

## Climatic projections vs. grapevine phenology: a regional case study

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### Abstract

From the middle of the 20th century, the majority of the world's highest quality wine-producing regions experienced an increase in temperatures during the growing season. Even if, through technological processes, this issue has been seen as an improvement, recent changes of climatic factors (mainly temperature, sunshine duration and rainfall) show a worrying trend. This study reveals the impacts of climate change in one of the oldest and most important vineyards in Eastern Europe (Odobești vineyard in Romania) on the quality of grapes. The varieties taken into study are 'Șarbă, Băbească gri' and 'Fetească regală', the first two being considered new created cultivars, while the latter is found on the largest areas of viticultural use. Grapevine phenology and composition were analysed according to literature and standard OIV regulations. Climatic data was gathered, throughout 50 years (1971-2021), by using a weather station of the Odobești Viticulture and Wine-making Research Development Station. A climatic assessment using Shared Socioeconomic Pathways (SSPs) was achieved, focusing on two SSPs (SSP1-1.9 and SSP5-8.5). The climatic predictions show that for the analysed region, phenophases will change due to a temperature increase of over 1.5 °C, leading to an acceleration of 15 (SSP1-1.9) or 24 days (SSP5-8.5) in the case of grape maturation. The hastening of the yearly vine life cycle is correlated to a wide range of undesirable effects, among which an unequilibrated physical-chemical composition of fruits for wine production is considered a sore point in wine sector economy.

**Keywords:** climate change; grape vine; phenology; Odobești vineyard; new grape varieties; SSPs

### Introduction

Climate change is a highly debated topic due to its significant impact on so-cio-economic activities and the environment. It refers to the long-term changes in weather patterns and average temperatures observed during the industrial era, primarily caused by human activities, particularly the emission of greenhouse gases such as carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons (Etminan *et al.*, 2016).

Received: 04 Sep 2023. Received in revised form: 15 Feb 2024. Accepted: 29 Feb 2024. Published online: 06 Mar 2024.

From Volume 49, Issue 1, 2021, Notulae Botanicae Horti Agrobotanici Cluj-Napoca journal uses article numbers in place of the traditional method of continuous pagination through the volume. The journal will continue to appear quarterly, as before, with four annual numbers.

The scientific community, as well as organizations like the United Nations Framework Convention on Climate Change (UNFCCC), are concerned about how the climate will evolve in the future. To estimate long-term surface air temperature, various theories, models, and scenarios have been developed (Phillips *et al.*, 1956; Pozzer *et al.*, 2011; Taylor *et al.*, 2012; Jones *et al.*, 2016; Lawrence *et al.*, 2016). Physical climate models, as well as Earth system models, are used to understand climate dynamics. However, physical climate models often cannot consider all sources of CO<sub>2</sub> as Earth system models do (Jones *et al.*, 2016; Lawrence *et al.*, 2016).

The future emissions of greenhouse gases depend on the public policies and how they are implemented by countries, as outlined in the Paris Agreement, 2015 (enforced in 2016). The complex and unpredictable nature of these policies requires the use of multiple scenarios. The Shared Socioeconomic Pathway (SSP) scenarios, which include nine different pathways, were proposed to account for the uncertainty and variability in future greenhouse gas emissions (Meinshausen *et al.*, 2020).

Climate change is currently occurring globally and is expected to become more pronounced in the coming decades. This will undoubtedly have a significant impact on horticultural species, particularly grapevines. Changes in temperature will influence the geographical distribution of grapevine varieties and rootstocks. Temperature is a crucial factor determining the cultivation areas, phenophases (stages of plant development), and ultimately, the quantity and quality of grape production (Jones *et al.*, 2010; Tomasi *et al.*, 2011; Biasi *et al.*, 2019).

Information of a plant's phenological features is important for *Vitis vinifera* L., where the optimum progress of fruit for winemaking is strongly correlated to phenological occurrence and timing (Jones *et al.*, 2000; Keller, 2010). Moreover, as vine phenology is intensely connected to climate, its dynamics have been studied and used as an instrument to understand climatic variability and impact on the world wine production (Chuine *et al.*, 2004; Jones *et al.*, 2005; Webb *et al.*, 2007). Studying the dynamics of phenophases in relation to environmental conditions is an important approach to quantify the climate change effects. Research conducted in various regions has demonstrated changes in the development and duration of vegetation phenophases, as well as the quality of grape production and the physicochemical and sensory characteristics of wines (Irimia *et al.*, 2017; Nistor *et al.*, 2019). However, it is important to consider the broader impacts of climate change on grape cultivation. While higher temperatures may initially seem beneficial, there are various other climate factors that can affect grapevine health and wine quality. Extreme heat events can lead to heat stress and sunburn on grapes, while changes in rainfall patterns can impact water availability for irrigation and affect vine growth. Shifts in pest and disease dynamics can also pose challenges to grape production.

To ensure the long-term sustainability and resilience of grape cultivation in the face of climate change, ongoing research is necessary. The research should focus on understanding the complex interactions between climate factors and their impacts on grapevine phenology, grape development, and wine characteristics. Additionally, proactive measures should be taken in vineyard management practices, such as selecting grapevine varieties and rootstocks that are better adapted to changing climatic conditions, implementing irrigation strategies, and adjusting canopy management techniques. The phenological rhythm of plants is ruled by a biological clock, strictly related to hormones and plant physiology and driven by a large set of environmental variables (temperature, solar radiation, photoperiod, soil water content). Due to the lack of comprehension of the underlying mechanism, temperature is often the only driving variable considered (Dobrei *et al.*, 2015). By studying the dynamics of phenophases and continuously monitoring environmental conditions, vineyard managers and researchers can make informed decisions to mitigate the negative impacts of climate change and optimize wine production. Adaptation strategies will play a crucial role in ensuring the continued success of the grape and wine industry in the face of ongoing climate change (O'Neill *et al.*, 2016).

A consensus of multiple wine grape suitability models representing a range of modelling approaches driven by global climate models (GCMs) under two Representative Concentration Pathways (RCPs). Habitat impact is assessed by using an "ecological footprint" index, which measures the intersection of viticultural suitability with remaining natural habitat (Sanderson *et al.*, 2002). The potential for impact on freshwater

provisioning is assessed by using the intersection of water stress (Alcamo *et al.*, 2003), projected changes in suitability for viticulture and projected changes in rainfall.

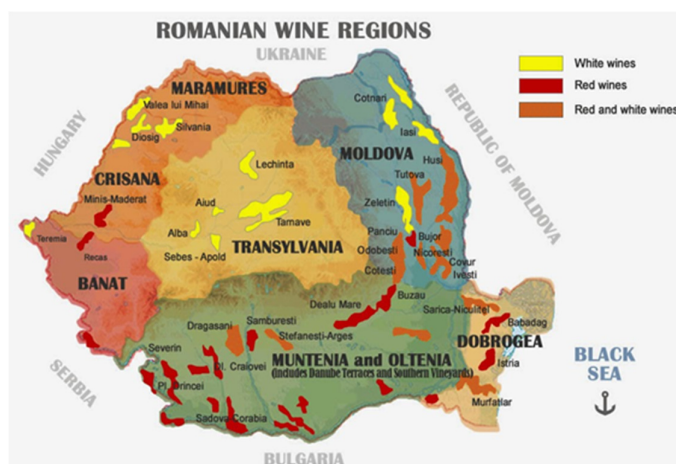
This study aims to conduct a climatic assessment of viticulture under climate change scenarios, according to Shared Socioeconomic Pathways (SSPs) developed and used globally by the Intergovernmental Panel on Climate Change (www.ipcc.ch). SSPs are emissions scenarios according to diverse socioeconomic assumptions (IPCC, 2021). More specifically, two SSPs (SSP1-1.9 and SSP5-8.5) corresponding to the most positive, with very low GHG emissions, when CO<sub>2</sub> emissions cut to net zero around 2050 and the most negative pre-dictions, with very high GHG emissions, when CO<sub>2</sub> emissions triple by 2075.

## Materials and Methods

### *Study site*

The research was carried out in the Odobești vineyard, one of the oldest and most appreciated vineyards in Romania (Figure 1), located in the area of the sub-Carpathians, strongly influencing the climate of the vineyard, having three wine-growing centers: Odobești, Jariște and Bolotești. Among Vrancea's vineyards, Odobești is placed on the hilly area parallel to the Vrancei Mountains, which includes the town of Odobești, sheltered by the highest hill, Măgura Odobeștilor (996 m) with Șarba, Vărsătura, Pădureni and Scânteia plains. The Odobești vine-growing center has as margins the parallel 45° 46" north latitude and the meridian 27° 40" east longitude, at an altitude of 150 m. The climate of the area is of temperate continental type, with excessive nuances due to the presence of eastern European air masses, the Atlantic from the west and northwest, all year round, but especially in the transitional seasons. The relief is hilly, with altitudes between 100 m and 300 m. Eastern and southern exposures dominate, with an average slope of 2-3%. The soil is cambic chernozem with loamy-clay texture, slightly acidic to neutral reaction (pH=6.5-7.7), humus content of 1.5-4.2%, formed on medium carbonate materials, with the depth of groundwater at over 25 m.

In the specific case of the Odobești vineyard located in the south of Moldova, significant increases in average annual temperature in recent years were recorded, with some years exceeding 13.0 °C. This suggests a more favourable environment for producing quality wines. These temperature increases likely have implications for the grapevines' phenology, grape development and overall wine production in the region.



**Figure 1.** Viticultural areas of Romania (Bosoi, 2023)

### *Biological material and cultivation technology*

The biological material was represented by three varieties of *V. vinifera* L. for wine production, of which two varieties were created at the Research and Development Station for Viticulture and Vinification Odobești

(SCDVV Odobești): ‘Șarba’ cv. (fertilization of the ‘Italian Riesling’ variety); authors Popescu *et al.* (1972) (approved for cultivation in 1972), ‘Băbeasca gri’ cv. (genetic mutation of the variety ‘Băbească neagră’ cv. by vegetative propagation; (Bosoi, 2023) and the variety ‘Fetească regală’ cv. (natural hybridization between the varieties ‘Grasă de Cotnari’ cv. and ‘Fetească albă’ cv., as considered by some authors (Constantinescu *et al.*, 1970; Rotaru, 2009). This cultivar has a wide distribution in the whole of vine-growing Romania.

The ‘Șarba’ variety (Figure 2) has a vegetation period between 165 and 177 days; bud-burst is late, towards the end of April, while full maturity of grapes is achieved in the second decade of September (the end of the IV<sup>th</sup> period). It achieves high and constant productions (18-20 t/ha) (Constantinescu *et al.*, 1970; Rotaru, 2009).



**Figure 2.** ‘Șarba’ variety - young shoot, grape and adult leaf (Bosoi, 2023)

In the case of ‘Băbească gri’ cv., (Figure 3) the vegetation period is between 190 and 205 days. Bud-burst takes place in the first half of April, veraison takes place in the first half of August. It is a late ripening variety (6th period). It ensures constant production (15-20 t/ha) (Rotaru, 2009).



**Figure 3.** ‘Băbească gri’ grape variety- young shoot, grape and adult leaf (Bosoi, 2023)

‘Fetească regală’ cv. (Figure 4) starts bud-burst during the second half of April, veraison takes place in the last part of July and can last up to the beginning of August, while full maturation is achieved at the end of September or even beginning of October. Production varies from 11 t/ha in Blaj to 27 t/ha in Odobești, with an average of 15-20 t/ha (Constantinescu *et al.*, 1970).



**Figure 4.** 'Fetească regală' grape variety -adult leaf and grape (Bosoi, 2023)

All three vine varieties are located in the biological field of SCDVV Odobești. The age of the plantation is 10 years and the varieties studied were grafted on the rootstock Berlandieri × Riparia Selection Oppenheim 4, clone 4. The planting distances were 2.2 m between rows and 1.2 m between plants per row, the cutting system practiced was Dr. Guyot, with 38 - 44 buds/trunk, distributed on 8 - 9 shoots and 2 spurs, on a semi-high trunk. The support system consisted of double wire trellis on three levels. The soil was maintained as a black field, with chemical fertilizers based on phosphorus, potassium and trace elements, not irrigated. Each variant (genotype) was represented in this study by three repetitions of five trunks. In each year of the study, the phenological spectrum was monitored by recording the unfolding of the vegetation phenophases (bud-burst, flowering, fruit formation, full maturity and leaf fall). Observations and determinations were made regarding the quality of grape production: sugar content (g/L), total acidity (g/L tartaric acid) and pH. To determine the full maturity of the grapes, the gluco-acidimetric index (IGA) was calculated, which represents the value of the ratio between the sugar content and the total acidity of the must:  $IGA = \text{sugars (g/L)} / \text{total acidity (g/L H}_2\text{SO}_4)$

Grape sampling was carried out according to OIV/VITI Resolution 371/2010 (OIV, 2023).

#### *Data and analysis*

##### Meteorological data

The meteorological information used in this research was recorded at the Adcon AgroExpert A733 addWAVE weather station of the Odobești Viticulture and Wine-making Research Development Station, located in the centre of the vineyard, at the base of the Șarba plain, with the geographical coordinates: 45°45" north latitude, 27°03" east longitude, and the altitude of 182 m. The multi-year climatic base of S.C.D.V.V. Odobești was also used. The parameters monitored in the period 2000-2022 were the following: daily temperature (maximum, minimum and average), amount of precipitation, air humidity (hygroscopicity), duration of sunshine (insolation). Also, based on the average daily temperature ( $T_m$ ), the sum of the global ( $\Sigma t^{\circ}g$ ), active ( $\Sigma t^{\circ}a$ ), and useful ( $\Sigma t^{\circ}u$ ) temperature degrees was calculated from the vine vegetation period (April-September), but also some bioclimatic indices such as the heliothermal index -  $I_{hr}$  (Branas *et al.*, 1946), the hydrothermal coefficient - CH (Seleaninov, 1936) the bioclimatic index of the vine -  $I_{bcv}$  (Constantinescu *et al.*, 1964), the oenoclimatic suitability index -  $I_{AOe}$  (Teodorescu *et al.*, 1987), the Huglin index -  $I_H$  (Huglin, 1978) and the night coolness index -  $I_F$  (Tonietto, 1999).

##### Vine grape phenology and grape composition

Vine phenology for the three cultivars was related to bud break, flowering, fruiting and full maturity and registered for the period 2000-2022. The bud-burst, flowering and maturation phenophases correspond to stages C, I and M defined according to authors (Oșlobeanu *et al.*, 1991). The data recorded for bud-burst, flowering and veraison correspond to the date when 50% of the vine sample taken in the study from each variety reached the respective phenological stage. Thus bud-burst is noted when 50% of the buds are in the "woolly" stage corresponding to Baggiollini's C stage, blooming is noted when 50% of the flowers of an inflorescence are open and veraison is recorded when 50% of the berries are elastic and start to change colour. The observations

were carried out on all the grapes on 10 vine shoots. Full ripening is considered when the grains have accumulated a high concentration of sugars (carbohydrates), when their mass is at the highest level, and the total acidity is moderate. Grapes harvested at full maturity ensure quality wines and high must yield. Technological maturity or industrial maturity is considered when grapes present an optimal composition for the production of a certain type of wine and a quality category, defined by the following parameters: sugar content, total acidity and pH.

To determine the sugar content, refractometry was used, which is also the most important official method recommended by OIV norms, for evaluating the sugar content of natural must (OIV-MA-AS2-02, 2012). The Zeiss handheld refractometer, used to perform the determinations, allows direct observations, under operational conditions, the precision required by STAS 12853-90 and ISO 2173:2003 is 0.1%, and it is necessary to perform at least three determinations. The readings were made in degrees Brix (°Bx), and the correspondence between the measurement scales of the sugar concentration of the must and the equivalence in g/L sugars were carried out according to the tables presented by Ribereau-Gayón (Ribereau-Gayón *et al.*, 2006). To analyse total acidity, the potentiometric method or titration with phenolphthalein was used as an indicator of the end of the reaction by comparison with a colour standard (OIV, 2023). The pH of the must was determined with the help of a potentiometer. Directly using the samples to be analysed, the readings were made twice at a temperature of 20 °C and the final result represented the average of the two determinations.

## Results

Climate change all over the world and its effect on abiotic resources for grapevine and other crops was analysed by different authors (Tomasi *et al.*, 2011; Mariani *et al.*, 2012). The discussion focused on the latitudinal effect of climate change on agricultural products.

The climate conditions in East of Romania are influenced by the Siberian anticyclone (H) in the cold season and by Asiatic cyclone (L) during summer. The weather is characterised by a humid continental climate according to Köppen-Geiger with precipitations evenly distributed throughout year, but Beck estimated that it will soon become a humid subtropical climate as early as 2100 (Beck *et al.*, 2018).

In Odobești vineyard, the mean sum of annual precipitation amount is 656 mm/year while mean annual air temperature is 12 °C, with an increase to 19.2 °C during the vegetative season. January is the coldest month (-0.4 °C) and in two months the average temperature exceeds 22 °C; July (23.5 °C) and August (23.9 °C).

The most important climatic indicators used in viticulture based on meteorological parameters were recorded from 1971-2022 (Table 1).

**Table 1.** Averages of bioclimatic indicators for Odobești vineyard over decades

| Bioclimatic indicators                   | 1971-1980 | 1981-1990 | 1991-2000 | 2001-2010 | 2011-2021 |
|------------------------------------------|-----------|-----------|-----------|-----------|-----------|
| IHr (real heliothermic index)            | 1.92      | 2.11      | 2.32      | 2.52      | 3.08      |
| CH (Hydrothermal coefficient)            | 1.52      | 1.14      | 1.32      | 1.17      | 1.18      |
| Ibcv (Bioclimatic index of the vineyard) | 5.56      | 7.90      | 7.22      | 8.15      | 8.68      |
| IAOe (Oenoclimatic aptitude index)       | 4241      | 4496      | 4554      | 4765      | 5073      |
| IH (Huglin index)                        | 1835      | 1947      | 2002      | 2145      | 2401      |
| IF (Cool night index)                    | 11.5      | 12.4      | 11.8      | 12.5      | 13.4      |
| IarDM (Aridity index De Martonne)        | 35.0      | 27.7      | 30.7      | 28.9      | 29.6      |
| Rainfall annual (mm)                     | 699       | 564       | 636       | 633       | 656       |
| Rainfall in vegetation period (mm)       | 459       | 356       | 418       | 404       | 418       |

In Odobești vineyard, the Huglin's index exceeded the value of 2100 after 2007, becoming, together with the sums of average daily temperatures, correct indicators regarding the heat transferred to and accumulated by vine.

Among all, two indices will be focused on: the viticultural bioclimatic index, as described by (Constantinescu *et al.*, 1964) integrates the influence of temperature, insolation, precipitation and the bioactive period of the air. Its applicability is limited to areas with a temperate climate, where rainfall can be considered an unfavourable factor for the quality of wine production; it does not allow the evaluation of the ecological potential of wine-growing areas in regions with an arid climate, where rainfall is a favourable factor for the quality of production (Hidalgo, 1977). The calculation relationship for Ibcv is

$$Ibcv = (\Sigma Ir \times \Sigma ta / \Sigma p \times Nzv) / 10$$

Ibcv = viticultural bioclimatic index

$\Sigma Ir$  = real insolation (hours)

$\Sigma ta$  = active thermal balance (°C)

$\Sigma p$  = sum of rainfall during vegetation period (mm)

$Nzv$  = number of days of vegetation period

The values recorded in Romanian vineyards varied between 4.0 and 15.0; the optimal ecological balance for the vine was recorded when  $Ibcv = 10 \pm 5$ . The small values (4-6) mean an abundance of water resources, while the high ones (12-15) correspond to the abundance of heliothermic resources and the lack of humidity. According to authors (Oşlobeanu *et al.*, 1991) the Ibcv values registered in Romanian viticultural areas were ranging between 4.8 and 11.5, as can be seen in Table 2.

**Table 2.** Values of the bioclimatic viticultural index in viticultural regions of Romania (as by authors (Oşlobeanu *et al.*, 1991))

| Viticultural region                                     | Bioclimatic viticultural index |                    |
|---------------------------------------------------------|--------------------------------|--------------------|
|                                                         | Mean                           | Variation interval |
| Transylvanian plateau                                   | 4.8                            | 3.9-5.9            |
| Moldavian Hills                                         | 8.0                            | 5.5-10.8           |
| Muntenia and Oltenia Hills                              | 7.8                            | 5.7-10.6           |
| Banat Hills                                             | 6.5                            | 5.3-8.2            |
| Crişana and Maramureş Hills                             | 6.1                            | 4.7-7.0            |
| Dobrogea Hills                                          | 11.5                           | 10.2-13.0          |
| Danube Terraces                                         | 10.3                           | 8.5-11.5           |
| Sands and other favourable lands from the Southern part | 9.3                            | 7.6-10.8           |

Presently, these values are obsolete and the new values have shifted more to the higher extremes of the range. Odobești vineyard, situated in the southern part of Moldova Hills region (Dealurile Moldovei) has values higher than 8.6.

The oenoclimatic aptitude index expresses the combined action of insolation, temperature and precipitation during the vine's vegetation period and reveals the possibility of producing red wines in the wine-growing area analysed (Teodorescu *et al.*, 1987). The calculation relationship is:

$$IAOe = \Sigma Ir + \Sigma ta - (\Sigma p - 250)$$

$\Sigma Ir$  = real insolation (hours)

$\Sigma ta$  = active thermal balance (°C)

$\Sigma p$  = sum of rainfall during vegetation period (mm)

250 = minimum amount of rainfall for non-irrigated vines during vegetation period (mm)

In the vineyards in Romania, the IAOe varies between 3700 and 5200. The lowest values are recorded in the cool climate of the Transylvanian Plateau, and the highest in the vineyards rich in heliothermal resources

in the south of the country. Traditional values of the Romanian IAOe in different viticultural regions can be seen in Table 3.

**Table 3.** Values of the oenoclimatic aptitude index in viticultural regions of Romania (as by authors (Oşlobeanu *et al.*, 1991))

| Viticultural region                                     | Oenoclimatic aptitude index |                    |
|---------------------------------------------------------|-----------------------------|--------------------|
|                                                         | Mean                        | Variation interval |
| Transylvanian plateau                                   | 3995                        | 3793-4158          |
| Moldavian Hills                                         | 4482                        | 4197-4744          |
| Muntenia and Oltenia Hills                              | 4656                        | 4345-4948          |
| Banat Hills                                             | 4508                        | 4355-4706          |
| Crişana and Maramureş Hills                             | 4270                        | 3993-4575          |
| Dobrogea Hills                                          | 4777                        | 4633-4893          |
| Danube Terraces                                         | 4893                        | 4776-5018          |
| Sands and other favourable lands from the Southern part | 4820                        | 4690-4980          |

The current values for IAOe of Odobeşti vineyard are also increasing fast, registering an average of 5043 for the decade 2011-2021, compared to the average of 4482 corresponding to the whole of the Moldova Hills viticultural region mentioned by Oşlobeanu *et al.* in 1991.

As chemical composition of grape must is highly connected to wine quality, it is imperative to know how these parameters will change in the future, as to be able to take pre-emptive steps in maintaining its typicity and its constant quality. As can be seen in Table 4, the estimate for the harvest date of the grapes in 2050 will have to happen 17 days earlier as to preserve its profile. The most positive prediction is that this date will be only 7 days earlier in 2050 so that the physico-chemical composition is upheld.

**Table 4.** The biochemical parameters of must at harvest and estimations for 2050

| Cultivar          | Biochemical characteristics of must |                                                     |                       | Harvest date of grapes |                   |                   |
|-------------------|-------------------------------------|-----------------------------------------------------|-----------------------|------------------------|-------------------|-------------------|
|                   | Sugars (g/L)                        | Total acidity (g/L H <sub>2</sub> SO <sub>4</sub> ) | Glucosidimetric index | Present                | Estimate SSP1-1.9 | Estimate SSP5-8.5 |
| ‘Şarba’           | 221.4                               | 5.7                                                 | 61.0                  | 23-Sep                 | 16-Sep            | 06-Sep            |
| ‘Băbească gri’    | 219.5                               | 7.7                                                 | 45.0                  | 22-Sep                 | 08-Sep            | 28-Aug            |
| ‘Fetească regală’ | 189.4                               | 6.5                                                 | 45.4                  | 19-Sep                 | 09-Sep            | 31-Aug            |

The statistical analyses highlighted that the glucosidimetric index has a high value (61.01) for ‘Şarba’, much higher than its counterparts. The ‘Băbească gri’ cultivar is sensitive of the number of days and heat accumulated during maturation stages. A long period in these stages makes the wine more acidic. The other two cultivars are not influenced by the time spent during veraison and ripening stages.

The simulation regarding the estimated time when grapes accumulated enough heat to pass to the next stage show that the number of days necessary to surpass phenophases decreases (Table 5), slowly at the beginning of the annual cycle and faster towards its end. It is important to be aware and manage these changes of so that the quality characteristics of the grapes and wines are still met for the consumers.

**Table 5.** Phenophases of vinegrapes in Odobești vineyard and estimations for 2050

| Growing stages | Cultivar          | 2001-2022 | Estimate<br>$\Sigma^{\circ}\text{t}$ global |                  | Estimate<br>$\Sigma^{\circ}\text{t}$ active |                  | Estimate<br>$\Sigma^{\circ}\text{t}$ useful |                  | No. of days in advance for each stage SSP1-1.9 in 2050 | No. of days in advance for each stage SSP5-8.5 in 2050 |
|----------------|-------------------|-----------|---------------------------------------------|------------------|---------------------------------------------|------------------|---------------------------------------------|------------------|--------------------------------------------------------|--------------------------------------------------------|
|                |                   |           | SSP1-1.9<br>2050                            | SSP5-8.5<br>2050 | SSP1-1.9<br>2050                            | SSP5-8.5<br>2050 | SSP1-1.9<br>2050                            | SSP5-8.5<br>2050 |                                                        |                                                        |
| Budding        | 'Şarba'           | 18-Apr    | 21-Apr                                      | 20-Apr           | 16-Apr                                      | 15-Apr           | 19-Apr                                      | 18-Apr           | 0                                                      | 0                                                      |
|                | 'Băbească gri'    | 19-Apr    | 21-Apr                                      | 19-Apr           | 16-Apr                                      | 15-Apr           | 19-Apr                                      | 18-Apr           | 0                                                      | 1                                                      |
|                | 'Fetească regală' | 17-Apr    | 19-Apr                                      | 18-Apr           | 14-Apr                                      | 13-Apr           | 16-Apr                                      | 16-Apr           | 1                                                      | 1                                                      |
| Bloom          | 'Şarba'           | 02-Jun    | 30-May                                      | 28-May           | 27-May                                      | 24-May           | 29-May                                      | 25-May           | 4                                                      | 8                                                      |
|                | 'Băbească gri'    | 02-Jun    | 31-May                                      | 28-May           | 27-May                                      | 25-May           | 29-May                                      | 25-May           | 4                                                      | 8                                                      |
|                | 'Fetească regală' | 31-May    | 28-May                                      | 26-May           | 25-May                                      | 22-May           | 27-May                                      | 23-May           | 4                                                      | 8                                                      |
| Veraison       | 'Şarba'           | 06-Aug    | 30-Jul                                      | 27-Jul           | 27-Jul                                      | 23-Jul           | 28-Jul                                      | 23-Jul           | 9                                                      | 14                                                     |
|                | 'Băbească gri'    | 12-Aug    | 07-Aug                                      | 03-Aug           | 04-Aug                                      | 31-Jul           | 04-Aug                                      | 30-Jul           | 8                                                      | 13                                                     |
|                | 'Fetească regală' | 03-Aug    | 27-Jul                                      | 23-Jul           | 24-Jul                                      | 20-Jul           | 24-Jul                                      | 19-Jul           | 10                                                     | 15                                                     |
| Maturation     | 'Şarba'           | 16-Sep    | 07-Sep                                      | 01-Sep           | 03-Sep                                      | 28-Aug           | 02-Sep                                      | 23-Aug           | 14                                                     | 24                                                     |
|                | 'Băbească gri'    | 21-Sep    | 14-Sep                                      | 07-Sep           | 10-Sep                                      | 03-Sep           | 08-Sep                                      | 28-Aug           | 15                                                     | 26                                                     |
|                | 'Fetească regală' | 14-Sep    | 04-Sep                                      | 29-Aug           | 30-Aug                                      | 26-Aug           | 30-Aug                                      | 21-Aug           | 15                                                     | 24                                                     |

Over three decades, the maturity stage will be reached two – three weeks early. This acceleration of the number of days in which the necessary temperatures are accumulated will have negative effects on the quality of the fruits, as the biological, physical and chemical processes are much speeded and the balance of the compositional structure of grape must and the future wine is challenged (Cotea *et al.*, 2021).

The earlier appearance of these phenophases can together reduce the grapevine development cycle substantially. These results are in agreement with recent studies worldwide, such as French (Duchene *et al.*, 2005), American (Jones *et al.*, 2005), Australian (Webb *et al.*, 2007; Petrie and Sadras, 2008) and German (Bock *et al.*, 2011). These changes towards earlier phenophase could hypothetically result in changes to the presently well-known wine features and typicity.

## Discussion

Simulations of the effect of climate change on the phenology of grapevines indicate shorter growing seasons, earlier manifestations of phases and shorter phase duration in the future, which impacts negatively on the quality of grapes and of the final products.

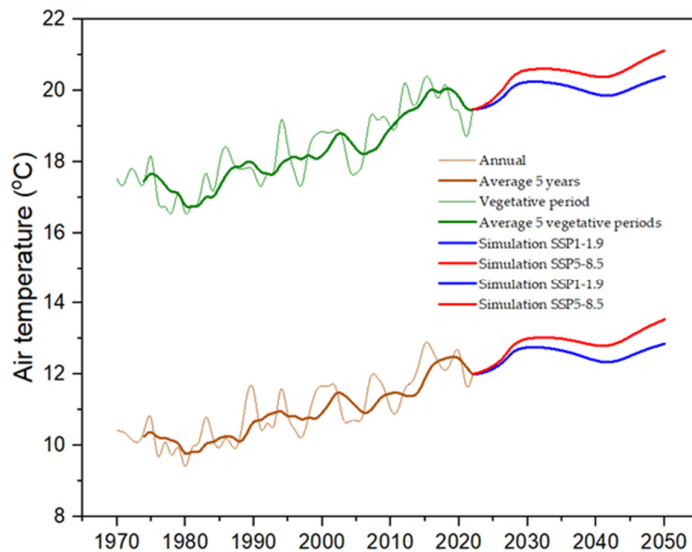
The influence of temperature on grapevine growth and wine quality throughout different stages of the growing season is of the utmost importance. During late summer and early autumn, noteworthy diurnal temperature ranges (difference between daytime and night time temperatures) contribute to increased sugar and tannin production in the grapes, which is important for wine production and balance (Ribéreau-Gayon *et al.*, 2006). Lower autumn temperatures, before the first frost, allow for a better balance of sugar and acidity, as well as increased flavour and aroma constituents in the grapes (Țârdea *et al.*, 2003). In winter months, minimum temperature thresholds are important to ensure proper budbreak in the spring (Oşlobeanu *et al.*, 1991). Effective chilling units (cold temperatures) are necessary for uniform budbreak. Grape hardiness increases through the winter and temperatures below -9 °C in late November and early December can increase grape production by preventing vine de-acclimation. However, temperatures below -20 °C can cause injury to most *V. vinifera* cultivars, and temperatures below -12 °C before mid-November can result in freeze damage, particularly to the primary buds. Severe damage can occur at temperatures below -25 °C, and at temperatures below -29 °C, entire vines may be killed (Rotaru, 2009). As can be seen from Table 1, however these events decrease in number, with 16 % less freezing days than in the 1970-1980s.

The number of days where the air temperature is higher than 30 °C has almost tripled in the last ten years compared to the 1970-1980 decade. The hotter and hotter climate will influence the physico-chemical composition as well as the harvest date of grapes (Chuine *et al.*, 2004; Mariani *et al.*, 2012).

In Romania, grape varieties are grown in ideal ecological conditions in their “Denumire de origine controlată” (Denomination of Controlled Origin - DOC) areas, which are registered on the complex sum of optimal soil, terrain and climate features, all combined to produce the best growing conditions for high vintage quality. In the coming decades, most probable from the following half of the 21<sup>st</sup> century, present DOC areas might no longer have the ideal climate for their specific grape varieties, and it may be necessary to shift them towards higher or cooler areas.

The possible effects of climate change are not restricted to the studied warming trend. Other consequences projected for the analysed region include higher water stress (Moriondo and Bindi, 2007; Fraga *et al.*, 2015) and increased frequency of climatic accidents, like hail, powerful storms, floodings or even vegetation fires (Santos, 2006; Santos *et al.*, 2007), including in Romania (Bucur and Babeş, 2016; Croitoru and Piticari, 2013). Extreme weather events, especially winter/spring weather events such as hail and frost, are projected to inflict important yield losses in several crops (IPCC, 2012). Given their unpredictable nature, they may represent an additional challenge for grapevines in future climates. Nonetheless, some positive impacts are also projected, given that the overall length of the growing season is expected to increase, triggered by enhanced warming from spring to autumn.

Simulations indicate that temperatures will continue to grow in the next decades and will have as impact a severe increase in the amount of heat and light accumulated during the growing season. Measured over the last 50 years, the mean air temperature in Odobeşti vineyard showed a speedy increase during the last decade, as can be seen in Figure 5. Air heat is given by radiative forcing contribution. Mean hours of sunshine in the last decade increased with 14%, respectively by 16.9% in the growing season compared to the 1971-1990 period. Real heliothermal index is steadily increasing, while hydrothermal coefficient has been decreasing.

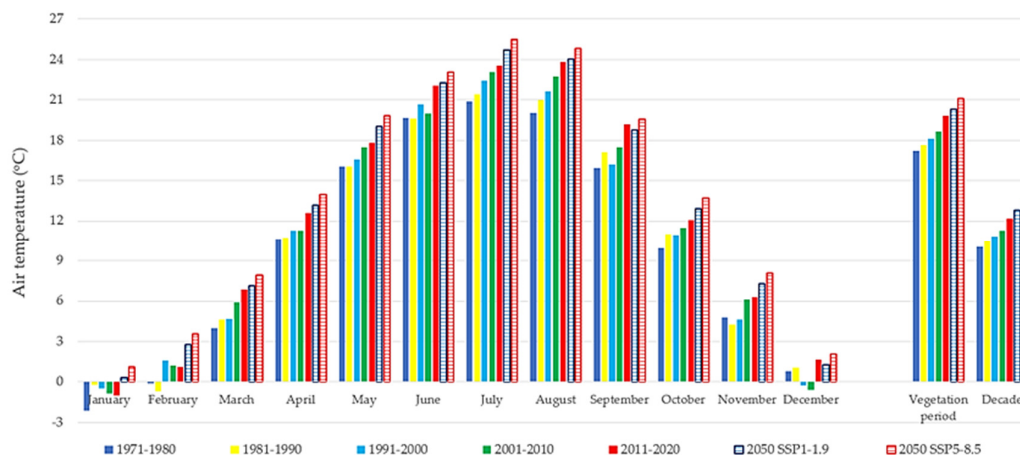


**Figure 5.** Annual and vegetation period air temperature from Odobeşti vineyard and the estimations for 2050

The temperatures from 1971 till 2022 were measured using WMO standard and the date for next two decades was simulated using SSP1-1.9 and SSP5-8.5 scenarios. In summer months, high temperatures above 30 °C can be beneficial for ripening grapes, but extended periods of heat can lead to various negative effects such

as heat stress, premature veraison, berry abscission (shedding of berries), enzyme inactivation and reduced flavour development, as well as decreased yield.

In viticulture, monthly temperatures are very important, especially from July and August, time for veraison and grape maturation (Figure 6). The average monthly temperature of July is 23.5 °C, while August registers 23.9 °C. It is estimated that in 2050 it will reach 25.1-25.9 °C in July and 24.0-24.8 °C in August, according to the most optimistic and pessimistic predictions. These values may pose a threat to the maturation phase of some grape varieties and also tilt the balance towards more reds than white wines (Webb *et al.*, 2007).



**Figure 6.** Annual, monthly and vegetation period mean air temperature in different decades and estimations for 2050

As can be seen in Figure 6, mean monthly temperatures in the warmest months have increased with more than 1.5 °C in the last decades, therefore the phenophases of the grapevine, mostly those of veraison and grape maturation, will be speeded, with an unclear result regarding their physical-chemical composition and the obtained wines (Scutarușu *et al.*, 2021). The grapes will tend to accumulate more sugars, making the wines more alcoholic (Biasi *et al.*, 2019), although the new trend is the opposite: consumer demand for wines with less or no alcohol is rising. Colder regions, where it is common to have less sugar and therefore less alcohol, may still benefit from climate change, while others will be forced to switch their main agricultural production.

## Conclusions

The projected increase in growing season temperatures could exceed the upper limits suitable for premium wine grape production (>21 °C), jeopardizing the continued success of this activity. High temperatures during the growing season can negatively impact grapevine health and grape quality. Excessive heat can lead to physiological stress in vines, affecting their growth, fruit development, and ultimately, the quality of the harvested grapes. Heat stress can also increase the risk of vine diseases and pests, impacting vineyard productivity and sustainability. However, it is worth noting that the projected increases in dormant season temperatures may have different implications. While warmer dormant seasons could reduce the risk of winter damage from cold temperatures, they may also create favourable conditions for pests to overwinter within the vineyards. This increased pest pressure can require additional pest management strategies to maintain vineyard health and productivity. In Romania, the 6th European viticultural country by surface, the climatic changes predictions (SSP1-1.9 and SSP5-8.5) point to a vast problem, that will need diverse and complex solutions in order to bypass the issues that arise. However, the mentioned solutions all require further

analysis and practical experience to undergo the climatic variations and their effects on viticulture, specific applied technologies in the field or the cellar and the effect on the final product, wine.

### Authors' Contributions

Conceptualization, L.C.C. and L.R.; methodology, I.Bosoi and I.Bodale.; software, I.Bodale.; validation, L.C.C. and I.Bosoi; resources, I. Bosoi and M.P.; writing—original draft preparation, L.C.C., I.Bosoi and I.Bodale ; writing—review and editing, L.L.C. and C.E.L.; visualization, I.Bodale; supervision, V.V.C. and L.R. All authors have read and agreed to the published version of the manuscript. All authors read and approved the final manuscript.

### Ethical approval (for researches involving animals or humans)

Not applicable.

### Acknowledgements

This research is funded by „Ion Ionescu de la Brad” Iași University of Life Sciences.

### Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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