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Viticulture in Warmer Climates: Mitigating Environmental Stress in Douro Region, Portugal

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Abstract

There is evidence that temperatures all over the planet are increasing slowly but steadily. The projections for the Mediterranean basin indicate a strong warming and decreased precipitation, especially in summer, and they are not favorable for agriculture in general and, in particular, for viticulture, which is a very climate-sensitive system. The vineyards of Douro Demarcated Region, located in the northeastern Portugal, are grown in marginal conditions, and the expected daily higher temperatures and decreased rainfall are bound to affect the yield and wine quality. Touriga Nacional and Tinta Roriz are two of the most valuable varieties for high-end wines of Douro, and they were subjected to a number of experiments on mitigation techniques to counteract the worse effects of adverse weather conditions. Irrigation, canopy shading, water nebulization, and kaolin coating can mitigate the losses caused by increasing stressful conditions, but they have detrimental effects on some wine characteristics. They even might not be sufficient to protect the already producing vineyards from aggravated weather conditions.

Keywords: viticulture, temperature stress, water stress, irrigation, canopy management, cooling techniques, climate change

1. Introduction

Today there is a large consensus that the earth's average temperature has been increasing slowly but steadily. The planet's average surface temperature has risen about 1.1°C since the late nineteenth century, and most of the warming occurred in the past 35 years; 2016 was the warmest year on record and every month from January through September, except for June, which was the warmest on record for those respective months [1]. Both projections from general circulation and regional climate models show that Southern Europe and the Mediterranean basin will experience strong warming and decreased precipitation,

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especially in summer, and more frequent and longer extreme climate events such as heat waves and prolonged drought [2, 3].

Such scenarios are not favorable for agriculture for an economic activity dependent upon and deeply connected to climate and weather. The cultivation of grapevines (*Vitis vinifera*), the fruit in Europe that is primarily used for winemaking and is a climate-sensitive agricultural system that has been used as an indicator of both historic and contemporary climate change [4]. Despite adaptation of *Vitis vinifera* to a wide range of climatic conditions, individual varieties, in particular premium wine grapes, have narrow climate ranges making the system very susceptible to minor changes in climate [5, 6]. Climate, especially air temperature, together with soil properties are considered the most important factors in defining the suitability of an area for wine production, affecting physiological behavior of the grapevine, the phenological phases of vine, the formation and maturity of the berry and its chemical changes, and finally, the characteristics of wines produced in a particular area [7, 8].

Portugal is expected to face aggravated weather conditions in coming years because the territory has suffered a pronounced decrease in precipitation in the spring, in particular in March, since the early 1950s [9] while a warming trend has been observed revealing a significant increase in extreme heat events for both spring and summer seasons, and a decrease in extreme cold events in winter [10]. All Portuguese wine regions are expected to experience an upper shift in temperature and lower precipitation. The Douro Demarcated Region (DDR), located in the northeastern Portugal, is classified as a Denomination of Controlled Origin (DOC), the highest Portuguese wine classification, given its distinctive climatic, topographic, and soil characteristics. It is of particular concern given its economic preeminence in Portuguese wine industry. Its strong Mediterranean climate influence shows the typical variability in precipitation along with high evapotranspiration during summer, the factors that limit grapevine development, yield, and quality components [11]. In these regions, meteorological averages from the period 1950–2000 show that during active vine development from April to September, rainfall varies from 190 to 326 mm but as low as 50 to 85 mm during the ripening stage (from July to September) coupled with high temperatures and intense solar radiation that give rise to very stressful conditions, particularly in the eastern end of the region (Alto Douro) [12] where grapevines can be subjected to a difference between evapotranspiration and precipitation as high as 730–750 mm from bud break to harvest [13]. Under these conditions, vineyards of DDR are, in general, grown in marginal conditions for agriculture production [14] that contribute to large fluctuations in interannual production and low yields averaging 30 hl ha^{-1} of wine well below the legal limit of 55 hl ha^{-1} permitted for DOC wine [12]. The expected higher daily temperatures and decreased rainfall [15] are bound to affect yield and wine quality.

Similar trends were observed in other wine regions worldwide where average temperatures have increased by 1.7°C during the growing seasons since 1950 and are expected to rise by an average of 2°C by 2050 leaving some regions at or near their optimum growing-season temperatures [16]. There are forecasts of further warming in Greek wine regions, pushing some of them past suitability for viticulture [17]. Three wine regions of the Northeastern Spain (Alt Penedès, Priorat, and Segrià) have experienced, from 1952 to 2006, overall growing-season warming of

1.0 to 2.2°C, while precipitation during the bud break to veraison period declined significantly, indicating more intense soil moisture stress during this critical growth stage [10].

Facing the most likely scenarios of climate change, wine farmers must adapt strategies to continue producing quality wines and to preserve their typicity from each growing location [18]. As a perennial crop, grapevines require a few years to reach maturity and can remain economically productive for several decades; thus, adaptation strategies must account for both short- and long-term impacts of a shifting environment. Perennial practices, such as choice of the planting site, choice of grapevine and rootstock variety, and vineyard layout, must be decided prior to planting. For those vineyards already under production, winegrowers will have to adapt using suitable short-term mitigation strategies [19], such as irrigation, canopy management, and cooling techniques.

2. Weather conditions in Alto Douro

Alto Douro has a total area of 120,000 ha with an average elevation of 420 m, but the best prized vintages are produced at lower elevations where records for the period 1950–2000 show an annual precipitation ranging from 600 to 800 mm, but only 200 to 300 mm occur during the growing season from April to October, while annual temperatures ranged between 14 and 16°C and growing season oscillated from 19 to over 21°C [20]. Located in Alto Douro, close to Douro river (41° 08′ North, 7° 08′ West), some mitigation techniques have been experimented to protect *Vitis vinifera* cv Touriga Nacional and cv Tinta Roriz (Syn. Aragonêz, Tempranillo) from intense abiotic stresses that might prove useful under more extreme conditions eventually brought about by climate change.

Touriga Nacional is one of the most valuable premium varieties of DDR. It is considered one of the best red varieties to produce quality wines with a unique aroma profile that can fetch high market prices [21]. It has good adaptation to environmental stresses, withstanding high light intensities that allow for better adjustment to warm conditions, provided an adequate water supply [22]. Tinta Roriz can be cultivated in a variety of soils and climatic conditions, because it resists well to moderate drought. It has a thick-skinned berry with a high anthocyanin concentration that makes for deep-colored wines with moderate tannins and moderate acidity. It provides some of the best red wines of Portugal and Spain [23, 24]. Despite Touriga Nacional and Tinta Roriz good adaptability, they can suffer serious yield losses under unfavorable weather conditions. An on-site automatic weather station provided records for the period 2004 to 2016 (**Table 1**). Average annual temperature was 16.1 and 21°C for the growing season, whereas total precipitation was 594 mm annually with 284 mm for the growing season. Calculated reference evapotranspiration (ET_0) [25] averaged 1946.8 mm a year, mostly occurring during the growing season (1631.3 mm) creating an imbalance between ET_0 and rainfall of 1349.3 and 1321.4 mm annually and for the growing season, respectively. Temperature was higher and rainfall was lower than the average values recorded for Alto Douro during the period 1950–2000. The average temperature for the growing season is already at the upper limit that is considered adequate for quality wine grape production [26].

	Rad (Kw m^{-2})	T (°C)	R (mm)	ET$_0$ (mm)
Annual	1757.8	16.1	594.0	1946.2
Nov–Mar	346.8	9.2	309.9	315.6
Apr–Oct	1411.0	21.0	284.2	1631.3

Table 1. Total solar radiation (rad), air temperature (T), precipitation (R), and reference evapotranspiration (ET$_0$) averages for the period 2004–2016 at location in Alto Douro 41° 08′ North, 7° 08′ West (on-site meteorological station).

2.1. Mitigation techniques in Alto Douro

2.1.1. Irrigation

Historically, vineyards of DDR in general and Alto Douro in particular are water stressed during the growing season, given the high atmospheric demand and the scarcity of rainfall that limits the soil water (SW) availability. SW has a complex relationship with air temperature that, when it rises, increases vapor pressure deficit, and more water is evapotranspirated from the soil; eventually, water availability becomes critical. In [27], SW will be the limiting resource in vineyards of Douro and it will become relatively more important than temperature for maintaining grapevine production. A model of SW annual distribution in Douro valley shows a sinusoidal pattern (**Figure 1**) that is consistent with temperature and rainfall distributions [28].
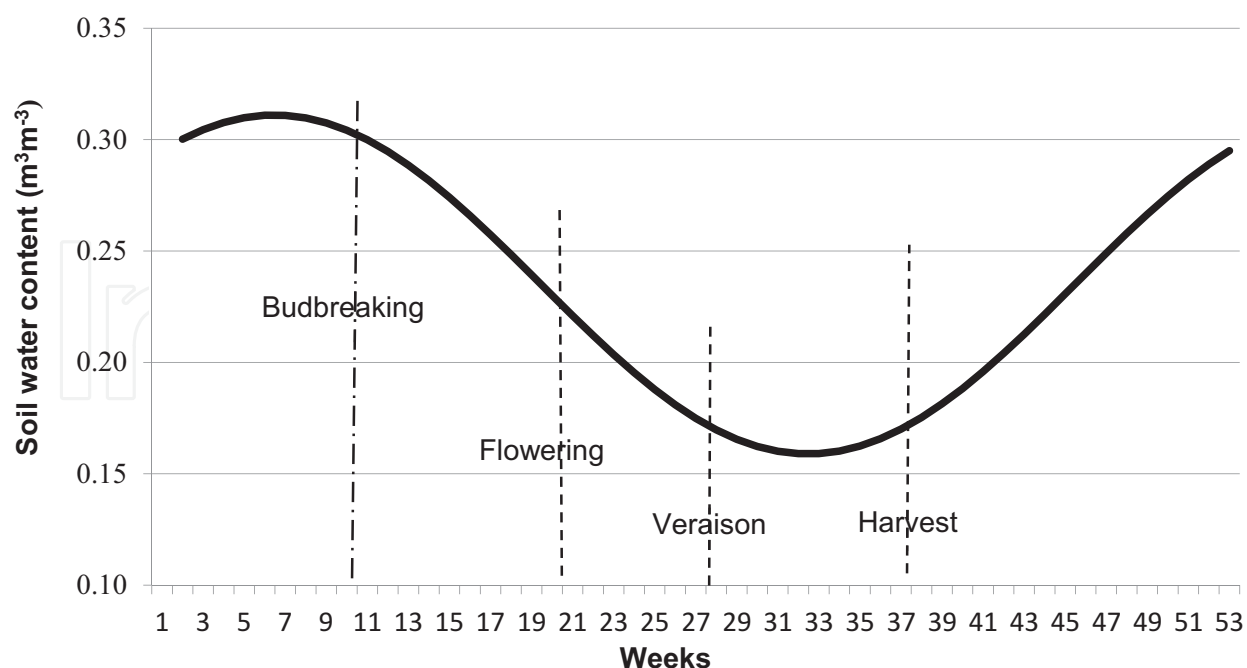

Figure 1. Time frequency (Fourier series) generated data of soil water content (m^3 m^{-3}) based on 364 historical observations from 1991 to 1997 and annual occurrence of main phenological stages of the grapevines: bud breaking, flowering, veraison, and harvest. (Adapted from Oliveira [28]).

The time frequency generated data in **Figure 1** shows that the minimum SW content is lower than the permanent wilting point (0.19), bringing the SW content of the important period from flowering to veraison to a critical level when irrigation will be most useful. As climate becomes warmer, grapevines in Douro show a clear tendency toward earlier phenological events [18, 29] a phenomenon also observed in Touriga Nacional and Tinta Roriz for the period 2004–2016, and in 2017, flowering occurred about 15–20 days earlier than usual across Alto Douro according to empirical observations. Earlier events could overlap with periods of higher SW content, but ripening might also occur in time of higher temperatures that are detrimental to quality [30, 31]. As rainfall is expected to diminish, SW will become scarcer and a short growing season might not bring any benefit. Under present conditions, rainfed vineyards in Alto Douro produce as little as 0.7 kg per plant and even less in drier years [32], not enough to cover production costs. Irrigation is then essential to ensure a stable production and minimize the risk of drought damage [33]. Experimental fields were set up in DDR to study the effects of irrigation in grapevines [32–35]. The main experimental field was a 2.5-hectare commercial vineyard (*Vitis vinifera* cv. Tinta Roriz) where six treatments comprising three adjacent grapevine rows each, 120 plants per treatment, laid out in a random design pattern and trained to a vertical shoot position (VSP). Each grapevine row had its own drip irrigation line and they were nonirrigated, irrigated from flowering to veraison at rates of 4 (total of 160 mm) and 8 mm a day (total of 320 mm), irrigated from veraison to commercial maturation at rates of 4 (total of 225 mm) and 8 mm a day (total of 450 mm), and irrigated from flowering to commercial maturation at a rate of 8 mm a day (total of 720 mm). Water use efficiency (WUE) was calculated as the ratio between a given parameter (*X*) and crop evapotranspiration (*Ec*) [36].

$$WUE = X/Ec \tag{1}$$

Ec was determined by soil water balance [37, 38] using SW data measured with TDR probes.

$$\left(h_i - h_{i-1}\right) = (P + I) - (Ec + R + D) \tag{2}$$

where *h* is the soil water storage at measurement time *i* and at preceding measurement time *i*-1, *P* is precipitation, *I* is irrigation, *Ec* is the water used by plant transpiration plus evaporation from soil, *R* is the surface run-off, and *D* is the soil drainage below the root zone (all units in mm). *R* and *D* can be safely ignored because low SW content and sparse precipitation during growing season, conditions similar to those found by other authors [39, 40].

At commercial harvest, three samples were collected from every treatment for laboratory analysis; each sample was a composite of berries collected from 10 randomly chosen grapevines (18 analyses repeated over 3 years).

Irrigation caused a significant increase in yield (**Table 2**) due to larger berries, rather than to a greater number of clusters or berries per cluster, and simultaneously, the compounds related to must quality (color, aroma, and soluble solids) were either diluted or their amount significantly reduced compared with musts from rainfed plants. On the other hand, there were no significant differences in pH, free anthocyanins, and total flavonols.

Irrigation (mm)	Ec (mm)	Y (g plant^{-1})	TSS (°Brix)	TA (g L^{-1})	TAc (g L^{-1})	MAc (g L^{-1})
0	193	721^a (3.7^a)	30^a (1.5^a)*	2.3^a(1.2^a)**	6.6^a(2.3^a)**	1.5^a(0.8^a)**
160	302	1002^b (3.3^b)	28^b (0.9^b)*	2.4^b(0.8^b)**	6.5^a(2.1^b)**	2.2^c(0.7^b)**
320	522	1003^b (1.9^c)	26^c (0.5^c)*	2.7^c (0.5^c)**	6.5^a(1.2^c)**	2.7^e(0.5^c)**
225	308	865^c (2.8^d)	27^c (0.9^b)*	2.4^b(0.8^b)**	6.9^b(2.2^a)**	2.3^d(0.7^b)**
450	548	889^c (1.6^e)	25^d (0.4^d)*	2.6^c (0.5^c)**	7.0^b(1.3 ^{c})**	2.2^c(0.4^c)**
720	744	1224^d (1.6^e)	24^e (0.3^e)*	3.0^d(0.4^d)**	6.8^b(0.9 ^{d})**	2.1^b(0.3^d)**

Different superscript letters on same column indicate a significant difference at $\alpha \leq 0.05$ (Tukey's HSD test). *Vitis vinifera* cv Tinta Roriz, Alto Douro (adapted from Refs. [32, 35]).

*WUE × 10.

**WUE × 100.

Table 2. Effect of irrigation on crop evapotranspiration (Ec), yield (Y), total soluble solids (TSS), titrable acidity (TA), tartaric acid (TAc), malic acid (Mac), and respective water use efficiency of each parameter (in parenthesis).

Titrable acidity increased with irrigation, but it is still too low for high-end wines with a preferred acidity of 6–7 mg L^{-1} that is equivalent of tartaric acid [41], which is a manifestation of the influence of high temperatures on degrading the main organic acids of the must, namely, malic and tartaric acids (**Table 2**).

Total soluble solids (TSS), polyphenol index (PI), total anthocyanins (TAn), and color index (CI) significantly decreased with irrigation (**Table 3**). TSS is very important for grape growers and winemakers because it determines how much sugar is available for conversion into alcohol. The relationship between irrigation and TSS is complex; more available water induces higher photosynthetic rate and accumulation of soluble solids but also augments yields and the berry size that can dilute the soluble solids, and in the end, their lower concentration produces a total volume of wine poorer in alcohol. PI is a phenolic parameter that measures the

Irrigation	TSS (°Brix)	PI	TAn (mg berry^{-1})	CI
0	30^a (1.5^a)*	233^a (13.4^a)*	13.8^a (7.9^a)**	0.25^a (12.0^a)**
160	28^b (0.9^b)*	203^b (7.2^b)*	11.9^b (4.1^b)**	0.21^b (6.9^b)**
320	26^c (0.5^c)*	196^b (3.9^d)*	12.3^b (2.4^c)**	0.18^c (3.5^d)**
225	27^c (0.9^b)*	176^c (6.1^c)*	10.6^c (3.8^b)**	0.16^d (5.3^c)**
450	25^d (0.4^c)*	174^c (3.2^d)*	9.2^d (1.7^d)**	0.15^d (2.8^d)**
720	24^e (0.3^d)*	138^d (1.8^e)*	9.1^d (1.2^d)**	0.13^e (1.5^e)**

Different superscript letters on same column indicate a significant difference at $\alpha \leq 0.05$ (Tukey's HSD test). *Vitis vinifera* cv Tinta Roriz, Alto Douro (adapted from Oliveira et al. [35]).

*WUE × 10.

**WUE × 100.

Table 3. Effect of irrigation treatments on total soluble solids (TSS), polyphenol index (PI), total anthocyanins (TAn), color intensity (CI), and respective water use efficiency of each parameter (in parenthesis).

polyphenolic content of must and wine, and it relates to color stability of red wines as it ages; irrigated plants produced musts with lower phenolic potential that contribute for producing red wines with lower aging potential irrespective of the irrigation schedule. Accumulation of anthocyanins (glucosides and aglycones) in grape skin is responsible for the dark color of red grapes, and their concentration is related to the berry size that increases with irrigation, resulting in musts with lower concentration of anthocyanins as the amount of available water is higher, especially if irrigation occurs close to harvest date. CI is directly related to TAn, and its values in must of irrigated plants follow the pattern of TAn.

It is then clear that irrigation rate and its schedule had a significant influence on yield and berry quality. Irrigated grapevines had better yields but, in general, the must characteristics revealed lower quality. The must quality of grapevines receiving water before veraison was better than from those irrigated after veraison. Excessive water stress before veraison causes poor fruit setting and reduced metabolic functions; berry growth is stunted and essential metabolites, such as organic acids, do not accumulate. Irrigation starting after veraison cannot make up for the losses already sustained. If water stress before veraison is moderate, berries still can attain size and composition adequate for winemaking but increasing the SW content after veraison might dilute soluble solids, acids, anthocyanins, and phenols, turning the must inadequate to high-quality wine.

For grape growers, profits are made up of both yield and quality and very low yield, no matter how the quality is, which is not profitable. The best balance between quality and yield and still attaining acceptable water use efficiency was reached with irrigation from flowering to veraison amounting to about 50% of the reference evapotranspiration of that period. When irrigation is halted at veraison, SW content declines slowly until harvest and probably there is enough water to sustain the vine metabolic functions and yield at higher levels than rainfed grapevines [32, 35]. In addition, it also permits a larger foliar area providing additional shade to partially offset rising temperatures.

Tinta Roriz had lower water use efficiency as more water is added (**Tables 2** and **3**), an important consideration in scenarios of scarcer water resources and competing uses. In dry weather conditions and sparse soil cover as vineyards, direct evaporation from soil becomes an increasingly larger proportion of evapotranspiration, and when more water is available, it results in higher crop water use that is not directly proportional to plant yield and to its metabolic functions; thus, WUE lowers in irrigated plants. Again, a compromise between yield, quality, and WUE can be achieved with deficit irrigation before veraison. Deficit irrigation at critical moments contribute to moderate water stress during the entire growing season to produce quality musts, acceptable yields, and still keep a judicious use of water.

2.1.2. Canopy management

High solar radiation intensity and elevated temperatures damage the grape berries. The fruit shrivels and can desiccate completely (raisining), making it inappropriate for winemaking. This is a phenomenon very common in Douro, also in other wine regions [42], given the actual climate conditions (**Table 1**), and it is bound to increase in the future. A north-south row orientation allows the fruits, on both sides of the canopy, reach a balance in photosynthetic

efficiency, and their exposure to radiation [43] and shade propitiated by a denser canopy can minimize the losses. However, slope might not permit a north-south orientation and additional shade provided by a denser canopy actually is not enough to prevent significant yield reductions. Shading the plants can reduce their exposure to radiation and heat but creates an imbalance in carbon budget, reducing vine biomass, and affects negatively the canopy photosynthesis [44]. To avoid these negative effects and still protect a rainfed commercial vineyard of *Vitis vinifera* cv Touriga Nacional in Alto Douro, planted in east-west oriented rows and VSP trained, had the lower third of their south-facing side (from ground to 20 cm above the insertion point of grape clusters) partially covered with a vertical double layer of white plastic netting attached to iron spikes driven into the ground at 3-m intervals [45]. At about 30 randomly laid out rows with 70 vines, each was divided into three groups with equal number of rows. One group was shaded after fruit setting, another after veraison, and the third was nonshaded (control). The net was removed just prior to harvest. The net reduced the total solar radiation by 23% and photosynthetic active radiation by 27%.

From the end of flowering to commercial harvest, every week on clear sky days at noon, two well lit, adult leaves of each five randomly chosen plants on each group were used to measure stomatal conductance (porometry) and leaf water potential (pressure chamber) (300 readings repeated over 3 years). On the same days and time but only after veraison, the temperature (infrared thermometry) of one cluster on 10 randomly chosen plants per treatment was measured (180 readings repeated over 3 years). At harvest, the same procedure described for irrigation section was used to sample berries for laboratory analysis (nine analyses repeated over 3 years).

Shading did not influence significatively either water status (leaf water potential) of the plants or their stomatal conductance; thus, it is reasonable to assume that they did not affect the net photosynthesis per unit of leaf area. Shaded vines consistently had significant higher yields (2100 g plant^{-1}) than nonshaded vines (1500 g plant^{-1}) because the percentage of shriveled berries per cluster was about 6.5% against 14%, respectively (**Table 4**). The number of clusters, weight, and size of the berries showed no significant differences. Shading does not totally prevent berry shriveling because the phenomenon is also caused by other factors like water stress [46].

Shading did not alter significatively the concentrations of total soluble solids (24.3 °Brix), tartaric acid (4.3 g L^{-1}), malic acid (1.7 g L^{-1}), glucose (118.2 g L^{-1}), and fructose (110 g L^{-1}) in

Shading	Yield (g plant^{-1})	% Shriveled berries per cluster	Weight 200 berries (g)	Volume 200 berries (cm^3)
Nonshaded	1504[a] (6000)[*]	14[a]	270[a]	136[a]
After fruit setting	2172[b] (8690)[*]	6[b]	257[a]	131[a]
After veraison	2076[b] (8300)[*]	7[b]	256[a]	131[a]

Different superscript letters on same column indicate a significant difference at $\alpha \leq 0.05$ (Tukey's HSD test). *Vitis vinifera* cv Touriga Nacional, Alto Douro (adapted from Oliveira et al. [45]).
[*]In parenthesis calculated yield kg ha^{-1}.

Table 4. Effect of shading on yield, percentage of shriveled berries per cluster, weight, and volume of 200 berries for each shading treatment.

the must. Must pH was higher (3.9) in nonshaded vines against shaded (3.8). These results suggest that photosynthetic carbon acquisition was not significantly different for all groups of plants, and they are consistent with values reported for the same region and they are typical for hot climate vineyards [47, 48]. The shaded berries were approximately 1°C cooler than nonshaded ones, a difference probably due to less radiation reaching the clusters [49]. There is evidence that berry temperature affects its composition, but only differences in 3°C or above are reported as causing changes [50, 51]. On the other hand, the biosynthesis of anthocyanins is sensitive to light environment and it decreases with lower light intensity [52, 53], and in fact, shaded berries from Touriga Nacional had lower concentration of total anthocyanins and extractable anthocyanins than nonshaded berries (**Table 5**).

Lower concentrations of anthocyanins, responsible for the red color intensity of wines, can be detrimental to the must quality [54, 55] with loss in market value but that might be offset by an additional yield of 2300 kg ha^{-1} in favor of shaded grapevines.

According to the net maker, the net can last to 10–12 years. The grower did support the cost of the net, 3000 euros per hectare, plus an expense outlay of 150 euros per hectare for handling of the net. These added expenses look reasonable for vineyards already planted in an inconvenient layout that can sustain heavy losses under spells of extreme weather conditions.

2.1.3. Cooling techniques

The temperature of plant leaves are closely related to air temperature, and the rising temperatures reduce stomatal conductance [55], decrease photosynthesis rate significantly due to the increase in respiration [56], restrict carbon assimilation per unit leaf area, affecting negatively the vegetative growth and yield [57], and impair several physiological processes, notably sugar accumulation [58]. Berries after veraison are very sensitive to a combination of intense solar radiation and high temperature, reducing in size and in soluble solid concentration [59].

High temperatures and light intensity cause berries to ripe more slowly and contribute to berry sunburn and shriveling as cells of the mesocarp die [60]. The negative effects of high-temperature events on vine physiology are more severe in vines experiencing water stress [61].

Two mitigation techniques are actually being experimented in Alto Douro region with rainfed Touriga Nacional to reduce the effects of adverse temperature and radiation. Nontreated

Shading	TAn (mg L^{-1})	EAn (mg L^{-1})
Nonshaded	1534[a]	825[a]
After fruit setting	990[b]	679[b]
After veraison	1240[b]	726[b]

Different superscript letters on same column indicate a significant difference at $\alpha \leq 0.05$ (Tukey's HSD test). *Vitis vinifera* cv Touriga Nacional, Alto Douro (adapted from Oliveira et al. [45]).

Table 5. Effect of shading on total anthocyanins (TAn) and extractable anthocyanins (EAn) for each shading treatment.

grapevines (control) are compared with plants treated from the end of flowering for 2 weeks before the forecast harvest date: (1): coated with a suspension of kaolin [$Al_4Si_4O_{10}(OH)_8$] at a rate of 12.5 kg ha^{-1} for every 20–25 days and (2): nebulized with water from misters located above the canopy for 30 seconds every 30 minutes as long as air temperature is higher than 32°C (The aperture of electro valves is automatically triggered by temperature records of the weather station.)

The sampling procedures described on above sections (irrigation, canopy management) were followed from the end of flowering to commercial harvest, to measure canopy temperature (average temperature of both sides of the canopy), cluster temperature, stomatal conductance, and berry sampling for laboratory analysis.

Infrared thermometry shows that nebulization keeps the canopies cooler at least 1°C than coated and control canopies (**Table 6**). Despite the reflective characteristics of kaolin, temperature of coated canopy is not significantly different from canopy temperature of control plants. Reduced stomatal opening, conducive to lower stomatal conductance, higher resistance of leaf boundary layer, and low photosynthetic photon flux density during part of the day are pointed out as explanations for these results [62, 63]. Stomatal conductance (g_s, cm s^{-1}) of nebulized plants (3.11) is significantly higher than of nontreated plants (2.14) (**Table 6**). Stomatal conductance is negatively correlated with leaf temperature [55], and as temperature raises, the plant reduces the opening of its stomata to conserve water and this mechanism reduces transpiration, a mechanism that rises the leaf temperature.

Evaporative cooling and kaolin coating had the same effect on cluster temperature, measured after veraison (infrared thermometry). Clusters of treated plants show a reduced temperature in relation to control plants, which are at least 1.3°C warmer (**Table 6**). Here, the scattering of radiation caused by kaolin is not counter acted by reduced transpiration and cluster temperature was maintained lower than air temperature.

Excessive temperature and radiation that cause fruit sunburn, a major factor in loss of production in grapevines of Alto Douro region, were effectively avoided by nebulization and kaolin coating (**Table 7**). Treated plants have 5–7% of shriveled berries per cluster compared with 12–13% in control vines. Reduced berry loss contributed to higher yield per plant.

Total soluble solids are 26.1°Brix for nebulized vines, and it is significantly higher than kaolin coated and control, 24.6 and 24.7°Brix, respectively (**Table 7**). Nebulized canopies show lower

	Temperature (°C)		g_s (cm s^{-1})
	Canopy	**Cluster**	
Control	30.3[a]	32.1[a]	2.14[a]
Nebulization	28.4[b]	31.1[b]	3.11[b]
Kaolin coating	30.1[a]	31.5[b]	2.09[a]

Different superscript letters on same column indicate a significant difference at $\alpha \leq 0.05$ (Tukey's HSD test). *Vitis vinifera* cv Touriga Nacional, Alto Douro.

Table 6. Effect of nebulization and kaolin coating on average canopy temperature and stomatal conductance (g_s) from flowering to harvest and for cluster temperature from veraison to harvest.

	Yield		Sunburnt berries	TSS
	g plant^{-1}	Kg ha^{-1}	%	°Brix
Control	868[a]	3470	12[a]	24.7[a]
Nebulization	983[b]	3930	7[b]	26.1[b]
Kaolin coating	1012[b]	4050	5[b]	24.6[a]

Different superscript letters on same column indicate a significant difference at $\alpha \leq 0.05$ (Tukey's HSD test). *Vitis vinifera* cv Touriga Nacional, Alto Douro.

Table 7. Effect of nebulization and kaolin coating on yield, percentage of sunburnt berries, and total soluble solids (TSS).

temperatures and, consequently, higher stomatal conductance (**Table 6**) that might permit an increased photosynthetic rate as observed by other authors [55, 56]. In turn, increased photosynthetic activity contributes to larger berry sugar content, evaluated as total soluble solids, as seen in **Table 7** and corroborated in other works [58, 59].

However, other characteristics of the must (pH, titrable acidity, tartaric acid, malic acid, total tannins, total polyphenols, and total anthocianins) do not show significant differences among treated and control plants (data not shown).

The cost of installation (2500 euros ha^{-1}) and running the water nebulization system (100 euros ha^{-1}) might be impeditive of its adoption. Infection by fungus and insect repellency are factors associated to water spray and kaolin coating, respectively, that must be considered but they have not been assessed at the time of this report.

3. Conclusions

Meteorological records and grapevine phenological occurrences in DDR are in agreement with forecasts of higher temperatures, lower precipitations, and advances of phenological stages. The environment of Douro is expected to become more stressful in coming years, and adaptations are imperative to save the viticulture as an economic activity. For the vineyards already in commercial production, efficient irrigation associated with shading and cooling techniques can reduce significatively water and temperature stress on grapevines and they can maintain acceptable yields with marketable quality wine. However, these techniques have some drawbacks in must quality and might not suffice to a large shift in temperature and precipitation given the actual conditions already at the limit of tolerance of the best grape varieties.

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