analyze adaptation farming techniques in terms of environmental sustainability aspects. Exposure analyses revealed that the study area will face several challenges regarding intensive drought periods in the future. Sensitivity indicators show the climate-related characteristics of the most popular grapevines and their relatively high level of susceptibility regarding changing climatic patterns. Since both external and intrinsic factors of vulnerability show deteriorating trends, the development of adaptation actions is needed. Adaptation interventions often provide unsustainable solutions or entail maladaptation issues, therefore, an environmental-focused sustainability assessment of collected interventions was performed to avoid long-term negative path dependencies. The applied evaluation methodology pointed out that nature-based adaptation actions are preferred in comparison to using additional machines or resource-intensive solutions. This study can fill the scientific gap by analyzing this wine region for the first time, via performing an ex-ante lock-in analysis of available and widely used adaptation interventions in the viticulture sector.

Keywords: adaptation; lock-in; viticulture; vulnerability

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1. Introduction

It can be declared that climate change will fundamentally modify the agricultural sector in the near future [1,2]. Furthermore, viticulture represents one of the most sensitive segments of the whole agricultural industry, with regards to changing climatic patterns [3–5]. From fruit ripening to selling high-quality wines, through producing the desired quantity and quality of wine: Climate change affects all of the supply chain elements [6–8]. Climate conditions are among the most determinative factors in the winemaking sector, since grapes are susceptible to meteorological features [9–11]. Nowadays, the wine industry is one of the most actively researched areas in relation to climate change, taking into account the related sustainability challenges and opportunities in many different scientific and geographical areas [12–15]. Numerous studies can be found that consider viticulture and climate change-related issues from Europe [16–20], North- and South-America [21–24], South-Africa [25–27], and Australia [28–30].

By considering the complex dependencies between climate change and viticulture, it is widely accepted that significant changes are projected to occur in suitable areas. Consequently, these regions face several socio-economic consequences [31,32]. Almost all traditional and emblematic vineyards in Europe are endangered by climate change-induced shrinkages, for example, the Rhone Valley, Bordeaux, and Tuscany. However, newly suitable areas are expected to appear in the northern regions of America and Europe [33–35]. However, widespread debates are occurring in the literature with regards to the methods for evaluating the geographical suitability of given grape varieties [36–39]. It is unnecessary to argue that changing climatic patterns and more frequent extreme weather events significantly increase the uncertainties in climate projections. Tóth and Végvári [40] identified potentially unsuitable areas for viticulture in Europe based on different climate scenarios. According to their study, more than 20% of the current wine regions are expected to disappear in Portugal, Spain, Italy, and France between 2050 and 2080. Based on the changing climatic conditions in northern Europe, Scotland, is considered a new suitable area for viticulture [41]. Nevertheless, it may be useful to conduct detailed analyses concerning climatic patterns. This way, hidden connections between projected future meteorological features can be revealed on a month by month basis.

In addition to the weather-related analyses of viticulture activities worldwide, it is worth emphasizing that adaptation issues shall also be taken into consideration. Marx et al. (2017) [14] stated after a comprehensive literature review, that research activities have shifted from analyzing the impacts of climate change on viticulture to evaluating and determining the adaptive capacity of the sector. Unfortunately, wine producers are faced with a severe lack of knowledge regarding climate change and its impacts on their industry. Consequently, raising producers' awareness and determining effective adaptation strategies are critical steps in improving the adaptive capacity of the wine industry [42]. However, adaptation-oriented papers regarding the viticulture sector cover a wide range of possibilities [31,36,43–47], while interconnections between sustainability and adaptive capacity are considered to be a less actively analyzed area [48–51]. The term "lock-in" dates back to the early 2000s, when the definition of carbon lock-in was developed. It represents market or policy failures that hinder the spread of less carbon-intensive technologies, regardless of their net positive sustainability features [52]. Although the phenomenon has been well documented for decades, practice-oriented methodologies regarding the sustainability-related aspects of adaptation policies and interventions are limited. However, several different lock-in types can be identified that decrease the sustainability transitions in a given sector and area [53]. Therefore, it can be stated that by revealing the potential lock-ins and path dependencies of widely accepted and applied adaptation interventions in the viticulture sector, the implementation of climate-conscious but unsustainable solutions can be avoided.

The main goal of this paper, based on the above-mentioned issues, is two-fold. First, to analyze the Szekszárd wine region, Hungary, in the face of changing climatic patterns by revealing two crucial elements of climate vulnerability, namely exposure and sensitivity. Studies regarding the Hungarian viticulture sector from climate change can be described with a narrow thematic focus [54–58] and with less attention on adaptation issues. After revising the existing literature, it became apparent that the Szekszárd wine region has not yet been analyzed in terms of climate change issues. The second aim of this study, is to collect suitable adaptation options based on the previously described climatic changes and related challenges in the region, whilst, analyzing them in terms of sustainability. Path dependencies, with regards to adaptation activities, can heavily burden long-term sustainability goals in many sectors [59,60]. However, the lock-in analysis of adaptation actions are lacking in the field of viticulture. Consequently, this study fills two scientific gaps by analyzing a previously un-studied wine region, and by revealing path dependencies of adaptation options regarding long-term sustainability impacts.

2. Materials and Methods

The study area is the Szekszárd wine region (SZWR), situated in the southern part of Hungary (see Figure 1). The wine region has a total cultivated area of 2600 ha, with approximately 2500 registered wineries growing their vine grapes mostly on loess, sand, and clay lands. The registered area with red varieties is more than 2100 ha: The region is mostly known for Kadarka red wine. However, another red variety, the so-called Kékfrankos (Blaufränkisch) is grown in almost one-third of the total red area. Merlot, Zweigelt, Cabernet Franc, and Cabernet Sauvignon are grown in 2–300 ha as main red varieties, while Kadarka is cultivated in less than 100 ha. Among the white varieties, Welschriesling (120 ha), Chardonnay (70 ha), Sylvaner (50 ha), and Sauvignon Blanc (40 ha) are the most popular ones. The climatic conditions of SZWR are continental, with hot and dry summers and rarely occurring frosts in spring and autumn. The number of sunny days is relatively high (cca. 2050 h/year), which is ideal for red varieties with long vegetative phases; while the annual precipitation is 500–600 mm with a high-level drought index. Until now, SZWR was out of the scope of current studies. Consequently, this study can be seen as a precursor of further evaluations regarding the complex interactions between changing climatic patterns and the wine-making activities in the area.

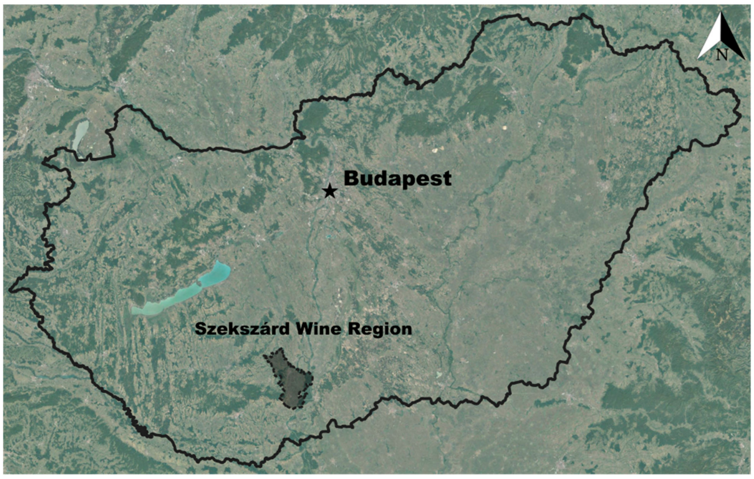

Figure 1. Location of the study area.

The selected methodology for assessing the need for effective adaptation activities in the studied area is a complex impact assessment model that contains two main pillars: First, the exposure and sensitivity of SZWR are evaluated; second, the sustainability-oriented lock-in analysis of the selected adaptation options is performed. The two-side evaluation, especially the sustainability-oriented lock-in analysis, can bridge the gap between the existing studies and further adaptation-centered analyses. As stated previously, the climate-related analysis of wine regions is well-known in the current literature. However, the elaborated lock-in analysis seems to be a new course of climate adaptation studies introduced to the sector. The climate vulnerability assessment is one of the most actively applied tools to define the challenges and consequences of climate change concerning a given sector or geographical area [61–64]. However, this study aims to reveal only two main vulnerability components, namely exposure and sensitivity.

During this study, exposure is interpreted as the physical consequence of climate change in a given area, such as changing temperature or precipitation over a given period [65–68]. In order to provide a more holistic insight into the exposure level of SZWR, historical meteorological data concerning the monthly average of precipitation (from 1977 to 2018) and temperature (between 1981 and 2018) were used to perform a detailed analysis of changing weather patterns and define anomalies regarding the study area. The dataset was provided by Mr. László Kővári (Szekszárd City Council), including detailed data with regards to the average precipitation and temperature values concerning the period indicated earlier. Data from SZWR were compared with long-term national average values of both precipitation and temperature data derived from the Hungarian Meteorological Service public database (https://www.met.hu/en/eghajlat/magyarorszag_eghajlata/eghajlati_adatsorok/), which provides detailed meteorological data of the five selected Hungarian cities from 1901 to 2019. The dataset contains standardized and homogenized information of monthly average precipitation and temperature values for the same periods as it was indicated above concerning five major cities: Budapest, Debrecen, Pécs, Szeged, and Szombathely. The location of these cities (see Figure 2) ensures the usability of meteorological data to develop national average values to compare them with the values from SZWR.

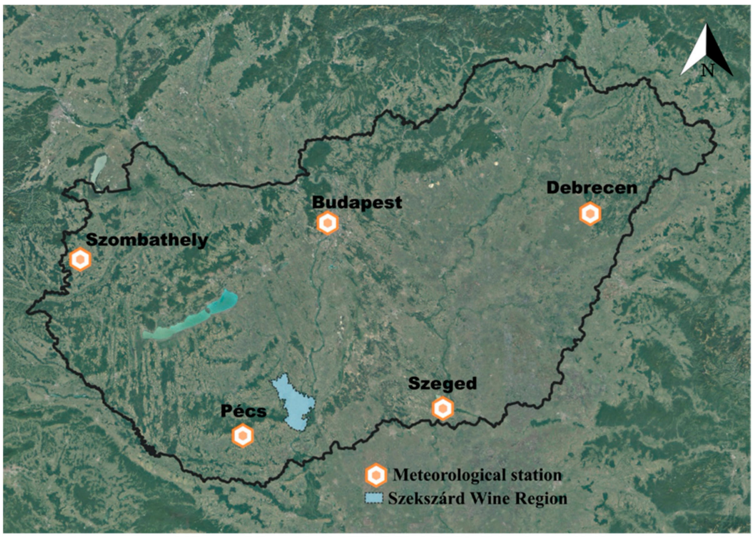

Figure 2. Location of the meteorological stations.

In addition to the historical meteorological data, a future-oriented exposure indicator, namely the change of the so-called Pálfai's drought index (PaDI0), was also taken into consideration during this study. This can be measured by applying the following equation [69,70]:

$$\mathrm{PaDI_0} = \frac{\frac{\left[\sum_{i=apr}^{aug} T_i\right]}{500}/5 * 100}{\sum_{i=oct}^{sept}(P_i * w_i)}, \quad (1)$$

where $PaDI_0$ is the drought index, °C/100 mm; T_i is the average temperature from April to August, °C; P_i is the monthly sum of precipitation from October to September, mm; w_i is the weighting factor of monthly precipitation (0,1 for September and October; 0,4 for November and December; 0,5 for January–April; 0,8 for May; 1,2 for June; 1,6 for July; and 0,9 for August, respectively).

According to the patterns of $PaDI_0$ values through Hungary (Figure 3) from 1961 to 1990, the study area can be described as a moderate and medium aridity zone. However, based on the results of climate models, the southern part of Hungary is projected to face more severe aridity than other areas. The change of this value is retrieved from the dataset of the National Adaptation Geo-information System (NAGiS), and it was calculated between 2021 and 2050 and 2071–2100 on the basis of 1961–1990 by using outputs of two regional climate models, namely RegCM4 and ALADIN-Climate. RegCM4 is the fourth generation of RegCM developed by [71], as the first limited area climate model, which has been applied for regional climate studies and future climate projections based on open sources [72]. ALADIN-Climate is a limited area climate model as well, based on a previously developed short-range tool [73], applying for a wide range of analyses in Hungary [74–76]. This future-oriented analysis of change in drought patterns regarding SZWR contributes to defining the relative exposure by comparing local data with the national average derived from an 1103–unit database.

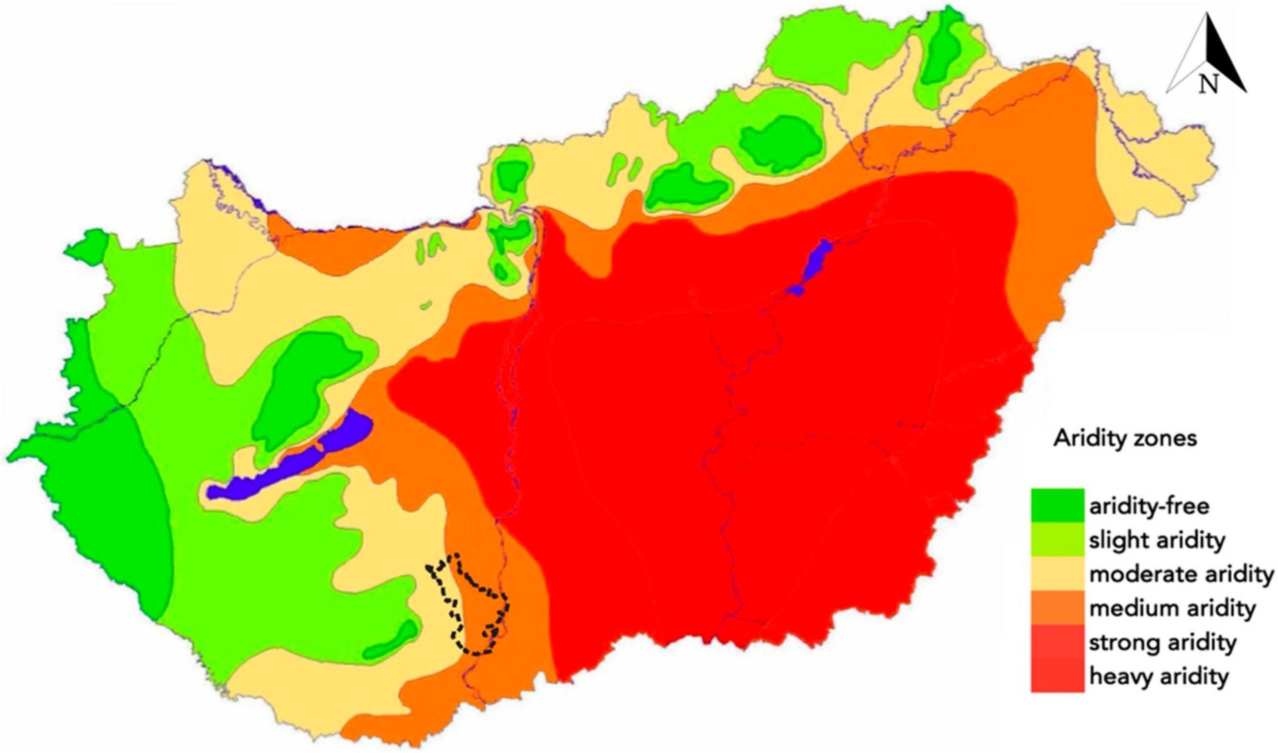

Figure 3. Pálfai's drought index for the period 1961–1990.

In addition to the exposure, as an external component of vulnerability, this study aims to assess the sensitivity of SZWR, as well. Here, sensitivity is defined as an intrinsic factor that describes whether a given impact driven by the changing climatic patterns is exacerbated or moderated by the responses of the analyzed system [77–80]. In the present study, sensitivity was evaluated in terms of suitability as it was applied by [81]: Whether changes in climatic features modify the suitability of the study area to grow currently existing red and white varieties. Therefore, the sensitivity analysis contains a detailed analysis of the grape varieties developed, based on their climate-related characteristics, such as different tolerances with regards to frost, drought, fungal diseases, and modification of the Huglin index [82]. In order to distinguish the different levels of sensitivity of the selected varieties, a five-step approach was applied. In essence, red and orange colors represent critically high and high sensitivity; white cells refer to neutral or not relevant impacts. In contrast, light and dark green cells show low and very low sensitivity of a given variety in terms of impacts. The climate-related features of the selected grape varieties (the most common four red and white ones from SZWR) have been identified based on the literature review [83–87].

After the evaluation of exposure and sensitivity, the last step was to define and analyze effective adaption options to enhance the adaptive capacity of SZWR by paying attention to long-term environmental sustainability requirements. First, to reach this goal, the available adaptation activities regarding viticulture from all over the world were collected by revising the literature with particular attention to farming techniques (Table 1). Second, path dependencies and lock-ins were revealed by applying a multi-criteria evaluation matrix, which contains the most often used adaptation techniques assessed in terms of various environmental aspects. The evaluation matrix and the applied methodology contribute to define maladaptation activities and conduce to restrain negative lock-ins in terms of the environmental issues of sustainability. Collected adaptation actions were evaluated regarding selected sustainability aspects, such as water consumption, energy consumption, air pollution, and biodiversity, as well. A five-step evaluation approach illustrated the potential positive and negative consequences of the interventions through direct and indirect impacts. Strong and moderate positive feedbacks were represented by "++" and "+", while the opposite direction was illustrated by using "− − " and "−" signs. "0" refers to those situations when both positive and negative impacts were revealed. Finally, "NR" signs non-relevant impacts in terms of a given sustainability issue. It is emphasized that the lock-in analysis is an actively researched area. However, most current studies focus on urban issues [88,89]. Therefore, it can be stated that viticulture-related evaluations are currently lacking and the presented methodology contributes to the widening existing knowledge of sustainable adaptation options.

Table 1. Collected literature to define the adaptation options.

Source	Spatial Focus
[90]	Tuscany, Italy
[91]	California, US
[42]	Roussillon (France) and McLaren Vale (Australia)
[92]	-
[93]	Australia
[44]	Spain, Portugal
[31]	-
[94]	New Zealand
[95]	-
[96]	Portugal
[97]	Tuscany, Italy
[45]	China
[98]	Anjou-Saumur winegrowing sub-region, France
[29]	Australia
[99]	Emilia Romagna, Italy
[30]	Australia
[50]	-
[100]	Mediterranean countries
[5]	-

3. Results

As it was stated above, detailed data concerning meteorological patterns of Szekszárd over the last 40 years were available. The precipitation variability between 1977 and 2018 regarding both SZWR and the national average is presented in Figure 4. Based on the available data, it can be stated that the amount of precipitation has a significant variability over the last 40 years in SZWR: In the case of May and August, the maximum amount of precipitation exceeded 200 mm (in 2010 and 2005, respectively). However, the minimum amount in these months was 8.5 mm in 1993 and 3 mm in 1992, respectively. Minimum values are under 10 mm every month, consequently, arid periods were observed from 1977. Comparing the dataset of SZWR and the national average, it is worth emphasizing that the variability of precipitation data regarding the study area exceeds the national average in the case of all months in the last four decades. Consequently, winemakers may be facing weather extremes in the future, which considerably increases the uncertainties concerning yield, wine quality, and profitability.

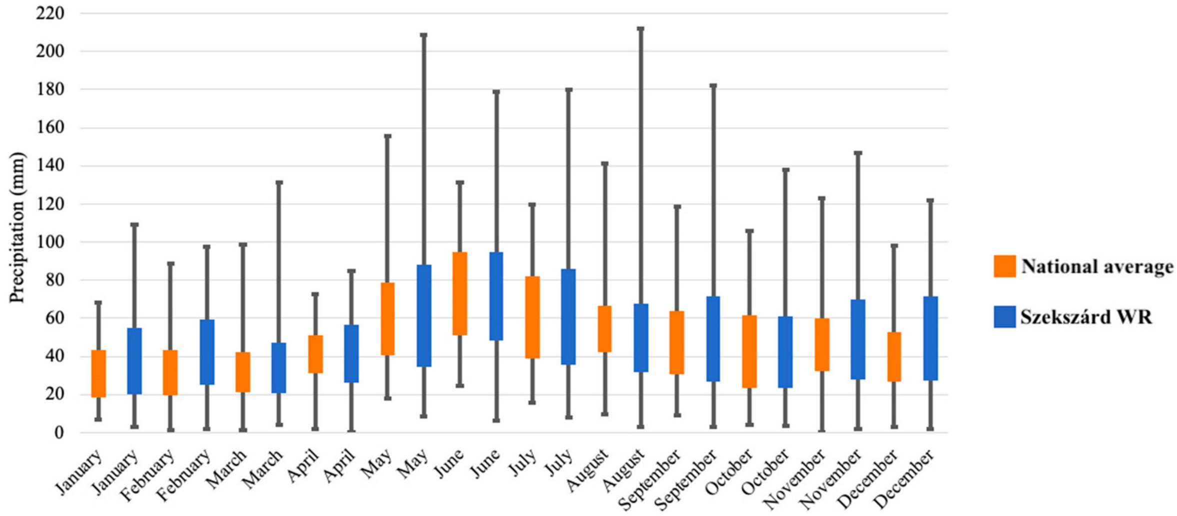

Figure 4. Monthly average precipitation and its variability between 1977–2018.

The data regarding the annual amount of precipitation (Figure 5) reveal anomalies during the analyzed period. It can be seen that considerable fluctuations have been observed in the case of SZWR, such as between 1999 and 2000, when the total amount of precipitation was 887 and 382 mm, respectively, in the studied area. Such a significant decrease also occurred between 2010 and 2011 when the total annual rainfall decreased by cca. 550 mm from 1028.4 to 425.1 mm during 1 year in SZWR. By considering the opposite part of precipitation anomalies, a sharp increase was observed between 1986 and 1987 (220 mm surplus), 2000 and 2001 (450 mm difference), and 2009 and 2010 when the amount of annual precipitation more than doubled. In the case of national average data, the same trends can be observed. However, the minimum and maximum values can be found considerably closer to each other, as shown in Figure 4. In summary, it may be noted that both monthly and yearly anomalies regarding precipitation patterns in SZWR exceed the national average values significantly for the same period.

Ranges between the minimum and maximum values of temperature data (Figure 6) are narrower than in the case of the above-mentioned precipitation patterns in both national and SZWR data. From May to August, the average temperature was above 20 °C, which is crucial and ideal for red varieties. However, maximum values above 25 °C profoundly endanger optimal maturity and ripening, while also concerning social aspects, as outdoor labor in vineyards. Months with minimum values below 0 are rare, frosty days are observed mainly in January, February, and December. However, according to regional climate models [101], these days are projected to disappear by the end of the 21st century in SZWR. According to the available climatic dataset, it is not surprising that red varieties are dominant in the studied area. However, further warming trends can modify the most popular varieties based on the suitability of the current cultivated area.

In addition to the historical meteorological data, a future-oriented exposure evaluation was also performed to assess the relative change of the $PaDI_0$ in the study area. Figure 7 illustrates that SZWR is facing an intensive rise of drought potential, in which the value exceeds the national average for almost all the simulated periods and regional climate models. Numerical results for 2021–2050 show that the average increase of the $PaDI_0$ value for the study area is projected to increase by 0.74 and 0.99, depending on the regional climate model applied. The national average for the same period using the same model results was calculated as 0.76 and 0.72, respectively.

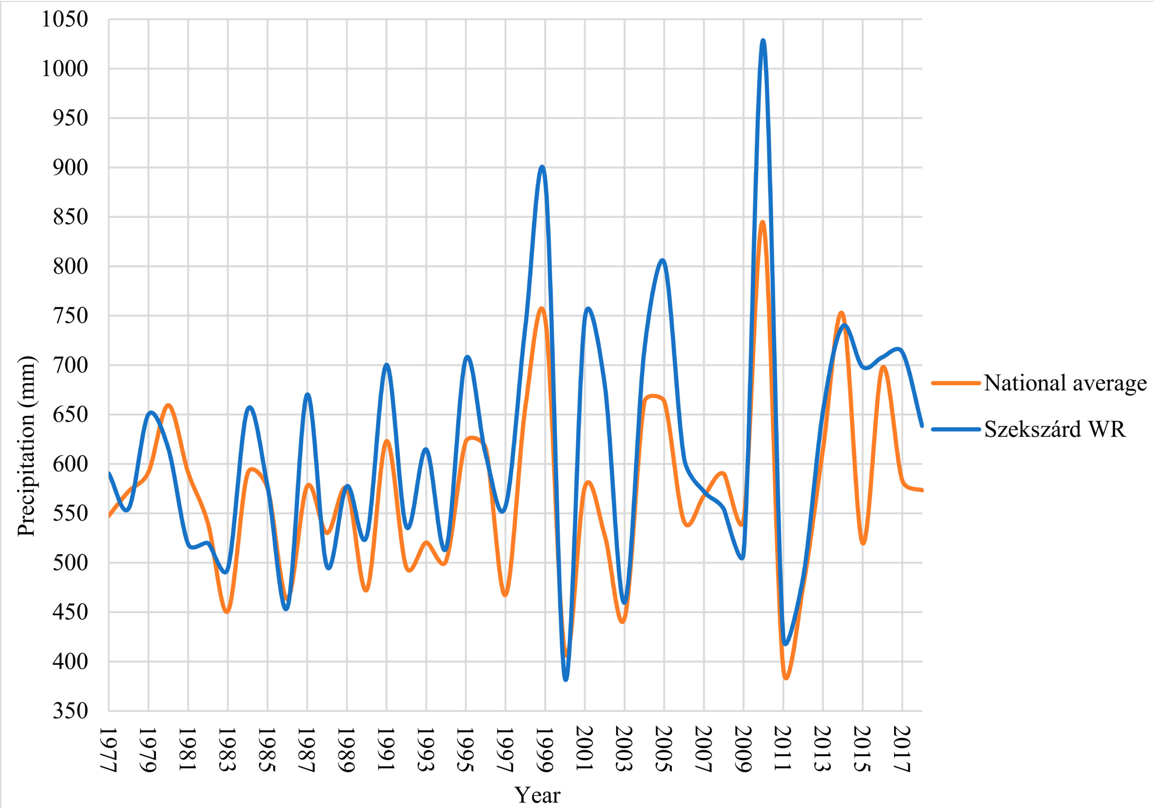

Figure 5. The cumulated annual precipitation (1977–2018) of Szekszárd wine region and Hungary.

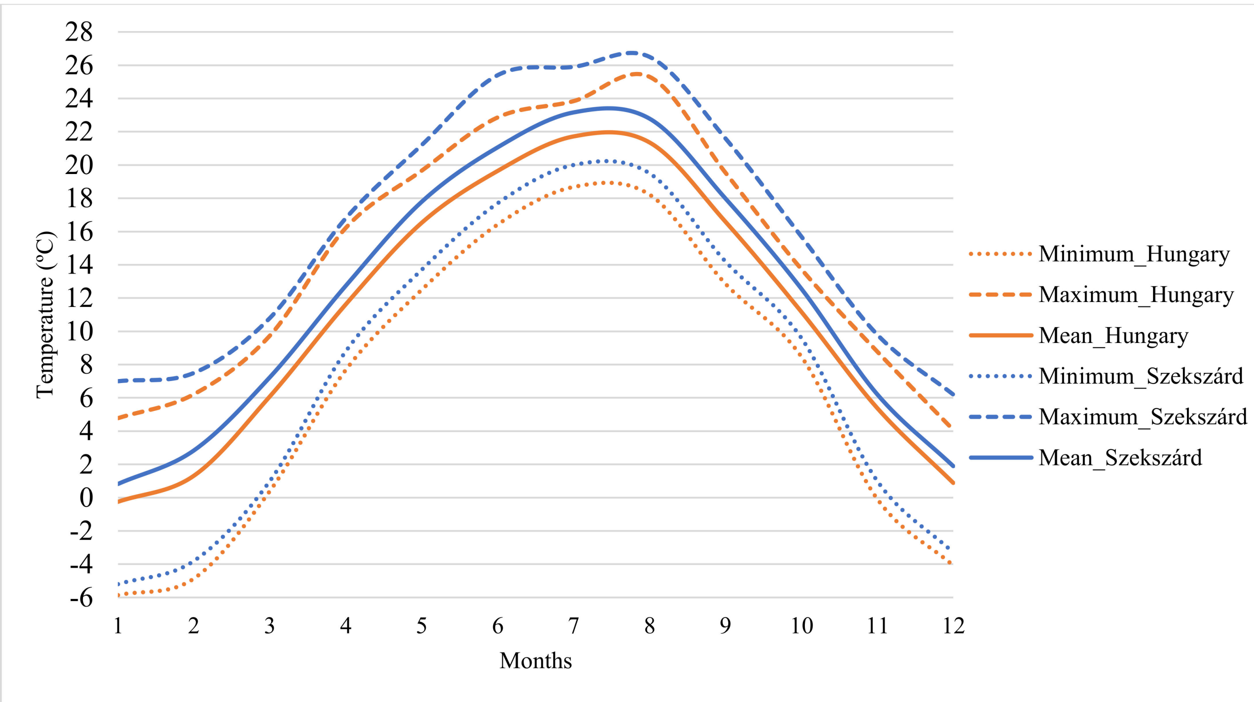

Figure 6. Forty-year average temperature (°C).

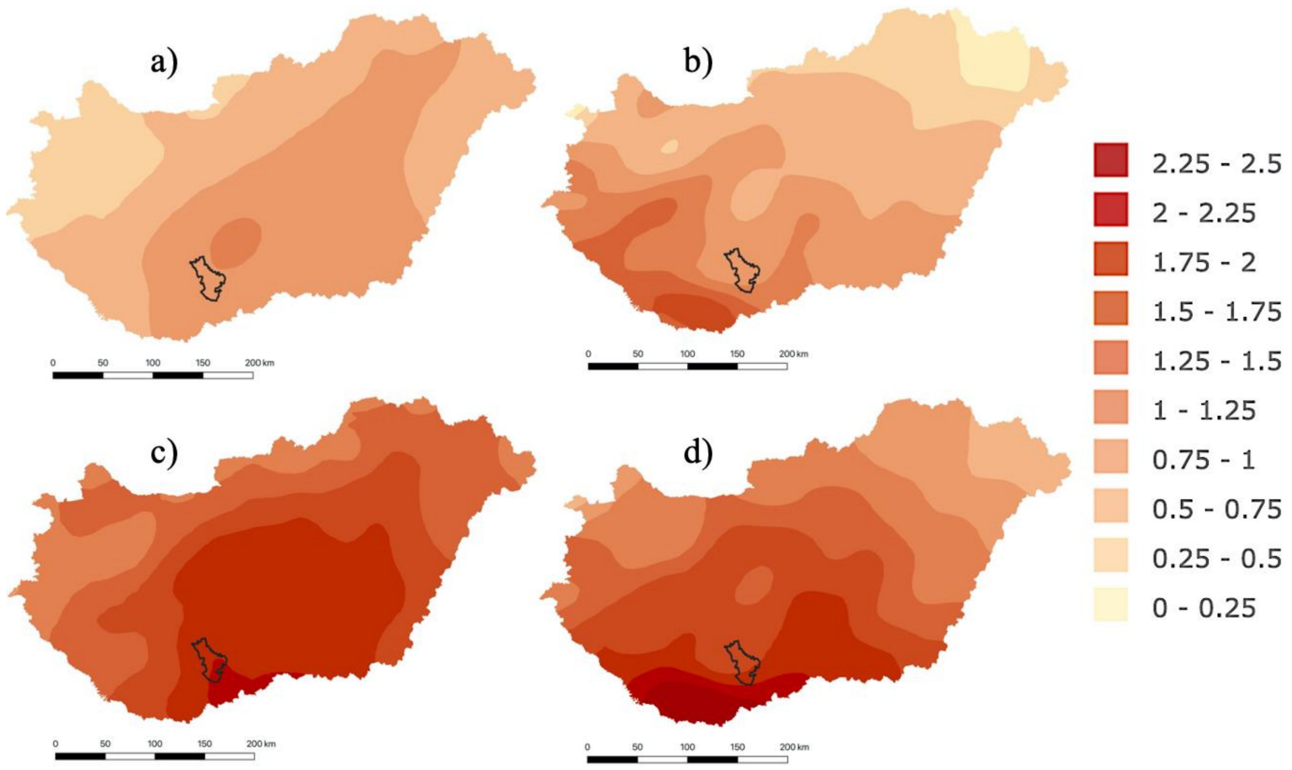

Figure 7. Change of $PaDI_0$ for the period 2021-2050 and 2071-2100. (**a**,**b**) Refer to the period of 2021-2050, while (**c**,**d**) illustrate the change of $PaDI_0$ for the period 2071-2100. Outputs of the RegCM model were applied to develop (**a**,**c**). Moreover, results of the ALADIN-Climate regional model were the inputs to create (**b**,**d**).

Consequently, it can be stated that according to the RegCM model, the $PaDI_0$ value of SZWR may change with the same dynamics as the national average. However, the ALADIN-Climate model predicts a considerable rise in future exposure features of the study area compared to the national values. The data analyses of the 2071–2100 period illustrate an intensified rise of the aridity risk in SZWR and Hungary. SZWR faces a remarkable rise of exposure values by 1.61 (RegCM) and 2.03 (ALADIN-Climate), while the national average was calculated as 1.39 and 1.57, respectively. Based on the previously interpreted results, it can be stated that the increase in the magnitude of aridity in SZWR will change in a more robust way than the national average, based on two different regional climate models in the case of both studied periods.

According to the selected methodology, the next step is to assess the sensitivity of the most dominant red and white grape varieties in terms of projected impacts driven by changing climatic features. Key climate-related characteristics of the most popular red and white grapevine varieties of SZWR are highlighted in Table 2, which shows the selected climate-related features, such as different heat tolerances, increase of the Huglin index (HI), and sensitivity to fungal diseases of a given variety on berries and leaf. The Huglin's heliothermic index is projected to increase significantly by the end of the century in the Carpathian basin by exceeding 3000 °C compared to the current level of 1600–2000 °C. This value shows a slightly modified rise by the middle of the century. However, the southern part of Hungary and SZWR can be described with appr. 2000–2200 °C [57].

Table 2. Climate sensitivity of the most popular grapevine varieties.

	Tolerance to . . .		**Increase of HI**	**Fungal Diseases on . . .**	
	Drought	**Frost**		**Leaf**	**Berries**
Blaufränkisch					
Merlot					
Cabernet sauvignon					
Kadarka					
Welschriesling					
Chardonnay					
Sylvaner					
Sauvignon blanc					

Red and orange colors represent critically high and high sensitivity; white cells refer to neutral or not relevant impacts. In contrast, light and dark green cells show low and very low sensitivity of a given variety in terms of impacts.

In general, red varieties are mainly drought-resistant ones, which make them ideal for growing in more arid conditions, which are predicted for the future. Blaufränkisch and Kadarka, as the two iconic red varieties of the wine region, are highly sensitive to the increase of HI. The most dominant red varieties, except for Cabernet sauvignon, are sensitive to fungal diseases on both leaves and berries. In light of the changing precipitation patterns, such as more intensive rainfalls projected to occur in summer, these features warn the local winemakers to think about planting more resilient varieties in the future. It can be seen that only Cabernet sauvignon has no critical susceptibility to the changing weather conditions and related meteorological consequences. Paying attention to the most popular white varieties, Chardonnay, Sylvaner, and Sauvignon Blanc are extremely sensitive to the increase of the heat sum Welschriesling, which is especially susceptible to droughts. Moreover, the most popular varieties are susceptible to fungal diseases caused by extreme precipitation events and heatwaves in the same days. Finally, it can be noted that currently, the most popular red and white varieties in SZWR can be described with an above-average sensitivity to extreme impacts of the predicted changing climatic patterns.

Table 3 represents the environmental sustainability-focused analysis of the collected and most often used adaptation techniques in viticulture. As stated previously, the listed actions focusing on farming techniques and all the aspects of sustainability have not been involved in the assessment, as well. The use of shading nets or foliar sunscreens has a strong negative feedback on biodiversity by reducing the number of flying animals. At the same time, impacts on the other three aspects were defined as non-relevant. Modifying the harvesting time increases energy consumption and air pollution due to using machines at night. Moreover, it can reduce local biodiversity through increased noise pollution. Damages caused by frost events and increased air humidity can be reduced using heaters or wind machines. However, the same adverse effects may be taken into consideration as in the case of extensive use of machines. Treating grapes with fungicides may increase the yield or stabilize wine quality. Nevertheless, the use of chemicals decreases the local biodiversity significantly. Moreover, it contributes to enhancing the air pollution levels. The use of non-chemical pesticides has non-relevant effects on water and energy consumption. However, local biodiversity patterns can be improved by applying nature-based solutions to reduce the economic loss due to harmful insects.

Numerous irrigation techniques with slightly different environmental impacts, such as permanent or drip irrigation can be found in the literature: Permanent irrigation significantly increases the water consumption. However, it may result in increased biodiversity, as drip irrigation needs a lower amount of water while similarly improving biodiversity patterns on the local level. The use of well-adapted varieties and canopy management entail a reduced water and energy consumption through the increased adaptive capacity. At the same time, both negative and positive effects on biodiversity may be defined in both. First, a more livable and adaptive environment may attract new species as a positive feedback, while native components of local ecosystems can disappear due to the changing environment. The water and energy demand of evaporative cooling are considerable. Therefore, significant adverse effects can be revealed, completed with slightly negative consequences regarding air pollution through the emissions of the machines used. Moreover, ecosystems disturbed by noise pollution and improved conditions for widening the existing biodiversity are two opposite effects, resulting in a net neutral consequence of the adaptation technique. Finally, soil preparation can reduce water consumption, while improved environmental factors may enhance local biodiversity. However, it needs a substantial amount of energy.

Table 3. Path dependencies of the selected adaptation actions.

	Environmental Sustainability Issues			
	Water Consumption	**Energy Consumption**	**Air Pollution**	**Biodiversity**
Use of shading nets/foliar sunscreens	NR	NR	NR	−−
Harvesting at night by machine	NR	−−	−−	−
Turning on heaters/wind machines	NR	−−	−	−
Allowing natural vegetation to grow	++	NR	+	++
Fungicide treatments	NR	NR	−−	−−
Site selection	+	−	−	0
Permanent irrigation	−−	−	NR	++
Use of well-adapted variety/rootstock	+	+	NR	0
Canopy management	+	+	NR	0
Evaporative cooling	−−	−−	−	0
Drip irrigation	−	−	NR	++
Non-chemical pest management	NR	NR	0	++
Soil preparation	+	−	0	+

According to the outcomes of the impact assessment methodology, it can be stated that nature-based solutions are preferred farming adaptation techniques rather than applying resource-intensive interventions. However, before making any decisions concerning the applicability of given actions, local environmental features, furthermore social and economic aspects, shall be considered to gain a related insight into deeper sustainability-related path dependencies. It is worth emphasizing that the present framework may be treated as a pilot assessment methodology due to the limited sustainability issues involved. Moreover, adverse direct and indirect effects, potentially negative lock-ins and long-term path dependencies can be defined.

4. Discussion

According to the previously presented results, SZWR can be described with an above-average need for climate adaptation due to its highly sensitive grape variety structure and changing climatic conditions by the end of the 21st century. The applied methodology has several limitations in selecting and using indicators and approaches, summarized as follows: The exposure analysis contains data of temperature anomalies in the past and future by involving national average values. Due to the limited availability of historical meteorological data, climate datasets from five cities were collected to calculate the national average values. It is worth mentioning that this dataset does not cover the total area of Hungary. Consequently, the representativeness of the dataset regarding spatial issues may be improved by widening the number of sampling points. In addition to the historical data of temperature anomalies, the same limitations and improvement opportunities can be taken into consideration in terms of the changing precipitation patterns. A future-oriented assessment of exposure includes the change of $PaDI_0$, as a composite index involving temperature and precipitation issues in calculating drought-related exposure patterns in Hungary. The primary limitations regarding local results concern a limited number of sampling points in the study area. $PaDI_0$ values were calculated by applying 10×10 km grids, thus, 1103 values can be created for the whole country. However, SZWR was covered by only six points. This number can be increased by widening the virtual border of the study area. As a result, values from 12 sampling points can be involved in the evaluation process, although future exposure is not changed significantly using this increased number of sampling points.

Regarding the second element of climate vulnerability, sensitivity was described in this study through a climate-oriented evaluation of the most commonly cultivated grape varieties. The sensitivity assessment may be completed with a detailed analysis regarding soil characteristics and geomorphological patterns. However, this information is not available, and therefore, this study uses secondary data solely. After evaluating the exposure and sensitivity, adaptation options regarding farming techniques were collected from the literature as components of climate vulnerability. It is worth emphasizing that a considerable amount of other adaptation interventions can be found in the literature. However, this study aims to assess only farming techniques in terms of their environmental sustainability aspects. The so-called lock-in analyses are hotspots of the current adaptation-oriented literature, although studies are lacking in agriculture.

As seen from the Introduction and Materials and Methods sections, current studies regarding viticulture and climate change can be incorporated into four main topics. First, the spatial analysis of changing climatic factors parallel with the potential impacts on viticulture reveal the most relevant challenges in the sector. Second, based on the results of these studies, the changing spatial suitability of given grape varieties is an actively analyzed issue. Third, adaptation options are drawn with regards to the increasing vulnerability to maintain the profitability of the sector. Finally, the fourth main analysis path is the molecular analysis of different grape varieties regarding the change in their phenological cycles and related impacts on quality and quantity. This paper applies a two-side analysis: The exposure and sensitivity analyses join one of the main research focuses in the current literature by revealing climate vulnerability aspects and defining the need for further adaptation. However, the developed lock-in analysis can be seen as a pilot assessment methodology involving four relevant sustainability issues: Water consumption, energy consumption, air pollution, and biodiversity. These aspects may be completed with various social and economic components as potential aims of subsequent studies.

In addition to the limitations mentioned above, it can be stated that locally effective and globally sustainable adaptation techniques are needed in the study area due to the revealed climate exposure and sensitivity patterns. The lock-in analysis of the most often used adaptation techniques highlighted that all interventions that need an increased amount of water and/or energy or reduce the existing biodiversity are controversial. Climate adaptation actions must be parallel with long-term sustainability issues. Therefore, locally applied techniques may be assessed in terms of sustainability dimensions by paying attention to direct and indirect impacts.

5. Conclusions

Winemakers face a range of challenges due to the variability in the rising temperature and the annual amount of precipitation and constant anomalies. Therefore, improving their adaptive capacity is crucial. The present paper aimed to assess the climate exposure and sensitivity of the Szekszárd wine region and evaluate the available farming adaptation techniques in terms of environmental sustainability issues to avoid maladaptation. Over the past 40 years, the historical climate dataset of precipitation and temperature patterns in Szekszárd revealed that a considerable variability is observed in precipitation from year to year compared to the national average. A future-oriented exposure evaluation was performed using the change of a complex aridity index, called Pálfai's drought index. According to the results, it can be stated that the study area is facing severe drought potential in the future since the $PaDI_0$ value is projected to rise more sharply than the national average in the analyzed future periods. The sensitivity analysis refers to the climate-related "answer" of the most commonly cultivated grape varieties in SZWR regarding the above-mentioned changing climatic patterns. To summarize the results of this vulnerability component, an above-average sensitivity is realized in the wine region, since only Cabernet Sauvignon has no critical susceptibility. However, the remainder of the varieties have at least one critical characteristic, which heavily burdens and decreases farmers' adaptive capacity if they want to grow these grapevines in the future. Based on the outputs of analyses performed in this study, Szekszárd wine region can be described with an above-average climate vulnerability due to its sensitive grape variety structure and intensively changing climatic conditions by the end of the 21st century. This statement is highly relevant based on the grape variety structure of the study area since grape varieties cultivated in the most extensive area are vulnerable to climate change. Consequently, it can be declared that prompt and effective adaptation options need to be developed to maintain the high quality of red wines produced in the study area. Since adaptation interventions often provide unsustainable solutions or entail maladaptation issues, an environmental-focused sustainability assessment of the collected interventions was performed. Although this research has several limitations in selecting and using indicators regarding vulnerability and lock-in analysis, it can widen the existing knowledge by involving a previously not analyzed region as well as performing a pilot lock-in analysis regarding adaptation techniques in the viticulture sector.

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