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Exotic Vs. Autochthonous Grapevine Varieties – A Case Study on Global Warming in Northeastern Portugal

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Abstract

Grapevines, an economic mainstay of the Douro Demarcated Region, are under increasing stressful conditions and they can suffer further losses due to climate change. Observations on weather patterns and behavior of two autochthonous grapevines and two exotic ones were made over several years. There are indications of an increase of 2°C from 2003 to 2019 responsible for the advancement of 10 to 15 days of phenological events on all grape varieties, a clear biological sign of climate change. Against the forecasted trends, rainfall showed a trend for increasing total amount but a lower proportion during the growing season that resulted in stronger seasonality. The yields of native varieties were about 2600 kg ha⁻¹ higher than exotic varieties, a difference supported by a larger leaf area, on average 1.7 m² higher, and better stomatal conductance in average 2.6 mm s⁻¹ and 2.1 mm s⁻¹ for native and exotic varieties, respectively. These differences suggest that natives are better suited to withstand aggravated environmental conditions than the exotic. The composition of the must show significantly higher total soluble content in autochthonous grapevines but they have a lower concentration of organic acids, tannins, and polyphenols, meaning poorer organoleptic profiles.

Keywords: *Vitis vinifera* L., phenology, yield components, warming temperature, climate change, stressful environment

1. Introduction

Viticulture is an economically important cropping system in many parts of the world and grapevines, a long-lived perennial is useful in bioclimatic studies as an indicator of both historical and contemporary climatic changes. The effect of temperature on grapevines and berry composition is well established and varieties are classified by their thermal requirements [1, 2].

The scientific community has largely accepted that the world climate is changing and the Mediterranean basin is experiencing a climate shift to become warmer and drier [3]. The Joint Research Center, the European Commission's science and

knowledge service, estimates that the average temperatures in the Mediterranean region have risen by 1.4°C since the pre-industrial era, 0.4°C more than the global average and summer rainfall is at risk of being reduced by 10 to 30% in some regions [4]. The Portuguese territory has suffered a decreased precipitation since the 1950s and a significant upward shift in temperature [5, 6]. The Douro Demarcated Region (DDR), located in Northeastern Portugal is classified as a Denomination of Controlled Origin (DOC), the highest Portuguese wine classification, and it has an economic preeminence in the Portuguese wine industry. Few crops are as susceptible to minor changes in climate as vineyards, especially those grown for premium wine quality grapes [7], and any significant change in the Douro environment is likely to affect its economy and social conditions [8].

These trends in weather will affect the grapevine growth and the berry composition:

1. Yield losses due to berry shriveling and sunburn [9]
2. Earlier onset of phenological stages [10, 11]
3. Increment of sugar accumulation and consequent higher alcohol content in wine [9, 12]
4. Organic acids are metabolized faster and their final content in the must will be lower that in turn make the must microbiologically unstable [12]
5. The wine aroma profile is poorer towards overripe [13]

The major abiotic stresses that affect grapevine production in the Mediterranean region are drought, excessive light intensity, and heat [14] all of them present in DDR. Yield losses due to high solar radiation coupled with elevated temperatures are common in DDR and a shift in phenological dates have been already observed [15, 16]. Higher sugar content and low acidity are common characteristics of musts of the region where the addition of tartaric acid during winemaking is necessary to correct their low acidity [17–19].

Effects of climate on grape yield and quality are cultivar-dependent as different grape cultivars grown under common climate conditions still show large variations [20–22]. This diversity helps growers adapt wine grapes to shifting conditions, planting varieties better adapted to current and future climate regimes [23]. However, the introduction and spread of world-renowned varieties in many wine growing regions all over the world has caused a loss of indigenous grapevine varieties traditionally grown and left the farmers with a shrinking pool of genetic variability. In Portugal, there are identified 236 grape genotypes with origin in the country [24]. In 1920, 120 varieties were cultivated in DDR but actually, only 20 varieties dominate the vineyards of the region [25] and a few of them have an exotic origin. The widespread cultivation of world-renowned varieties has caused great losses of indigenous grapevine varieties traditionally grown [26]. Viticulture faces new challenges to respond to consumers' demands and particularly to climate change. Thus, characterization and preservation of this grapevine genetic background prospected, mainly of late-ripening cultivars, is of crucial importance to face alterations in temperature, precipitation, frequency and duration of extreme weather events, and also their resulting abiotic consequences [27].

Touriga Franca and Touriga Nacional are two Portuguese red cultivars very common in DDR were Cabernet Sauvignon and Syrah, two red cultivars of exotic origin, are also planted. Touriga Franca covers 22% of the planted area (IVDP, 2017), it is a hardy variety with good tolerance to heat, high yield and it can produce wines with complex, intense aromas [28]. Touriga Nacional covers about 8% of the planted area, it is also heat tolerant but has a lower yield. Both varieties are grown over a large range of thermal conditions [29] and are two of the most valuable premium varieties to produce quality wines with a unique aroma profile that can fetch high market prices [30, 31].

Cabernet-Sauvignon is now one of the most cultivated wine grapes in the world, about 5% of world vine area, and Syrah occupies about 2.5% [32]. In DDR they are dispersed and represent a small planted area but there is a tendency to increase it. In Australia, Cabernet Sauvignon and Shiraz are reported to be better suited to warmer climates as compared to other exotic varieties [33]. Cabernet Sauvignon tends to produce full-bodied wines with high tannins and noticeable acidity that contributes to the wine's aging potential. Syrah is consistently full-bodied with softer tannins.

During 4 years we followed the development, yield, and must characteristics of Touriga, Nacional, Touriga Franca, Cabernet Sauvignon, and Syrah that were planted just a few meters apart on rainfed plots. The field observations took place at the Eastern end of DDR where the climate conditions during the growing season are semi-arid, with high temperatures and intense solar radiation. In near future, the climate is forecasted to become drier and hotter, and the growers must have clear information on how to adjust their vineyards to face such projected scenarios [34]. The objective was to compare the agronomic performance of exotic to autochthonous grapevine varieties subjected to a stressful environment and predict which ones are better suited to withstand likely aggravated climate conditions.

2. Materials and methods

The vineyard is located at 41.148654 N, 7.127574 W (**Figure 1**), on a rainfed flat land with an Inceptisol Durixerpt 70 to 90 cm deep [35]. The vines (*V. vinifera* L.) are grown in vertical shoot positioning and trellised as simple guyot. Each vine row is about 60 m long, 2 meters apart from each other, and 1 meter between plants of the same row. At full development, the rows formed a continuous hedge kept at a maximum of 170 cm high and 70 cm thick by mechanical trimming. The weeds were mowed between the rows and controlled by very shallow tillage within the row. Four grapevine varieties - Touriga Nacional (TN), Touriga Franca (TF), Cabernet Sauvignon (CS), Syrah (S) – occupy two selected rows on each plot.

An on-site meteorological station provided data from 2003 to the present at 5 minutes intervals averaged over 1 hour. During the same time period, the average dates for each phenological stage [36], computed over all varieties grown in that particular farmstead, were also recorded.

The experiment with the four mentioned varieties took place between 2016 and 2019 and from the start 40 plants of each variety were randomly chosen. Phenological stages [36] were recorded individually on each plant and it was calculated the average date each stage occurred for a given variety. Harvest date was determined by the usual commercial approach when the Brix degree of the must reached the maximum value. As soon as the clusters were visible, one cluster per plant was clearly marked to follow its development from flowering to harvest. At flowering, the number of flowers per cluster was counted using an artificial vision technique [37] and the number of

Figure 1.
DDR location in Northeast Portugal and the experimental site.

berries at harvest was counted manually excluding the shriveled and the sunburnt berries. Every 15 days from flowering to harvest, the total leaf area (tla) per plant was estimated using the reduction of solar radiation crossing the canopy ([38] and the stomatal conductance (g_s - mm s^{-1}) was measured (AP4 porometer, Delta-T Devices, www.delta-t.co.uk) at solar noon on clear sky days on one well-exposed adult leaf out of 10 of the 40 choose plants of each variety. From the clusters harvested, three samples of about 400 g each were set up for laboratory analysis of the must [39]: total soluble solids, titratable acidity, pH, glucose and fructose sugars, malic, and tartaric acids, tannins, polyphenols, and anthocyanins.

The thermal requirements to reach the phenological stages were expressed in Growing Degree Days (GDD), and agroclimatic indicator related to the growth cycle of plants, calculated as [11]:

$$GDD = \sum_{ti}^{tn} (T - Tb)$$

where t_i is the starting day, t_n the final day, T is the average daily temperature, and T_b is the base temperature. The commonly accepted standard T_b in viticulture literature is 10°C [40] a value that was considered adequate for calculating GDD in DDR [15].

The statistical layout was a completely randomized design with two main factors: variety (4) and year (4). Tukey HSD was used for mean separation. The analyses were performed with SPSS statistical package (SPSS for Windows release 20, SPSS Inc. 2011, Chicago).

3. Results

The records of the meteorological station show that air temperature is significantly different ($P \leq 0.05$) among the years (2003 to 2019) and a tendency for a steady rise. Average temperature increased about 2°C in 16 years, a mark that should be reached

only sometime in 2050 according to [41]. The average temperature for the grapevine growing season, Abril to September, did not show a significant difference among years, suggesting that the annual increase is mostly dependent on higher winter temperatures. Nevertheless, the average temperatures of every growing season have been above 21°C, considered the upper limit for producing high-quality wines [42].

Annual precipitation shows a significant augmenting trend that is related to winter precipitation as rainfall during the growing season has shown no significant differences among seasons. However, the number of rainy days (over 1 mm day⁻¹) per year has decreased year after year, suggesting higher rainfall intensities per rain event, a phenomenon that favors runoff at expense of water infiltration and soil water storage that might aggravate water shortages during the drier periods and soil erosion. The rainfall did not follow the prediction for the Mediterranean areas [41] but the lower proportion of precipitation falling during the growing season translates into stronger seasonality [43].

The budbreak (b) took place 70 to 74 days after 1 January (average 71 days) with no significant ($P > 0.05$) differences among varieties and years (**Tables 1** and **2**). Flowering (f) occurred about 10 days earlier for CS and S than for TN and TF. After

Variety	Year	1 Jan to budbreak		Budbreak to flowering		Flowering to veraison	
		d	GDD	D	GDD	d	GDD
CS	2016	69 ^a	67.8 ^a	77 ^a	300.8 ^a	43 ^a	547.5 ^a
S		70 ^a	67.8 ^a	79 ^a	318.9 ^a	42 ^a	567.0 ^a
TN		69 ^a	67.8 ^a	84 ^b	350.4 ^b	44 ^a	625.9 ^b
TF		69 ^a	67.8 ^a	86 ^b	361.9 ^b	41 ^a	586.8 ^b
CS	2017	71 ^a	68.2 ^a	65 ^a	398.5 ^a	51 ^a	911.5 ^a
S		71 ^a	68.2 ^a	67 ^a	415.9 ^a	51 ^a	935.1 ^a
TN		69 ^a	68.1 ^a	76 ^b	484.0 ^b	53 ^a	1005.9 ^b
TF		69 ^a	68.1 ^a	79 ^b	560.5 ^c	51 ^a	976.4 ^b
CS	2018	72 ^a	66.3 ^a	82 ^a	412.5 ^a	43 ^a	551.4 ^a
S		73 ^a	68.9 ^a	82 ^a	416.8 ^a	40 ^a	516.7 ^a
TN		69 ^a	64.1 ^a	94 ^b	481.4 ^b	42 ^a	609.0 ^b
TF		70 ^a	65.9 ^a	91 ^b	459.6 ^b	45 ^a	615.1 ^b
CS	2019	70 ^a	67.4 ^a	84 ^a	417.9 ^a	45 ^a	561.3 ^a
S		73 ^a	67.1 ^a	81 ^a	420.1 ^a	41 ^a	527.6 ^a
TN		70 ^a	65.5 ^a	95 ^b	472.3 ^b	41 ^a	600.1 ^b
TF		70 ^a	64.8 ^a	94 ^b	465.1 ^b	44 ^a	620.2 ^b
	2016	69 ^a	67.8 ^a	75 ^a	333.0 ^a	43 ^a	581.8 ^a
	2017	70 ^a	68.2 ^a	72 ^a	464.7 ^b	42 ^a	557.2 ^a
	2018	71 ^a	66.3 ^a	87 ^b	442.6 ^b	43 ^a	773.1 ^b
	2019	71 ^a	66.9 ^a	88 ^b	470.3 ^b	44 ^a	748.1 ^b

Different superscript letters on the same column and pertaining to varieties grouped by years mean significant difference (Tukey's $HSD_{0.05}$).

Table 1.
Number of days (d) and growing degree days (GDD) to reach a phenological stage until veraison across cabernet sauvignon, Syrah, Touriga Nacional, and Touriga Franca from 2016 to 2019.

Variety	Year	Veraison to harvest		1 Jan to harvest	
		D	GDD	d	GDD
CS	2016	52 ^a	924.3 ^a	241 ^a	1840.5 ^a
S		49 ^a	871.2 ^b	240 ^a	1824.9 ^a
TN		53 ^a	956.0 ^c	250 ^b	2000.1 ^b
TF		51 ^a	921.5 ^a	247 ^b	1938.0 ^b
CS	2017	51 ^a	804.1 ^a	238 ^a	2182.2 ^a
S		52 ^a	818.0 ^a	241 ^a	2237.2 ^b
TN		47 ^a	721.9 ^b	245 ^b	2279.9 ^b
TF		49 ^a	747.0 ^b	248 ^b	2351.9 ^c
CS	2018	49 ^a	805.9 ^a	246 ^a	1836.1 ^a
S		51 ^a	834.1 ^a	246 ^a	1836.5 ^a
TN		48 ^a	779.2 ^b	253 ^b	1933.8 ^b
TF		48 ^a	777.7 ^b	254 ^b	1918.3 ^b
CS	2019	50 ^a	825.3 ^a	249 ^a	1871.9 ^a
S		50 ^a	825.2 ^a	245 ^a	1840.0 ^a
TN		51 ^a	852.1 ^b	257 ^b	1990.0 ^b
TF		49 ^a	849.7 ^b	257 ^b	1999.8 ^b
	2016	51 ^a	718.3 ^a	238 ^a	1700.9 ^a
	2017	50 ^a	772.7 ^b	234 ^a	1862.8 ^a
	2018	49 ^a	799.2 ^b	250 ^b	2081.2 ^b
	2019	52 ^a	854.3 ^b	255 ^b	2139.6 ^b

Different superscript letters on the same column and pertaining to varieties grouped by years mean significant difference (Tukey's HSD_{0.05}).

Table 2. Number of days (d) and growing degree days (GDD) to reach the harvest across cabernet sauvignon, Syrah, Touriga Nacional, and Touriga Franca from 2016 to 2019.

flowering, the length of time to reach any of the next stages was about the same for all varieties. After budbreak, all phenological stages occurred later in 2018 and earlier in 2017 with no significant interaction between year and variety. The longer period of time necessary for TN and TF to reach f and the coincidence of the later stages with periods of warmer weather was conducing to about 100 GDD in excess to S and CS at harvest.

The number of clusters per vine varied between 25 and 28 (average 26) independently of the variety or production year. The vine load is determined by the winter pruning and it was kept at the same level every year as usual commercial practice. The number of flowers per cluster is a variety characteristic (Table 3) and the native varieties TN and TF usually had significantly more flowers per bunch than the exotic ones. A larger proportion of the flowers present at f resulted in a larger number of mature berries for TN and TF than for CS and S. One consequence of a larger number of berries per bunch at harvest is a higher average weight per bunch and increased productivity.

Variety	Year	Num. flowers per cluster	Num. berries per cluster	Avg. weight per cluster (g)	Yield (kg ha ⁻¹)
CS	2016	204.4 ^a	115.5 ^a	140.3 ^a	3416.8
S		182.0 ^b	92.6 ^a	110.5 ^b	2742.1
TN		259.4 ^c	186.9 ^b	176.4 ^c	5049.7
TF		254.1 ^c	174.1 ^b	171.7 ^c	4560.6
CS	2017	123.0 ^a	41.8 ^a	51.2 ^a	1338.5
S		72.5 ^b	55.8 ^a	117.6 ^b	2976.1
TN		156.3 ^c	91.8 ^b	139.2 ^c	4227.6
TF		115.7 ^c	75.2 ^c	133.8 ^c	3846.0
CS	2018	116.9 ^a	86.5 ^a	104.6 ^a	2558.9
S		72.9 ^b	33.7 ^b	41.3 ^b	970.9
TN		162.1 ^c	146.9 ^c	222.5 ^c	6410.2
TF		202.3 ^d	160.4 ^d	241.5 ^c	5982.5
CS	2019	130.2	57.1	88.7	2335.0
S		85.4	48.3	52.6	2178.1
TN		170.8	151.8	227.8	5762.5
TF		198.2	181.6	190.3	4098.4
	2016	250.0 ^a	109.8 ^a	149.3 ^a	3942.3
	2017	119.0 ^b	81.2 ^b	110.5 ^b	2847.1
	2018	129.4 ^b	106.9 ^a	152.5 ^a	3980.6
	2019	131.8 ^b	115.7 ^a	161.8 ^a	4021.9

Different superscript letters on the same column and pertaining to varieties grouped by years mean significant difference (Tukey's HSD_{0.05}).

Table 3.
Mean separation of a number of flowers at flowering and berries at harvest per cluster, cluster weight, and yield per hectare (extrapolated average) across cabernet sauvignon, Syrah, Touriga Nacional, and Touriga Franca from 2016 to 2019.

The higher productivity of native varieties is supported by a larger canopy, more leaf area in total (**Tables 4 and 5**), and a higher stomatal conductance that might increase the photosynthetic rate. The canopies reached their largest development a few days after veraison, 4 to 5 m² for TN and TF and 2 to 3 m² for CS and S. Stomatal conductance decreased from flowering to harvest ranging from 3.47 to 1.47 mm s⁻¹.

The composition of the must show significant differences between the native and the exotic varieties (**Tables 6 and 7**). TF and TN had higher total soluble content (higher °Brix) that is related to higher sugar (glucose and fructose) concentration. On other hand, the concentration of organic acids (malic and tartaric) and of tannins and polyphenols are higher in must of S and CS. Titrable acidity and pH showed no significant differences among varieties or they were of no enological significance. It was found significant differences in total anthocyanin but no clear distribution among the varieties.

Variety	Year	Flowering		Midterm		Veraison	
		tla (m ²)	g _s (mm s ⁻¹)	tla (m ²)	g _s (mm s ⁻¹)	tla (m ²)	g _s (mm s ⁻¹)
CS	2016	2.48 ^a	3.01 ^a	2.61 ^a	2.59 ^a	2.74 ^a	2.11 ^a
S		2.24 ^a	3.04 ^a	2.35 ^a	2.68 ^a	2.47 ^a	2.08 ^a
TN		4.40 ^b	3.99 ^b	4.75 ^b	2.87 ^b	5.11 ^b	2.56 ^b
TF		3.40 ^c	3.87 ^b	3.92 ^c	2.98 ^b	4.06 ^b	2.68 ^b
CS	2017	2.21 ^a	3.11 ^a	2.42 ^a	2.87 ^a	2.62 ^a	2.54 ^a
S		2.10 ^a	3.13 ^a	2.38 ^a	2.97 ^a	2.45 ^a	2.50 ^a
TN		3.52 ^b	3.88 ^b	3.89 ^b	3.02 ^a	4.86 ^b	2.80 ^b
TF		2.65 ^b	3.85 ^b	3.09 ^c	3.24 ^b	3.71 ^c	2.91 ^b
CS	2018	2.59 ^a	3.20 ^a	3.03 ^a	2.79 ^a	3.38 ^a	1.82 ^a
S		2.75 ^a	3.35 ^a	2.74 ^b	2.87 ^a	2.93 ^b	1.72 ^a
TN		4.85 ^b	3.57 ^b	4.87 ^c	2.99 ^a	5.37 ^c	2.56 ^b
TF		3.96 ^c	3.63 ^b	4.05 ^d	2.86 ^a	4.11	2.56 ^b
CS	2019	2.40 ^a	3.21 ^a	2.54 ^a	2.64 ^a	2.78 ^a	2.06 ^a
S		2.63 ^a	3.15 ^a	2.61 ^a	2.51 ^a	2.80 ^a	2.15 ^a
TN		4.06 ^b	3.62 ^b	4.29 ^b	2.89 ^b	4.41 ^b	2.55 ^b
TF		4.14 ^b	3.58 ^b	3.87 ^b	3.10 ^b	3.87 ^b	2.81 ^b
	2016	3.13 ^a	3.48 ^a	3.34 ^a	2.78 ^a	3.56 ^a	2.36 ^a
	2017	2.62 ^b	3.49 ^a	2.94 ^b	3.03 ^b	3.41 ^a	2.69 ^b
	2018	3.54 ^c	3.44 ^a	3.67 ^c	2.88 ^a	3.95 ^b	2.14 ^c
	2019	3.45 ^c	3.41 ^a	3.14 ^d	2.99 ^a	3.74 ^b	2.29 ^a

Different superscript letters on the same column and pertaining to varieties grouped by years mean significant difference (Tukey's HSD_{0.05}).

Table 4.
Mean separation of total leaf area (tla) and stomatal conductance (g_s) from flowering to veraison across cabernet sauvignon, Syrah, Touriga Nacional, and Touriga Franca from 2016 to 2019.

Variety	Year	Midterm		Harvest	
		tla (m ²)	g _s (mm s ⁻¹)	tla (m ²)	g _s (mm s ⁻¹)
CS	2016	2.80 ^a	1.56 ^a	2.80 ^a	1.21 ^a
S		2.50 ^a	1.55 ^a	2.50 ^a	1.23 ^a
TN		5.31 ^b	1.86 ^b	5.36 ^b	1.59 ^b
TF		4.06 ^b	1.78 ^b	4.07 ^c	1.50 ^b
CS	2017	2.54 ^a	1.59 ^a	2.35 ^a	1.32 ^a
S		2.40 ^a	1.68 ^a	2.16 ^a	1.40 ^a
TN		4.83 ^b	2.42 ^b	4.72 ^b	2.01 ^b
TF		3.50 ^c	2.48 ^b	3.36 ^c	1.75 ^c
CS	2018	3.22 ^a	1.26 ^a	2.94 ^a	1.05 ^a
S		2.97 ^a	1.41 ^b	2.90 ^a	1.12 ^b
TN		5.35 ^b	2.01 ^c	5.26 ^b	1.98 ^c
TF		4.80 ^c	1.79 ^c	4.56 ^c	1.51 ^c

Variety	Year	Midterm		Harvest	
		tla (m ²)	g _s (mm s ⁻¹)	tla (m ²)	g _s (mm s ⁻¹)
CS	2019	2.76 ^a	1.39 ^a	2.61 ^a	1.29 ^a
S		2.72 ^a	1.42 ^a	2.72 ^a	1.14 ^a
TN		4.36 ^b	2.05 ^b	5.00 ^c	1.75 ^b
TF		4.28 ^b	2.12 ^b	4.15 ^b	1.65 ^b
	2016	3.67 ^a	1.69 ^a	3.68 ^a	1.38 ^a
	2017	3.32 ^b	2.04 ^b	3.15 ^b	1.62 ^b
	2018	4.08 ^c	1.62 ^a	3.91 ^c	1.42 ^a
	2019	3.78 ^d	1.75 ^a	3.51 ^a	1.37 ^a

Different superscript letters on the same column and pertaining to varieties grouped by years mean significant difference (Tukey's HSD_{0.05}).

Table 5.
Mean separation of total leaf area (tla) and stomatal conductance (g_s) at midterm between veraison and harvest and at harvest across cabernet sauvignon, Syrah, Touriga Nacional, and Touriga Franca from 2016 to 2019.

Variety	Year	°Brix	Titrateable acidity (mg L ⁻¹)	pH	Glucose (g L ⁻¹)	Fructose (g L ⁻¹)
CS	2016	25.2 ^a	3.69 ^a	3.90 ^a	113.25 ^a	84.06 ^a
S		25.1 ^a	3.69 ^a	3.15 ^a	117.36 ^a	82.70 ^a
TN		26.5 ^b	3.30 ^b	3.85 ^a	133.21 ^b	100.69 ^b
TF		26.8 ^b	3.40 ^b	3.86 ^a	135.85 ^b	99.01 ^b
CS	2017	22.3 ^a	3.98 ^a	3.90 ^a	105.98 ^a	75.56 ^a
S		21.6 ^b	3.94 ^a	4.20 ^a	108.79 ^a	73.68 ^a
TN		24.5 ^c	3.89 ^a	3.85 ^a	115.60 ^b	90.15 ^b
TF		24.2 ^c	3.87 ^a	3.77 ^a	118.44 ^b	87.75 ^b
CS	2018	23.6 ^a	3.87 ^a	3.88 ^a	109.02 ^a	79.90 ^a
S		23.4 ^a	3.13 ^b	4.13 ^a	105.60 ^a	77.29 ^a
TN		24.6 ^b	3.79 ^a	3.88 ^a	130.10 ^b	92.49 ^b
TF		25.4 ^c	3.95 ^a	3.86 ^a	127.92 ^b	89.86 ^b
CS	2019	23.8 ^a	3.17 ^a	3.83 ^a	106.21 ^a	80.15 ^a
S		24.0 ^a	3.83 ^a	3.91 ^a	110.65 ^a	78.25 ^a
TN		25.1 ^b	3.59 ^a	3.98 ^a	128.22 ^b	95.68 ^b
TF		25.6 ^b	3.57 ^a	3.81 ^a	131.58 ^b	91.26 ^b
	2016	25.9 ^a	3.52 ^a	3.69 ^a	124.92 ^a	91.62 ^a
	2017	23.2 ^b	3.92 ^b	3.93 ^a	112.20 ^b	81.79 ^b
	2018	24.2 ^c	3.69 ^c	3.94 ^a	118.16 ^b	84.88 ^b
	2019	25.0 ^c	3.65 ^c	3.91 ^a	121.20 ^c	85.90 ^b

Different superscript letters on the same column and pertaining to varieties grouped by years mean significant difference (Tukey's HSD_{0.05}).

Table 6.
Mean separation of must characteristics (Brix, acidity, pH and sugars) across cabernet sauvignon, Syrah, Touriga Nacional, and Touriga Franca from 2016 to 2019.

Variety	Year	Malic acid (g L ⁻¹)	Tartaric acid (g L ⁻¹)	Total tannins (mg berry ⁻¹)	Total polyphenols (mg berry ⁻¹)	Total anthocyanins (mg berry ⁻¹)
CS	2016	1.20 ^a	4.21 ^a	8.59 ^a	266.0 ^a	2.26 ^a
S		1.23 ^a	4.32 ^a	9.15 ^a	303.0 ^a	2.78 ^b
TN		1.16 ^a	3.65 ^b	5.69 ^b	212.0 ^c	2.02 ^c
TF		1.17 ^a	3.80 ^b	6.81 ^b	237.0 ^{ac}	2.16 ^c
CS	2017	1.31 ^a	3.63 ^a	6.95 ^a	224.0 ^a	1.89 ^a
S		1.32 ^a	3.70 ^a	7.85 ^a	271.0 ^b	2.47 ^b
TN		1.24 ^a	3.08 ^a	7.01 ^a	238.0 ^a	2.11 ^c
TF		1.26 ^a	3.10 ^a	6.86 ^a	255.0 ^{ab}	2.55 ^b
CS	2018	2.18 ^a	3.46 ^a	7.40 ^a	240.0 ^a	2.07 ^a
S		2.26 ^a	3.71 ^a	8.22 ^b	275.0 ^b	2.47 ^b
TN		1.85 ^a	2.50 ^b	6.76 ^c	229.0 ^c	2.00 ^a
TF		1.93 ^a	2.31 ^b	6.86 ^c	240.0 ^a	2.18 ^a
CS	2019	1.78 ^a	3.96 ^a	7.99 ^a	251.6 ^a	2.12 ^a
S		2.01 ^a	3.78 ^a	8.54 ^a	278.2 ^b	2.59 ^b
TN		1.98 ^a	2.87 ^a	6.49 ^b	240.1 ^a	2.09 ^a
TF		1.89 ^a	2.56 ^a	6.51 ^b	248.7 ^a	2.11 ^a
	2016	1.19 ^a	3.98 ^a	7.56 ^a	254.5 ^a	2.31 ^a
	2017	1.28 ^a	3.35 ^b	7.17 ^b	247.0 ^b	2.26 ^a
	2018	2.06 ^b	2.98 ^c	7.31 ^c	246.0 ^b	2.18 ^b
	2019	1.31 ^a	2.65 ^d	7.28 ^c	256.4 ^a	2.21 ^b

Different superscript letters on the same column and pertaining to varieties grouped by years mean significant difference (Tukey's HSD_{0.05}).

Table 7.
Mean separation of must characteristics (organic acids, tannins and phenols) across cabernet sauvignon, Syrah, Touriga Nacional, and Touriga Franca from 2016 to 2019.

4. Discussion

The trend for higher temperatures from 2003 to 2019 was already observed in the period 1980 to 2009 in the DDR and its correlation with earlier phenological events was statistically significant [15] as it was also reported by other authors [10, 21, 44]. Shifts in phenology are a clear biological signal of climate change [45]. Although the observed pattern of precipitation from 2003 to 2019 is not aligned with the predictions for the Mediterranean, the tendency for higher rainfall intensity during winter might aggravate the drought stress during summer because infiltration and soil water storage might be negatively affected. Drought associated to elevated temperatures can cause photoinhibition, increase the reduction of growth, yield and alter the berry composition [20, 46].

Budbreaking occurred 71 days after 1 January, with no significant difference among the four varieties, and it was very similar with the occurrence between 2003 to 2019. Flowering was shifting to earlier dates from the first days of June to late May that is consistent with the observation in DDR and other wine regions of the world

[15, 47, 48], however, the two exotic varieties CS and S flowered about 10 days earlier than TN and TF and the late ones need higher temperature accumulation (GDD) to start flowering. The date for the posterior phenological event was set by the flowering date as the time span for reaching the next stage was the same for every variety, either exotic or autochthonous, but always later for TN and TF and the associated GDD was necessarily larger because the average temperatures were progressively higher till earlier August. Climate alone does not explain all phenological variation as different grape cultivars grown under similar conditions still show large variations in the timing of different events [21]. The number of days and the GDD necessary to complete the growing cycle of these four varieties were close to the figures reported by other authors but TN and TF can grow over a wider range of thermal conditions that favors their adaptability to different climatic conditions [29, 49–51].

Commercial practice on winter pruning sets the number of potential developed inflorescences to an equal value, independently of grape variety, but the number of flowers per inflorescence is determined by genetics and environmental factors [52]. In this experiment all plants were subjected to the same environment, thus it is reasonable to assume that the lower number of flowers per inflorescence in SC and S than in TN and TF is a varietal characteristic and it has a large influence on fruit setting [47]. Fruit set also increases with larger leaf area [53], a phenomenon recorded, that together with cluster number accounts for about 90% of grapevine yield variation [54]. The higher yields obtained by TN and TF over SC and F are consistent with these facts. However, the positive influence of higher temperatures on fruit set [53] was not observed as the number of flowers per inflorescence and the yields were lower in 2017 the hottest year; other factors are at play that could not be determined in this experiment.

The higher productivity of TN and TF were supported by their larger total leaf area and superior stomatal conductance. As the envelope volume of the canopies were limited by mechanical trimming, tla was related to the number of leaves, eventually their size (not measured), which was larger for TN and TF. Low g_s reduce the amount of CO_2 available impairing the photosynthetic rate [55] and together with smaller leaf area probably results in a lower photosynthetic capacity for SC and S comparatively to TN and TF which can partially explain better yields for the regional varieties. The mechanistic adaptation of grapevines varieties to summer stress is mediated by the stomatal sensitivity and the anisohydric cultivars, like TN, are better adapted than iso- or near-isohydric ones, like Syrah, because they can maintain high values of g_s regardless of their water status [13, 14]. However, there is no consensus among innumerable authors about the classification of each variety regarding their water stress behavior and the same variety can have both iso- and anisohydric stomatal responses to water deficits [56].

Temperature displays various effects on the physiology of the grapevine fruit. High temperatures accelerate organic acids breakdown [57], a decrease in anthocyanins with possible variations in acylation in red-berry cultivars [58] that are associated with changes in aromatic potential [12]. Moderate warming favors soluble solids concentration (mostly primary sugars) [59] whereas very high temperatures can impede sugar accumulation [57].

All varieties show a similar effect of organic acids degradation by elevated temperatures as a far below the value of titratable acidity from the preferable 6 to 7 mg L⁻¹ equivalent of tartaric acid for producing high-end wines [60]. The lack of must acidity has to be corrected in the winery by the addition of tartaric acid, a common commercial practice.

Soluble solids concentration is high, about 21 to 27°Brix [61], given the concentration of primary sugars, glucose, and fructose, as it is expected from a warm climate.

TN and TF accumulated more primary sugars than SC and S resulting in higher °Brix. From the financial perspective of the growers, higher °Brix is a clear advantage because the berry prices vary proportionally to sugar content; in addition, TN and TF have better yields making them a more attractive crop. However, SC and S retain a better organoleptic profile as their tannins and polyphenols reach higher concentrations at harvest. Under prevailing conditions during the duration of the experiment, the temperature threshold for reduced accumulation of soluble solids was not yet reached as the Brix at harvest is still high.

Must pH display values commonly found with no significant differences among the four varieties and a relationship between pH and genetic makeup of the grapevine was never established [61]. The anthocyanins concentration showed no clear distribution among the cultivars although their actual values might reflect the reduced capacity for their synthesis under the observed temperatures [61] but other authors report that temperature does not modify anthocyanins concentration [20].

The results suggest clearly that the effect of climate on grape yield and quality is cultivar-dependent as reported [20]. Some authors mention that most of the differences in the composition of individual fruit at harvest can be related to differences in the date of flowering [47], a phenomenon observed here when local varieties flowered about 10 days earlier than exotic ones, thus later berries would develop under different weather conditions.

Autochthonous varieties might have high adaptability because they are grown over a large range of thermal conditions [29] providing adequate water supply [62]. Thus, rainfed viticulture might not be possible in a near future given that the actual conditions during the Mediterranean summer that are already severe water-stressed [63] and increased stress is forecasted.

5. Conclusions

Observed weather conditions over several years coupled with reports by other authors clearly indicate a climate shift towards a more stressful environment in the DDR as annual temperature increased 2°C in 16 years. However, total annual precipitation increased contrary to the general predictions but it was due to higher rainfalls only in winter that favors runoff at expense of infiltration. The phenological advance of grapevines was imparted mostly by the advance of about 10 to 15 days in flowering and it is an unmistakable biological signal of climate change which has also altered the composition of the fruits. Autochthonous varieties have rendered results that suggest a better adaptation to temperature stress-producing higher yields, about 2000 kg ha⁻¹ higher, and concentrations of sugars that are economically important, about 1.5 to 2°Brix higher, than exotic cultivars. However, the exotic varieties, so far, have kept a better organoleptic profile with higher concentrations in berries of malic and tartaric acids, total tannins, and total polyphenols. Given the predicted increase in stressful conditions in a near future, new plantations with autochthonous varieties will be more likely to withstand coming shifting conditions but, probably, only with irrigation.

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Declaration of interests

The authors declare no conflict of interests or any undue benefit from the present work.

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