

Impacts of climate change on selected agrobiological and technological traits of the 'Fetească Neagră' cultivar: A comparative study of the Murfatlar vineyard (Romania) and the Codru wine region (Republic of Moldova)

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ABSTRACT

Over the past decade, shifts in key climatic parameters in both wine-growing regions have brought notable changes to the agrobiological behavior of the indigenous 'Fetească Neagră' cultivar. These include a shorter vegetative period, an earlier onset of full ripening, and an advance in the grape harvest date. Traits such as fertility, productivity, and resilience to stress factors (drought, pathogen pressure) are directly shaped by these climatic shifts. This paper presents a comparative analysis of the evolution of principal climatic factors recorded between 2015 and 2024 and examines their impact on the phenology and grape quality of the 'Fetească Neagră' cultivar cultivated in both regions. The findings indicate an increase in average temperatures during the vegetative phase by 0.8–0.9°C in both areas, coupled with uneven rainfall patterns marked by alternating dry periods and months with normal precipitation. In both vineyards, the vegetative cycle was reduced by 10–15 days, with full ripening now occurring in early September; the average vegetative period lasted around 120 days. Berry development accelerated by about 9 days at Murfatlar, where the ripening phase now begins at approximately 100 days of vegetation. At Codru, the ripening phase was shortened to 17 days instead of the previous 35. In terms of grape yield, no significant differences were observed between the two regions during the study period. However, improvements in quality were recorded: at Murfatlar, must sugar levels increased by 6.6g/L, accompanied by a decrease in acidity; at Codru, must sugar levels rose by 8.39g/L, with acidity stabilizing at 4.5g/L tartaric acid. Correlation analyses highlight the considerable influence of temperature and precipitation on grape quality parameters for the 'Fetească Neagră' cultivar. The challenges posed by climate change for this variety in both regions are clear. To sustain wine quality, adaptive cultivation measures are needed, including improved soil water conservation, canopy management, grape shading, and other responsive viticultural practices.

Keywords: climate change, phenology, grape quality, sustainability, resilience

INTRODUCTION

Climate change represents a major challenge to the viticultural sector, directly affecting the agrobiological and technological characteristics of grapevine cultivars. Extreme climatic phenomena, such as prolonged droughts, increased frequency of high temperatures, and heavy rainfall, significantly influence the biological processes of the plant, leading to changes in phenology, the duration of the vegetative period, and grape chemical composition (Jones *et al.*, 2005; Fraga *et al.*, 2016). In recent decades, the rise in temperatures has caused an earlier ripening of grapes, affecting the sugar-acid balance in the must—an essential factor in shaping the sensory profile of wine (Moriondo *et al.*, 2013; Caffi *et al.*, 2016). In this context, identifying and assessing the impact of climate change on the agrobiological and technological traits of grapevine cultivars—particularly indigenous ones—has become a critical priority for ensuring sustainable viticulture. During the vegetative season, grapevines require daily average temperatures above 10 °C to initiate vegetative growth, followed by sufficient thermal accumulation to ensure full ripening of the grapes (Huglin, 1986). However, extreme temperatures during key phenological stages can cause physiological stress, premature ripening, yield losses, enzymatic inactivation, and poor development of aromatic compounds (Coombe, 1987). In the wine-growing regions of southeastern Europe, including Romania and the Republic of Moldova, the effects of climate change are already evident. These areas, with a long-standing viticultural tradition, are now facing a variety of risks associated with extreme weather events such as persistent droughts and flooding (Lafon *et al.*, 2013). Additionally, changes in precipitation patterns—marked by alternating extended dry periods and torrential rains—have created conditions conducive to major challenges, such as efficient water management and increased pressure from diseases and pests (Fraga *et al.*, 2016). Recent studies have shown that climate change affects not only grapevine phenology but also the chemical composition and sensory profile of wines, by altering concentrations of phenolic compounds, organic acids, and sugars in the grapes (Webber *et al.*, 2018; Brillante *et al.*, 2019). Moreover, significant variations in rainfall patterns and rising average temperatures can lead to yield fluctuations and negatively impact fruit development, with direct consequences on the volume and quality of viticultural production (Schultz, 2010).

The effects of climate change are further amplified by additional factors such as water resource management and the protection of grapevines from biotic and abiotic stress. These issues highlight the urgent need for integrated and sustainable approaches in viticultural practices (Caffi *et al.*, 2016). Traditionally, viticulturists have selected wine grape cultivars based on phenotypic traits that adapt most effectively to local microclimates (Wolkovich *et al.*, 2018) and soil types. Only cultivars that deliver consistent yields under specific climatic conditions and maintain an optimal balance of sugars, acidity, and other compounds with technological and sensory value are retained in cultivation (van Leeuwen and Darriet, 2016). 'Fetească Neagră' is one of the oldest and most valuable indigenous grapevine cultivars in Romania and the Republic of Moldova, holding a unique historical and cultural significance. However, in the context of recent climate change, significant alterations have been observed in the agrobiological and technological behavior of the variety, underlining the necessity of in-depth evaluation of these influences to support a sustainable and high-performing viticulture. The present paper aims to analyze the impact of climate change on the 'Fetească Neagră' cultivar grown in two distinct wine regions of southeastern Europe: Murfatlar (Romania) and Codru (Republic of Moldova). The objective is to highlight differences and similarities in the cultivar's response to climatic variations, with a focus on agrobiological traits and enological potential.

MATERIALS AND METHODS

The study was conducted on the red wine grape cultivar *Vitis vinifera* L. cv. 'Fetească Neagră', cultivated in two renowned vineyards: Murfatlar (Romania) and Codru (Republic of Moldova). The vineyard in the Murfatlar wine center was established in 2008, with vines grafted onto the Berlandieri x Riparia rootstock, Oppenheim selection 4, clone 4 (SO4-4). The vine rows are oriented north–south, with a spacing of 2.2 meters between rows and 1.2 meters between vines within the row. The training system used is Guyot, with a trunk height of 0.8 meters and bilateral cordons. The vineyard in the Codru region was established in 2016, using the same rootstock type (SO4-4). The rows are also oriented north–south, with 3.0 meters between rows and 1.5 meters between vines within the row. The training system consists of a trunk height of 70 cm and two lateral cordons, each bearing four fruiting canes pruned to 3–4 buds. Climatic parameters such as maximum temperature, minimum temperature, and precipitation were recorded using automatic weather stations: iMetos 3.3 (Murfatlar) and PTM-48A (Codru). Based on these data, several climatic indices relevant to viticulture were calculated, including the Huglin Index, Winkler Index, and Martonne Index (Serdinescu, 2020). Must parameters, including sugar content (g/L), total acidity (g/L expressed as tartaric acid), and pH, were determined in accordance with standard methods outlined in the OIV Compendium of International Methods of Analysis of Wines and Musts. The correlations between climatic variables and grape quality parameters were evaluated using the Pearson correlation coefficient. The statistical significance level was set at $p < 0.05$, and only significant correlations were considered. To assess the impact of climate change on the Murfatlar (Romania) and Codru (Republic of Moldova) vineyards during the 2015–2024 period, compared to the 2005–2014 interval, a Principal Component Analysis (PCA) was performed. This analysis was conducted using the XLSTAT Add-in for Microsoft Excel, version 15.5.03.3707 (Addinsoft, New York, NY, USA).

RESULTS AND DISCUSSIONS

A comparative analysis of climatic parameters for the Murfatlar (Romania) and Codru (Republic of Moldova) wine regions during the 2015–2024 period, relative to the previous decade (2005–2014), reveals a series of significant climate changes, summarized in Table 1. In both vineyards, a marked increase in annual average temperature (T_{avg}) was observed: $+0.8^{\circ}\text{C}$ in Murfatlar and $+0.93^{\circ}\text{C}$ in Codru, indicating a clear warming trend in the regional climate. Maximum temperature (T_{max}) increased by 0.7°C in Murfatlar and 1.5°C in Codru, reflecting an intensification of extreme heat stress events, which may negatively affect grapevine physiology and, consequently, the quality of production. Minimum temperature (T_{min}) also recorded significant increases: $+7.0^{\circ}\text{C}$ in Murfatlar, suggesting improved overwintering conditions and reduced risks of severe frost, and $+3.8^{\circ}\text{C}$ in Codru, indicating a similar trend. Regarding the average temperature during the vegetative season (GST_{avg}), Murfatlar recorded a slight decrease (-0.8°C), while Codru experienced a moderate increase ($+0.65^{\circ}\text{C}$). These differences demonstrate that while global warming is a general trend, its effects are modulated by local microclimatic conditions. As for precipitation, annual precipitation (AP) showed a sharp decline in Murfatlar (-75.4 mm), while the reduction in Codru was less pronounced. During the growing season, precipitation (GSP) decreased by 23.83% in Murfatlar, whereas Codru registered a slight increase ($+4.3\%$). Seasonal precipitation distribution shows that around 50% of annual rainfall accumulates during the vegetative season in Murfatlar and approximately 65% in Codru. The Winkler Index (WI), which reflects cumulative growing degree days (GDD) from April 1 to October 31, exceeded 2200 units in both regions, placing Murfatlar and Codru in Winkler Region V ($WI > 2220$), characteristic of very warm climates. This climatological classification suggests a potential

imbalance between sugar accumulation and acid retention, with implications for the sensory profile of the resulting wines. The increase in the Heliothermal Index (IH), by +158.6 units in Murfatlar and +116.5 units in Codru, indicates greater solar radiation and thermal intensity, favorable conditions for the biosynthesis of sugar compounds. Likewise, the average values of the Huglin Index (HI) confirm that both vineyards fall within the "very warm" climate class ($2400 < HI \leq 3000$), underscoring the need to adapt viticultural technologies to ensure sustainable production and maintain quality under new climatic conditions. At Murfatlar, the De Martonne Index (IM) dropped from 23.7 in 2005–2014 to 19.2 in 2015–2024, indicating a 4.5-unit decrease. According to the De Martonne classification, these values place the region in the subhumid category; however, the proximity to the lower limit of this class signals a potential transition toward semiarid conditions (Frich et al., 2002). This decline is correlated with the significant reduction in annual precipitation (AP: -75.4 mm) and that of the active vegetation period (GSP: -77.9 mm), alongside a slight increase in average and maximum temperatures. In the Codru vineyard, the decrease in the Martonne Index (IM) was more moderate, from 22.4 to 20.4 (-2 units), keeping the region within the subhumid class. Although a slight increase in both annual precipitation (+12.6 mm) and growing season rainfall (+15.4 mm) was recorded, the rise in maximum temperatures (T.max: +1.5°C and GST.max: +4.1°C) contributes to enhanced evapotranspiration and the onset of moderate water imbalance, potentially affecting the ecophysiological behavior of the grapevine.

Table 1. Climatic parameters recorded in both wine regions, Murfatlar and Codru

Climatic parameters	Murfatlar, Romania			Codru, Republic of Moldova		
	2005-2014	2015-2024	Diff. 2015-2024 2005-2014	2005-2014	2015-2024	Diff. 2015-2024 2005-2014
T.avg	13,9	14,7	0,8	10,92	11,85	0,93
T.max	40,2	40,9	0,7	24,5	26	1,5
T.min	-22	-15	7	-12	-8,2	3,8
GST.avg	22,3	21,5	-0,8	17,61	18,26	0,65
GST.max	32,4	34	1,6	28,5	32,6	4,1
GST.min	-5	-4,5	0,5	-3,5	-1,3	2,2
AP	567,6	492,2	-75,4	541,3	553,9	12,6
GSP	326,8	248,9	-77,9	357,9	373,3	15,4
IW	2272,9	2437,8	164,9	2150,6	2485,1	334,5
HI	2722,6	2881,2	158,6	2655,6	2772,1	116,5
IM	23,7	19,2	-4,5	22,4	20,4	-2

Figure 1 highlights significant phenological changes in the ‘Fetească Neagră’ cultivar during the 2015–2024 period compared to the 2005–2014 interval in both analyzed wine regions. A systematic advancement of the main phenophases is evident, particularly the onset of the growing season—a phenomenon correlated with the rise in average and extreme temperatures. In the Murfatlar wine center, budburst (BBCH 08–09) occurred up to 12 days earlier, with bud development observed as early as the beginning of April. In the Codru region, the shift was less pronounced but maintained the same trend of earlier phenological development. The most substantial advances were recorded in the veraison (BBCH 85) and full maturity (BBCH 89) stages, with a 15–20-day advancement at Murfatlar and 10–14 days at Codru. As a result of these changes, the total length of the growing season was reduced from 210 to 199 days in Murfatlar and from 215 to 199 days in Codru. In both vineyards, an advancement of the phenological calendar and a compression of key stages within the growing season can be observed, particularly during the second half of the cycle (veraison →

harvest). This behavior reflects the influence of higher average and maximum temperatures recorded over the past decade and suggests an accelerated adaptation of the cultivar to the new climatic conditions. This shortening of the growing season has direct implications for determining the optimal harvest time, the chemical composition of the grapes, and, consequently, the quality of the wine. It underscores the need for adjustments in vineyard management practices and oenological strategies tailored to the specific conditions of each region.

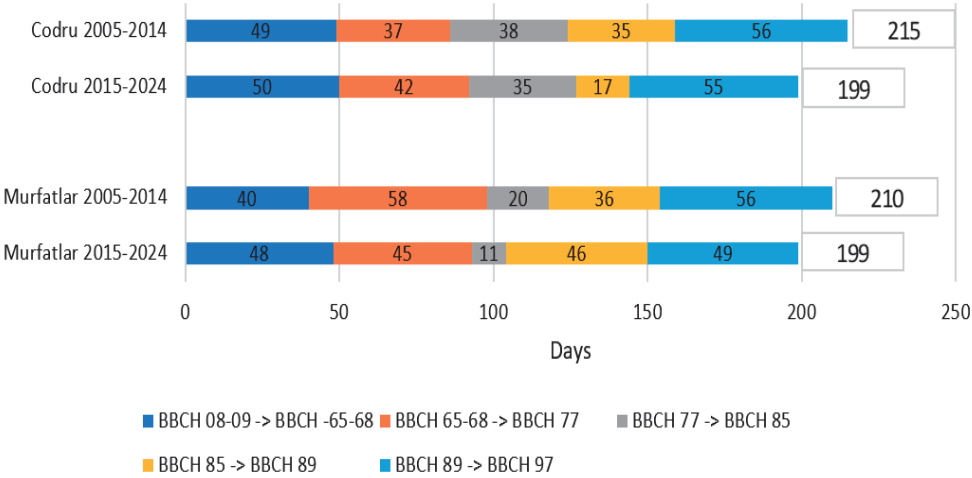


Figure 1. Phenophase development in the Murfatlar and Codru vineyards

The climate-induced changes observed in the Murfatlar and Codru vineyards are directly reflected in the evolution of grape quality parameters, as shown in Table 3. The analyzed parameters—sugar content, total acidity, must pH, and yield per vine—offer valuable insights into the cultivar’s adaptation to new climatic conditions and its oenological potential. Sugar content showed a significant increase in both vineyards: +6.6 g/L in Murfatlar and +8.39 g/L in Codru, correlated with higher temperatures and a shortened vegetative period. These changes are also supported by Jones *et al.* (2022), who describe this phenomenon as one that may lead to wines with higher potential alcohol content. However, such evolution may result in taste imbalances if acidity levels are negatively affected (van Leeuwen and Seguin, 2006). Total acidity showed a slight decrease in both areas: -0.15 g/L in Murfatlar and -0.24 g/L in Codru. This trend is typical for vineyards subjected to warmer and drier summers, conditions that accelerate the degradation of organic acids, particularly malic acid (Teixeira et al., 2018). Changes in must acidity are also reflected in the evolution of pH, which increased visibly by +0.21 in Murfatlar and +0.35 in Codru. This rise indicates a reduction in effective acidity and a possible decline in microbial stability, as a result of accelerated ripening and faster consumption of organic acids (Cholet *et al.*, 2021).

Although pH values remain within acceptable ranges, this trend calls for close monitoring and adjustments in winemaking technology. Yield per vine increased slightly, by +0.1 kg in Murfatlar and +0.15 kg in Codru, which may suggest effective adaptation of the cultivar to the new climatic conditions, as well as optimized cultivation practices and an extended duration of photosynthetically active periods (Bertin *et al.*, 2020).

However, higher productivity does not automatically equate to superior quality, since increased fruit load per vine can dilute aromatic and phenolic compounds, thereby affecting the complexity of the resulting wine (Jackson and Lombard, 2019).

Table 2. Grape quality parameters from both vineyards – Murfatlar and Codru

Quality parameter	Murfatlar, Romania			Codru, Republic of Moldova		
	2005-2014	2015-2024	Difference 2015-2024 2005-2014	2005-2014	2015-2024	Difference 2015-2024 2005-2014
Sugars g/L	216,3	222,9	6,6	210,5	218,89	8,39
Total Acidity g/L tarttric acid	5,02	4,87	-0.15	4,59	4,35	-0.24
pH	3,14	3,35	0,21	3,00	3,35	0,35
Yield/vine (Kg)	1,6	1,7	0,1	1,5	1,65	0,15

The correlation analysis between climatic variables and grape quality parameters for the ‘Fetească Neagră’ cultivar (Table 4) reveals the significant influence of temperature and precipitation on grape quality. Both average and maximum temperatures show strong positive correlations with sugar accumulation and yield per vine, suggesting that a warmer thermal regime promotes physiological processes involved in the synthesis of compounds important for enological purposes. For instance, annual average temperature (T.avg) is highly correlated with sugar content ($r = 0.858$) and yield per vine ($r = 0.818$), indicating a direct relationship between a warmer climate and the productive performance of the grapevine. In contrast, growing season precipitation (GSP) is negatively correlated with these parameters: $r = -0.893$ for sugar content and $r = -0.996$ for must acidity. These results suggest that excessive moisture can dilute the must composition and reduce the qualitative potential of the harvest. This highlights the necessity of achieving a climatic balance between thermal input and rainfall regime to produce grapes with optimal technological traits. Elevated temperatures promote the accumulation of quality parameters, while excessive precipitation may lead to their reduction and, implicitly, to a decrease in the quality of the resulting wine (Jones and Davis, 2000).

Table 3. Pearson correlations between climatic variables and grape quality parameters.

Var	T.avg	T max	GST.avg	AP	GSP	IH	IM	Kg/butuc	Sugars	Total acidity
T.avg	1	0,926	0,990	-0,963	-0,991	-0,977	-0,979	0,818	0,858	0,995
T.max	0,926	1	0,949	-0,970	-0,885	-0,824	-0,852	0,541	0,601	0,922
GST.avg	0,990	0,949	1	-0,951	-0,985	-0,950	-0,973	0,763	0,803	0,996
AP	-0,963	-0,970	-0,951	1	0,918	0,895	0,887	-0,666	-0,724	-0,940
GSP	-0,991	-0,885	-0,985	0,918	1	0,988	0,997	-0,863	-0,893	-0,996
IH	-0,977	-0,824	-0,950	0,895	0,988	1	0,988	-0,923	-0,948	-0,972
IM	-0,979	-0,852	-0,973	0,887	0,997	0,988	1	-0,886	-0,910	-0,988
Kg/Stump	0,818	0,541	0,763	-0,666	-0,863	-0,923	-0,886	1	0,996	0,815
Sugars	0,858	0,601	0,803	-0,724	-0,893	-0,948	-0,910	0,996	1	0,850
Total acidity	0,995	0,922	0,996	-0,940	-0,996	-0,972	-0,988	0,815	0,850	1

**Values in bold are different from 0 with a significance level $\alpha=0.05$*

The principal component analysis (PCA) highlights the impact of climate change on the Murfatlar and Codru vineyards during the 2015–2024 period, in comparison with the previous decade (2005–2014). The first two axes explain 97.23% of the total variability, suggesting an effective discrimination between the analyzed timeframes and regions. On axis F1 (77.40%), thermal variables (T.avg, T.max), pH, sugar content, and yield are strongly associated with Murfatlar 2015–2024, indicating a warmer climate favorable to the rapid accumulation of quality parameters. By contrast, Codru 2015–2024 is influenced by high values of the Heliothermal Index (IH) and growing season precipitation (GSP), suggesting increased water stress and a potential risk of quality degradation in the must.

The regions recorded during the 2005–2014 period are positioned at the opposite end of the spectrum, correlated with more moderate temperatures and thermal indices (e.g., GST.min), reflecting more temperate climatic conditions. This separation clearly illustrates the effects of climate change and its differentiated impact on the technological behavior of the ‘Fetească Neagră’cultivar, thereby justifying the need for adaptive strategies at both the viticultural and oenological levels.

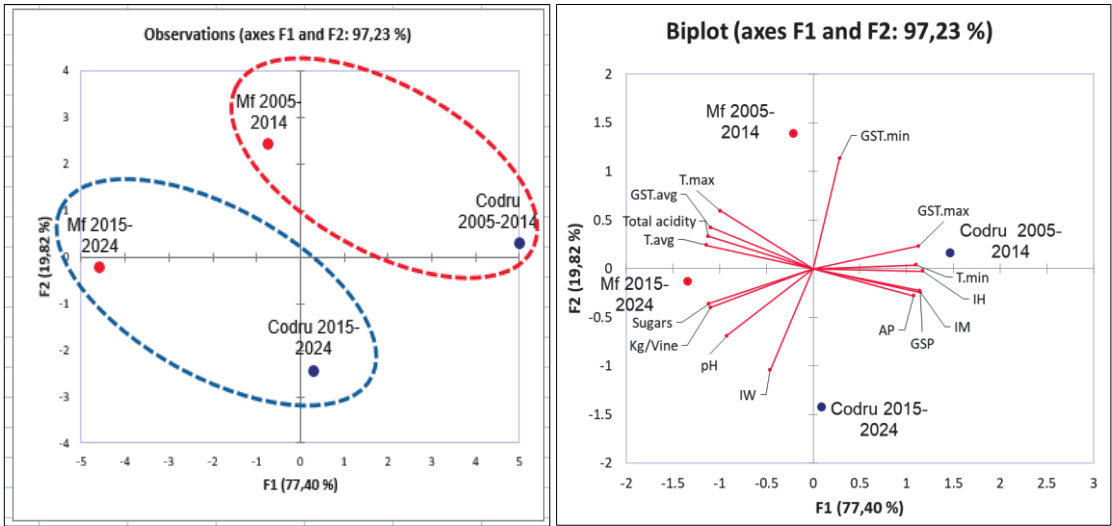


Figure 2. Differentiation of the wine-growing zones (Mf = Murfatlar and C = Codru, along with the analyzed periods 2005–2015 and 2012–2022) based on climatic variables and quality parameters of ‘Fetească Neagră’ grapes.

CONCLUSIONS

The comparative analysis between the Murfatlar and Codru vineyards reveals significant climate changes, marked by increased average and maximum temperatures, along with shifts in precipitation patterns, all of which can influence the quality parameters of ‘Fetească Neagră’grapes. In particular, regions with higher thermal regimes and lower precipitation levels, such as Murfatlar, are experiencing an accelerated ripening process, as well as an increased risk of drought and heat stress. These conditions can directly impact must quality and, consequently, the organoleptic profile of the resulting wine. In contrast, the Codru vineyard, characterized by a more balanced climate and a more even distribution of precipitation, benefits from a more uniform ripening process and a lower risk of damage from extreme climatic factors. These observations suggest that climate change can bring both challenges and opportunities for viticulture. In warmer regions like Murfatlar, it is essential to implement adaptation strategies, such as optimized irrigation management and protection against thermal stress to maintain wine quality. Furthermore, investment in research is necessary to support the development of viticultural and oenological techniques tailored to extreme conditions. Meanwhile, the Codru vineyard, with its more temperate and stable climatic profile, continues to provide favorable conditions for consistent grape ripening and reduced exposure to extreme weather impacts. In conclusion, maintaining the technological and qualitative performance of the ‘Fetească Neagră’cultivar requires adaptation to climate change and the adoption of sustainable vineyard management strategies, especially in light of the accelerated pace of climatic shifts observed in recent decade.

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