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MINI-REVIEW ARTICLE

Effects of shading nets as a form of adaptation to climate change on grapes production: a review

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ABSTRACT

Viticulture worldwide is threatened by the environmental modification caused by climate change. Higher temperature and atmospheric CO_2 concentration determine an acceleration of the ripening process, which can be detrimental to wine quality. Hence, adaptation and mitigation strategies are necessary to reduce heat and water stress and improve the qualitative production levels. Amongst all the various techniques available, shading nets represent an interesting alternative for their effects on canopy microclimate and grape production. However, these effects vary strongly depending on the intensity of the shading treatment, the timing of its application, environmental conditions, and differences in cultivar response. The reduction in photosynthetic activity can improve water use efficiency and slow down the ripening process, preserving must acidity. Phenolic compounds, which benefit from light exposure for their synthesis, are negatively affected by shading, while aromatic composition can be improved by it. Vine reserve accumulation is reduced by the lower photoassimilates production. Photoselective nets, thanks to their colour, not only reduce light intensity but also change the quality of the light spectrum reaching the canopy, thus, determining specific responses in the plants.

KEYWORDS: climate change, shading net, must composition, grape quality, photosynthesis

INTRODUCTION

It has been remarked that climate change is driving us towards an increase in global surface temperature, atmospheric CO_2 concentration and extreme climatic phenomena (i.e., heat waves, heavy precipitations, agricultural and ecological drought etc.) (IPCC., 2021), with a subsequent reduction in water availability for agriculture. In this context, viticulture is exposed to drastic changes in the elements of the terroir and grape production (De Toda *et al*., 2016; De Toda and Balda, 2015).

Moreover, due to the berry ripening shift during late summer, grapes are more exposed to excessive solar radiation, with subsequent increase in sunburn damages and visual and organoleptic alterations in the berries (Palliotti *et al*., 2014; Gambetta *et al*., 2021).

Hence, there is huge interest in developing techniques able to delay phenological development and control ripening (Silvestroni *et al*., 2018), for example, by regulating the efficiency of the canopy (Naor *et al*., 2002; Lanari *et al*., 2013) or delaying vine growth through winter pruning carried out later in the season (Friend and Trought, 2007; Frioni *et al.,* 2016; Silvestroni *et al*., 2018; Silvestroni *et al*., 2020).

The possibilities of actions are wide and various, moving from long-term strategies (i.e., use of resistant cultivars, changes in the training system) to short-term adaptation techniques, like the induction of competition for nutrients between different plant organs, the reduction in source availability, or an early harvest, etc. (Palliotti *et al*., 2014). Another possible way to contain source supply is using shading nets, cloths positioned to cover different parts of the canopy to reduce the amount of solar radiation reaching the leaves, thus inducing a restriction of photosynthetic activity. The effects of shading nets have been studied extensively, and this review aims to assess the consequences of using artificial shading on grape production.

SHADING NETS

1. Effects on irradiance and photosynthetic activity

The lower solar radiation reaching the canopy due to shading has as its primary effect the reduction in the photosynthetic activity of the plants.

On potted Chardonnay grapevines, the use of different shading intensities three weeks after potting led to a significant reduction in the photosynthetic activity, as indicated by the lower NCER (Net Carbon Exchange Rate) registered in the shaded vines (Heuvel *et al*., 2004). Furthermore, it was observed that this reduction tended to grow with higher shading intensities, with a difference of 54 % registered when a 99 % level of shading was applied. Another study carried out on Chardonnay led to similar conclusions, with a reduction in net assimilation found after a 50 % shading net was used before bud break until after harvest (Porro *et al*., 2001).

Shading caused a 70 % reduction in irradiance on Semillon vines, with considerable effects on the microclimate and a reduction in cluster temperature of almost 5 °C (Greer *et al*., 2010) and a decrease in photon flux density which reduced net photosynthesis by 40 % (Greer *et al*., 2011).

A linear regression between shading intensity and the reduction in incoming photosynthetic active radiation (PAR) at the canopy level, and subsequently of photosynthetic activity, was observed on Aglianico grapevines (Basile *et al*., 2015).

Similarly, a 60 % shading treatment applied at the end of fruit set caused a significant reduction in PAR values on Cabernet-Sauvignon vines grown in open field conditions in California, thus lowering net carbon assimilation and cluster temperature (Martínez-Lüscher *et al*., 2020). This study also showed that the leaves not covered by the net maintained high assimilation levels, in some cases even higher than those of control vines, suggesting some form of compensation. In the same way, in the semi-arid conditions of Manas County (China), a 75 % shading net was used to cover the bunch zone of Cabernet-Sauvignon vines four weeks after flowering, reducing net assimilation in a significant way (Lu *et al*., 2021). However, in this case, the comparison between uncovered leaves and those of untreated vines did not show any difference, indicating that no form of compensation might have occurred.

2. Effects on grape production

It has been proven that grape berry mass can significantly vary depending on the level of exposure, with overexposure resulting in a higher loss of water by dehydration (Torres *et al*., 2020). However, from all the studies that have been reported, no universal paradigm can be inferred regarding the effects of shading nets on vine yields (Table 1). Grapevine's response seems rather to be influenced by numerous factors, such as genotype, environment, the period of application of the treatment and its intensity.

In this sense, a study carried out in the Franciacorta area in northern Italy highlights the different responses to the same shading treatment applied at the beginning of the veraison of Chardonnay and Pinot noir vines. Chardonnay shaded vines increased both average cluster weight and total yield by almost 30 %, while no difference in average cluster weight and a reduction in the total yield of about 13 % were determined in shaded Pinot noir vines (Ghiglieno *et al*., 2020), apparently confirming the hypothesis that each cultivar has its own specific response to light exclusion.

Shading reduced the bunch weight of Cabernet-Sauvignon vines by 10.6 % and the total yield by 11 %, thus reducing the ratio between the total leaf area and the yield and the ratio between the yield and the pruning weight in the following dormant season, also known as Ravaz index (Lu *et al*., 2021), as well as bunch biomass of Semillon grapevines, due to lower carbon assimilation and allocation in treated plants (Greer *et al*., 2011). A light reduction of 50 % during the whole season lowered Chardonnay bud fertility, negatively affecting vine yield over three consecutive years (Porro *et al*., 2001).

TABLE 1. Effect of artificial shading on vine total yield.

Article	cv.	Effect
1. Lu *et al.*, 2021	Cabernet Sauvignon	- -
2. Caravia *et al.*, 2016 *°	Shiraz	- - / - / + / ++
3. Porro *et al.*, 2001 *	Chardonnay	- - / - - -
4. Downey *et al.*, 2008 *	Shiraz	= / - - -
5. Oliveira *et al.*, 2014 *	Touriga nacional	+++
6. Martinez-Lüscher *et al.*, 2020 °	Cabernet Sauvignon	- / - -
7. Basile *et al.*, 2015 *°	Aglianico	- / - -
8. Ghiglieno *et al.*, 2020	Chardonnay	++
	Pinot noir	- -
9. Pagay *et al.*, 2013 °	Cabernet franc	+ / +++

= denotes no effect; - / + denotes slight reduction/increase lower than 10 %; - - / ++ denotes reduction/increase between 10 and 30 %; - - -/ +++ denotes reduction/increase higher than 30 %; * indicates a multi-year study; ° indicates a study with different shading treatments under analysis

Different shading intensities applied before flowering until full fruit set caused an increasing reduction in the fruit set of Aglianico grapevines, resulting in a lower total yield per vine of treated plants (Basile *et al*., 2015).

Even though not statistically significant, a slight reduction in total yield, about 10 %, was observed in Cabernet-Sauvignon vines covered with a 60 % shading net at full fruit set (Martinez-Lüscher *et al*., 2020). Despite that, shaded bunches were well protected against excessive exposure, as indicated by the significantly lower incidence of berry damage and dehydration compared to exposed bunches.

Conversely, other studies reported an increase in grape production after applying the shading treatment. The use of artificial shading on Grillo grapevines in Sicily has led to an increase in berry weight (Scafidi *et al*., 2013). Specifically, the treatments consisted of a shading net (50 % shading) and grape boxing (100 % shading) from fruit set to harvest. At harvest, both showed higher fresh berry weight than control vines and even though a reduction in berry water content was seen in all the vines under analysis, the dehydration in shaded berries was much lower, suggesting that artificial shading prevents excessive berry water loss. In Canada, bird netting was applied at different periods of the vegetative growth of Cabernet franc grapevines: at post-bloom, at bunch closure and at veraison. Despite only the bunch closure application resulting in a significantly higher yield, with a 47 % increase with respect to control vines, the other two treatments, though not statistically significant, still registered higher values, perhaps also due to a lower incidence of bird predation (Pagay *et al*., 2013). Shading the fruiting zone of Touriga nacional grapevines both after fruit set and veraison significantly reduced the number of shrivelled berries per cluster (which was halved compared to exposed vines), thus increasing yield by around 40 % in two years, a level capable, as stated by the authors, of offsetting the costs sustained for the installation of the net and increasing growers returns (Oliveira *et al*., 2014).

In contrast, other research works on different cultivars have reported no effects at all concerning vine yield. In Australia, by covering Syrah grapevines from veraison to harvest with a white cloth with a 62 % shading capacity above the canopy, shaded berries resulted in a higher berry water content and berry fresh mass due to the lower dehydration level, but no difference in total yield was observed since shaded vines registered a lower number of bunches per meter (Caravia *et al*., 2016).

Another study on Syrah grapevines cultivated in Australia reported no effect on berry development and average weight with a bunch shading treatment applied before and after flowering in all but the first year of the study, when the total yield of treated plants resulted in more than 30 % lower value than the untreated ones (Downey *et al*., 2008).

3. Effects on must composition

The reduction in photosynthetic activity certainly affects berry ripening, strongly affecting sugar accumulation rate and organic acid depletion.

At harvest, a lower TSS content of 1.5 °Brix, a lower pH and a higher titratable acidity were registered in Shiraz grapevines after a post-veraison use of a white cloth above the canopy (Caravia *et al*., 2016).

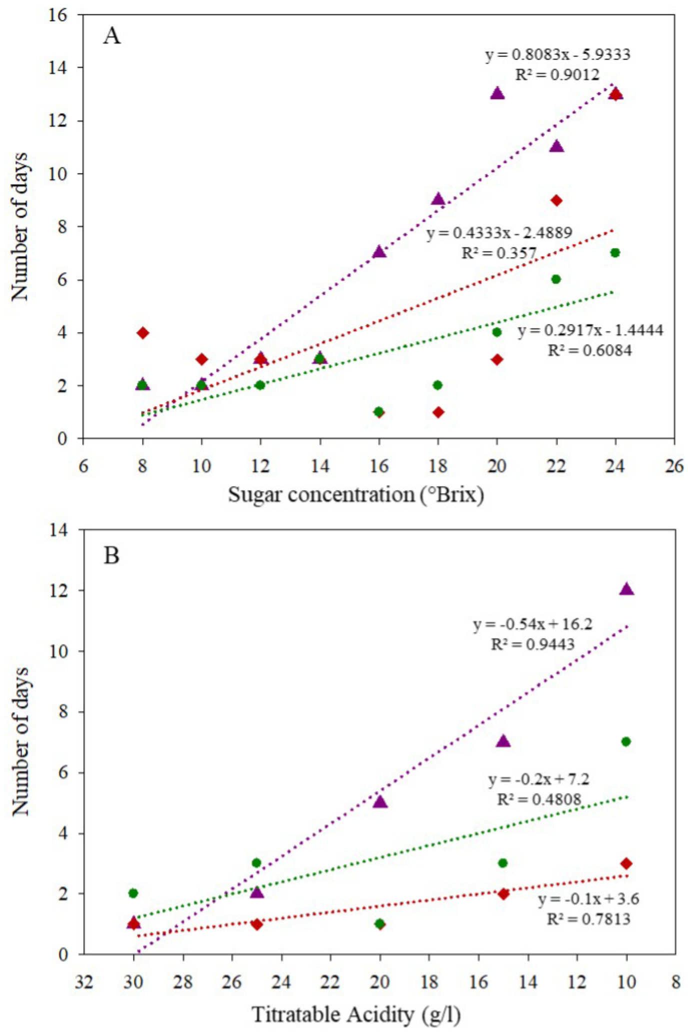

FIGURE 1. Delay in the grape ripening of shaded Cabernet-Sauvignon vines.

Delay (number of days) in reaching the same (A) sugars concentration (°Brix) and (B) organic acids concentration (g/l) in the grapes of Cabernet-Sauvignon shaded vines under different light regimes: ∆ 75 % shading level (from Lu *et al.*, 2021), ◊ 60 % shading level with an 80 % ETc water supply (from Martínez-Lüscher *et al.*, 2020) and • 60 % shading level with a 40 % ETc water supply (from Martínez-Lüscher *et al.*, 2020). In the figure, the equation of each trend line and the respective value of R2 are reported.

Ripening has been slowed down with the use of a shading net in both Pinot noir and Chardonnay cultivated in Italy, either showing higher titratable and malic acidity contents in the musts (Ghiglieno *et al*., 2020). Another study carried out in southern Italy is somewhat consistent with these results (Scafidi *et al*., 2013). As a matter of fact, the use of bunch netting and boxing on Grillo cv. Led to a lower depletion of organic acids with respect to control vines. On the contrary, sugar accumulation maintains significant differences at harvest only for the boxed treatment (where the intensity of the shading was higher), while for netted grapes, this trend was maintained only during an early phase of the ripening, with no significant differences recorded at harvest.

Anti-hail nets with a 16 % shading capacity have been tested on Nebbiolo grapevines during 2006 and 2007 vintages (Chorti *et al*., 2010). In the first year, the use of the shading treatment only affected the ripening process during an early stage but not close to the harvest; in 2007, it had a negative effect on TSS accumulation. In addition, regardless of the effects on sugars, nets provided effective protection against sunburn in the berries in both years.

In France, the shading treatment (applied when berries reached around 5 mm in diameter) generally delayed grape ripening of Syrah vines for two consecutive years, with major and significant effects registered for high-intensity treatments (90 % and 70 % shading levels) where the higher values of total acidity (95 and 97 mequiv/L) and the lowest sugar concentrations (124 and 174 g/L) were found (Bureau *et al*., 2000).

The use of a bird net in different stages of the vegetative growth of Cabernet franc grapevines resulted in a significant decrease in both must soluble solids and pH (Pagay *et al*., 2013). It is interesting to observe how the earliest treatment, applied shortly after bloom, showed a lower difference with the control of 0.5 °Brix, probably because vines had more time to grow longer lateral shoots to compensate for the shading effect with respect to the other treatments (post-bunch-closure and post veraison applications), applied at a time when the growth of laterals is generally slower, resulting in a difference of 1.2 and 1.9 °Brix, respectively.

A severe bunch shading treatment (about 99 % intensity) applied at veraison also proved to be effective in the restraint of the ripening of Riesling in Germany (Friedel *et al*., 2016). Shaded grapes had a lower sugar concentration throughout the entire sampling period and higher values of total and malic acidity. At harvest, shaded grapes still had a lower sugar content and higher total acidity and, even though not significant, higher malic acidity.

On Cabernet-Sauvignon, two studies demonstrated that shading could effectively delay sugar accumulation and organic acids depletion in berries (Figure 1). In China, vines covered four weeks after flowering with a 75 % shading net took almost 2 weeks more than exposed ones to reach a sugar concentration of 24 °Brix, thus, resulting in less alcoholic wines with less residual sugar (Lu *et al*., 2021). At the same time, the degradation of organic acids was slower with respect to control vines due to minor exposure to stress conditions of shaded vines. Similar effects were observed in California with a 60 % shading level in combination with two irrigation regimes (40 and 80 % replacement of crop evapotranspiration) applied at the end of fruit set (Martínez-Lüscher *et al*., 2020). In both cases, shading effectively reduced sugar accumulation and this effect was emphasised by the higher level of water supply. On berry acidity, the effects of shading were milder, especially in vines with an 80 % ET_c supply. However, vines subjected to higher water stress conditions seem to have benefited more from shading, and a little delay in the depletion of organic acids was observed.

Contrarily, in other studies, the evidence seems to highlight that the use of shading nets affects the components of the must quality but not total soluble solids concentration. Two different intensities of shading (50 and 75 %) applied during the whole season caused an increase in total acidity (of 0.17 and 0.2 % expressed as a percentage of tartaric acid) and a decrease in must pH (of 0.15 points) in Pinot noir vines (Ranjitha *et al*., 2015). In the same way, organic acids concentration, including malate, was increased in Cabernet-Sauvignon (Reshef *et al*., 2017) with the use of 30 and 60 % shading nets from veraison to harvest, while a 23% solar radiation exclusion lowered the pH of Touriga Nacional musts (Oliveira *et al*., 2014). Similarly, bunch shading did not affect the sugar accumulation of Shiraz grapevine over three consecutive years, but in this case, the reason for this is the fact that only bunches were shaded, while the leaves were fully exposed, with no repercussions on their photosynthetic activity (Downey *et al*., 2008).

Finally, an increase in total soluble solids in the berries was observed in Alphones Lavallée and Narince grapes with the use of black nets starting from veraison (Sabir *et al*., 2021). However, it is essential to underline that, in this case, the primary aim of the study was to evaluate the effectiveness of nets as a protection tool against the decay of grape clusters in vineyards. To do that, both nets and bunches were kept on vines until December, far over the harvest period. Hence, the higher sugar concentration found is related to berries shrivelling and dehydration phenomena and to the transformation of organic acids to sugars thanks to gluconeogenesis.

4. Effects on phenolic and aromatic composition

The effects of light exposure on the synthesis of phenolic substances are well documented. Hence, several studies moved in this way to analyse the effects of artificial shading on the biosynthesis of these compounds.

Various research activities have demonstrated that there is a negative correlation between shading and phenolic accumulation in the berries of different cultivars in disparate environmental conditions. Specifically, shading decreased phenols and anthocyanins concentration in Pinot noir wine (Ranjitha *et al*., 2015), total and extractable anthocyanins of Touriga Nacional grapevines (Oliveira *et al*., 2014), total flavonols in Chardonnay grapevines (Ghiglieno *et al*., 2020), and caused a lower accumulation of anthocyanins, phenols, tannins and epicatechins in Shiraz overshaded vines, even though the difference was no longer significant neither in the must at harvest nor in the wine (Caravia *et al*., 2016).

TABLE 2. Effect of artificial shading on must total anthocyanins content.

Article	cv.	Effect
1. Lu *et al.*, 2021	Cabernet Sauvignon	+
2. Martinez-Lüscher *et al.*, 2020 °	Cabernet Sauvignon	++
3. Oliveira *et al.*, 2014 *	Touriga nacional	- / - -
4. Caravia *et al.*, 2016 °*	Shiraz	- / =
5. Pagay *et al.*, 2013 °	Cabernet franc	-
6. Downey *et al.*, 2008 *	Shiraz	+ / - -
7. Ghighlieno *et al.*, 2020	Pinot noir	+

= denotes no effect; - / + denotes slight reduction/increase lower than 20 %; - - / ++ denotes reduction/increase between 20 and 40 %; - - - / +++ denotes reduction/increase higher than 40 %; * indicates a multi-year study; ° indicates a study with different shading treatments under analysis

A study carried out over two consecutive years showed that shading, albeit some differences related to the intensity of the shading treatment and the vintage itself, caused a decrease in phenols concentration in shaded vines (Bureau *et al*., 2000). Similarly, a study carried out on Grillo grapevines demonstrated that there is a linear correlation between shading intensity and flavonols concentration, which decreased proportionally to the lower light intensity (Scafidi *et al*., 2013). Proanthocyanidins concentration registered a decrease in strongly shaded vines, which reduces the risk of incurring the browning phenomena in the wines due to the lower catechins content, while a 50 % shading treatment did not affect their accumulation apparently, since no difference was seen between this treatment and control vines. On Cabernet franc, the use of bird-netting at different phenological stages had a detrimental effect on anthocyanins and total phenolic concentration both in the berries and the wines, leading to a decrease in these compounds (Pagay *et al*., 2013). The results of this study also suggest that the intensity of the effects of the shading treatment is strongly influenced by the period in which the nets are applied and the subsequent time of response of the vines themselves, with the earliest treatments showing the highest differences with respect to the control one.

However, a study carried out in the hot climates of California on Cabernet-Sauvignon gives evidence that if it's true that the synthesis of phenolic compounds is stimulated by light, it is also true that excessive exposure can have detrimental effects on their concentration (Martìnez-Lüscher *et al*., 2020). In fact, all the vines experienced a loss of anthocyanins due to the high temperature, but regardless of the water regime, this drop was more restrained in shaded ones, resulting in a higher concentration at harvest. In this sense, the use of shading nets seems to have protected grapes from excessive heat, thus, reducing the degradation of phenolic compounds stimulated by high temperatures. Furthermore, shading also caused changes in the anthocyanin profile in relation to the different antioxidant capacities of each compound, which determined diverse degradation rates. On the other hand, flavonol content increased in exposed vines, although even in this case, their degradation was more contained in shaded vines. The reason for this is attributable to the different sensitivity to the temperature of flavonols, whose regulation appears to be mainly influenced by UV-B radiation.

In the same way, a similar response of Cabernet-Sauvignon to partial canopy shading was observed in another study (Lu *et al*., 2021). Grapes from shaded vines registered a higher total anthocyanins concentration, lower total flavonols concentration and no difference in flavan-3-ols content. Qualitative changes in their respective profile were observed as well: amongst the anthocyanins, shaded berries had higher concentrations of cyanidin, delphinidin, peonidin and petunidin, while within the flavonols, lower concentrations of kaempferol, quercetin, myricetin, and syringetin. Wines produced from these grapes differed significantly between the two treatments: the shading treatment caused an increase in wine anthocyanin content and lightness and a reduction in its chromaticity and flavonols and flavan-3-ols content, with the latter result unexpectedly different from what was seen in the berries. Apparently, it seems that anthocyanins accumulation, which normally is stimulated by sunlight exposure, benefit from shading and light exclusion in those areas where the climate is particularly hot and dry, thus, reducing the risk of incurring their degradation (Table 2).

Shading from veraison to harvest resulted in a lower synthesis of anthocyanins in Nebbiolo grapes because of the reduced sunlight, though at harvest, their concentration was not different from control ones (Chorti *et al*., 2010). Interestingly, shading caused an alteration of anthocyanin composition and their level of acylation, with a decrease in 3'-hydroxylated anthocyanin and an increase in 3',5'-hydroxylated anthocyanin and 3-coumaroyl-glucosides, whose concentration in Nebbiolo berry skins is usually low.

Anthocyanins metabolism of Shiraz berries seems more affected by temperature than light, as seen in a study carried out in Australia where bunches were shaded with boxes at different developing stages (Downey *et al*., 2008). Bunch shading, even though it resulted in a lower anthocyanins content, did not prevent the accumulation of these compounds, suggesting that a reduction in light exposure might not be so detrimental. Moreover, consistently with other studies, shading seems to affect the enzymatic pathways responsible for the synthesis of the various anthocyanins, as demonstrated by the reduction in malvidin, delphinidin and petunidin and the increase in peonidin and cyanidin. Tannins concentration at harvest did not change between the two treatments while, even in this case, shading caused changes in the composition of the proanthocyanidins, with higher levels of condensation in shaded berries. Consistently with other studies, flavonols content in shaded bunches was much lower than in control ones. Specifically, their biosynthesis was strongly reduced from the moment that the shading treatment was applied, suggesting that the expression of the gene encoding the flavonol synthase (FLS) is light-dependent and affected by light exclusion.

In Israel, on Cabernet-Sauvignon, the reduction in sunlight caused a decrease in flavonols and an increase in flavan-3-ols content, while the overall levels of anthocyanins increased with the application of a shading treatment, but the various compounds showed different responses, with cyanidin and peonidin reducing their content while the other anthocyanins showed an optimum with a 30 % shading level (Reshef *et al*., 2017).

The correlation between light exposure and the expression of the genes for flavonols biosynthesis has been carried out on Riesling grapevines in Germany (Friedel *et al*., 2016). Exposed vines were compared to bunch-shaded vines, resulting in a lower concentration of phenolic substances in shaded grapes. Moreover, shaded grapes, after being reilluminated twenty days before the harvest, showed an increase in the concentration of these compounds, particularly significant for quercetin glycosides, which comprise 85 % of the total flavonols present in Riesling.

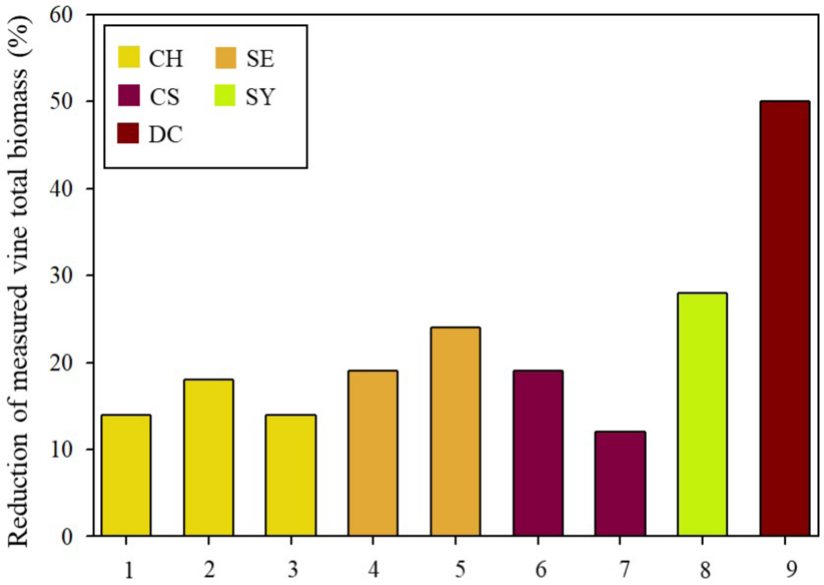

FIGURE 2. Percentage reduction in measured total biomass in some grapevine cultivars after using different shading intensities.

CH: Chardonnay, SE: Semillon, CS: Cabernet-Sauvignon, SY: Seyval blanc, DC: De Chaunac. Numbers in the x-axis represent different studies: 1 (90 % shading - Heuvel et al., 2004), 2 (99 % shading - Heuvel *et al*., 2004), 3 (50 % shading - Porro *et al*., 2001), 4 (70 % shading - Greer *et al*., 2010), 5 (70 % shading - Greer *et al*., 2011), 6 and 7 (60 % shading - Martínez-Lüscher *et al*., 2020), 8 and 9 (80 % shading - McArtney and Ferree, 1999).

The explanation behind this lies in the expression of VvFLS1, the key enzyme in flavonols metabolism, which wasn't detected in shaded treatments.

Sensory traits of must and wine are as well strongly influenced by sun exposure, however, those traits typical of ripened berries are often associated with higher levels of cell death. Moreover, excessive heat and water deficit might cause a decoupling of the ripening, leading to unbalanced wines (Bonada *et al*., 2013). In this sense, shading, by reducing the incidence of solar radiation on the vines, affects the synthesis of these compounds.

Syrah shaded vines experienced, albeit with some variability related to the vintage and the intensity of the shading treatment, a decrease in C6 compounds, alcohols, terpenols and C13-norisoprenoids (Bureau *et al*., 2000).

On the contrary, the use of shading nets on Cabernet-Sauvignon in a semi-arid environment significantly increased the concentration of fatty acids, C6 and C9 compounds in the must (Lu *et al*., 2021). The effects of shading were even more pronounced in the wines, thanks to the action of yeasts, where the shaded treatment caused a significant increase in ethyl esters, norisoprenoids, fatty acids and acetate esters. The intensity of floral, fruity, fatty, caramel, roasted, and chemical aromas were increased, resulting in an overall better sensory profile. Similarly, Pinot noir wines produced in tropical environments benefited from the use of shading nets and the subsequent reduction in temperature, improving their flavour because of a better retention of linalool, octanoic acid, decanoic acid and other highly volatile compounds (Ranjitha *et al*., 2015).

Conversely, there is evidence from another study that shading negatively affects monoterpenes concentration in Riesling grapes, with a higher amount of both free and glycosylated monoterpenes in control vines. (Friedel *et al*., 2016). The authors suggest that the reason for this lies in the different climatic conditions where grapevines are grown: in cooler climates, shading seems to have a detrimental effect on the accumulation of these substances, while, on the other hand, in warmer climates, the reduction in volatilisation caused by strong sunlight and temperature helps in preserving them. As a matter of fact, in Sicily, south Italy, where light intensities and temperature are high, artificial shading of Grillo grapevines reduced grapes temperature to a level that ensures the synthesis of aromatic compounds but prevents their volatilisation (Scafidi *et al*., 2013). This resulted in changes in both their quantity and quality, with a higher concentration of total non-glycosylated and glycosylated compounds, increased benzenoid concentration and a more abundant bound fraction compared to the free one.

5. Effects on vines' vegetative growth and accumulation of reserves

The reduction in photosynthetic activity after applying the shading treatment is very likely to affect vines' vegetative growth and the accumulation of reserves. Specifically, the lower production of sugars that can be moved to the trunk and the other organs can negatively affect the growth in the following season, as it strictly depends on stored reserves (Yang *et al*., 1980, Keller *et al*., 1995).

Several studies reported a reduction in reserves storage as a side effect of the application of the shading treatment (Figure 2).

A study on Seyval blanc and De Chaunac grapevines demonstrated that a high level of shading from flowering until harvest reduced root dry weight in treated vines (McArtney and Ferree, 1999). Moreover, in the following years, in shaded plants, the concentrations of soluble sugars and amino nitrogen in the xylem were lower, thus, forcing vines to rely more on roots starch for their growth. Ultimately, in the year after shading, the total leaf area per shoot was reduced due to the lower number and size of leaves. A 70 % shading cloth applied on Semillon grapevines from budburst to harvest altered vine vegetative growth, i.e., modified proportions of shoot length and delayed shoots and fully-grown leaf area expansion, and reduced vines biomass by almost 20 % (Greer *et al*., 2010).

A deeper analysis of the effects on reserve mobilisation showed that due to shading, Semillon vines faced a decrease in their carbon acquisition and biomass allocation (negatively affecting leaves and bunches), thus, forcing them to rely on their reserves for over 6 weeks after budbreak, when they were finally able to supply their growth autonomously. As stated by the authors, the reduction in carbon acquisition and in its allocation represents a side effect capable of reducing the worth of the benefits derived from the protection against heatwaves in some cases (Greer *et al*., 2011).

On Cabernet-Sauvignon, it was observed that shading caused a reduction in the starch content in the canes of 16.4 % (Lu *et al*., 2021) and a decrease in the dormant pruning mass of 19 and 12 % (Martínez-Lüscher *et al*., 2020) even though it is unknown if this might have had some effects in the following years.

On Chardonnay, it was observed that, despite a significant increase in shoot growth, shading strongly reduced dry matter accumulation by 14 % (Porro *et al*., 2001). Yet, in another study, Chardonnay shaded vines showed a lower total vine dry weight, the higher the intensity of the shading. Interestingly, the various vines' organs were not affected in the same way by this reduction. While the trunk seems to be the least affected, the roots, which comprise the main pool for reserve accumulation, suffered the most by the lower availability of photoassimilate, as indicated by their dry weight and the root-to-shoot ratio. Even in this case, the authors claim that in the long-term, the reduction in the dry matter partitioning to the permanent organs, such as the roots, might result in ramifications for the vines, a decreased resistance to freezing temperature and a lower availability of resources for spring growth (Heuvel *et al*., 2004).

PHOTOSELECTIVE NETS

A new frontier in the use of shading nets is represented by photoselective nets, which in the last years has focused the attention of several studies worldwide.

This innovative strategy combines the protective effects of nets (i.e., protection from hail, excessive radiation, wind etc.) with that of filtering light given by the colour of the chromatic elements incorporated in the net itself. Hence, the effects on the plants are strongly determined by the different wavelengths of the light spectrum that pass through the net (Shahak *et al*., 2016).

Several years of studies in different crops have demonstrated that blue nets tend to lower vegetative growth and stimulate dwarfing; red and yellow nets stimulate vegetative growth and delay plant phenological stages, and yellow nets also increase antioxidants concentration and reduce pre- and post-harvest fungal diseases (Shahak *et al*., 2016).

Pearl nets have been compared to black nets of the same shading capacity on three different cultivars of sweet peppers. Pearl netting induced an increase in net photosynthesis and light use efficiency due to the reduction in UV radiation, the increase in the PAR/UV ratio and a major transmission of PAR even in the more internal layers of the canopy. The alteration of the light environment induced various changes in leaf morphology, reducing the thickness of the epidermis, the carotenoids concentration and changing the ratio between chlorophyll a and b (Kong *et al*., 2017).

For different types of photoselective nets of blue, red, grey and white colour were used on kiwifruit vines in south Italy (Basile *et al*., 2008; Basile *et al*., 2014). The presence of the nets altered the quality of the light passing through them, with changes in the red/far-red ratio and the blue/red ratio in the scattered light. Vegetative growth was stimulated by red and grey nets, while blue nets reduced vigour and induced dwarfing. This is then reflected in the vines' dry weight, which was significantly lower in the blue net treatment and significantly higher in the red one. Production was affected as well: the shading caused by the nets determined a decrease in shoot fertility, resulting in a lower crop load which, however, induced an increase in fruit size and a consequent higher commercial value of fruits.

In Chile, Pinot noir grapevines were shaded with red and pearl nets with the same shading capacity of 20 % for two consecutive years (Corvalán *et al.,* 2016). In the 2013 and 2014 vintage, an increase in vegetative growth of 29 % and 48 % and an increase in total leaf area of 55 % and 43 % were observed with respect to not-shaded vines with the use of pearl and red nets, respectively. Reserve accumulation in the roots was increased by photoselective nets, too, with an 84 % and 45 % increase in root dry weight for pearl and ret nets.

CONCLUSION

As the global temperature is continuously increasing, artificial shading represents an innovative protection strategy against excessive exposure and heat waves.

The reduction in light intensity lowers the photosynthetic activity of the canopy, leading to the lower production of photoassimilates. Whereas the effects on vine yield appear variable, grapes benefit from a lower exposure with a reduced incidence of sunburn, berry dehydration and cell death. By lowering carbon assimilation, nets provide a slowdown of the ripening process, leading to a lower concentration of sugars in the musts and less alcoholic wines.

In general, the organic acid content is increased by netting due to the containment of their depletion, and must pH is usually lowered. Phenolic concentration is mostly decreased by shading since the reduction in light intensity affects the genetic pathways that lead to their biosynthesis, altering the quantity and the proportions of these compounds. The effects on the aromatic components seem rather variable depending on the environment: in warmer climates, where temperature can reach high values determining their volatilisation, net shading improved the aromatic profile of musts and wines by preserving them, while in cooler climates, it seems that grapes exposure to sunlight might increase their production. Reserves accumulation is influenced by the reduced production of photoassimilates, and the constriction of dry matter partitioning seems to take place mostly at the expense of the roots.

Photoselective nets, thanks to their combined protection from adversities and filtration of determined regions of the light spectrum, represent a new horizon in the research on this topic, ensuring a wide range of results in relation to the types of nets used and the response of the various cultivars.

Therefore, using artificial shading represents a valid alternative in viticulture to mitigate the effects of global warming. Albeit with some differences related to the period and method of application and to the intensity of light reduction, at the expense of a reduction in the accumulation of reserves, it allows to slow down the ripening process, prevent the volatilisation of the aromatic compounds and reduce the damages caused by bunches overexposure.

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