AJEV | American Journal of Enology and Viticulture

Research Report
DOI: 10.5344/ajev.2023.23022

Sunburn and its Relation to Maturity and Concentration of Aromatic Compounds in Bush-Trained Muscat of Alexandria Vines

Kasandra Ibarra I,[1] Ignacio M. Serra,[1] Álvaro Peña-Neira,[2] Nicolás Bambach,[3,4] Pedro Puentes,[1] and Arturo Calderón-Orellana[1*]

Abstract

Background and goals

Sunburn is one of the most important problems in fresh fruit production, but little information exists about its effect on the winegrape industry. The objective of this study was to physically and chemically characterize the severity of sunburn in berries from traditionally farmed Muscat of Alexandria vineyards.

Methods and key findings

Three Muscat of Alexandria nonirrigated vineyards, each of a high (~50 cm from the soil) and a low (2 to 10 cm from the soil) fruit zone height, were selected in the Itata valley, Chile. Sunburn damage at commercial harvest was estimated for two consecutive years. There were no differences in soluble solids concentration, weight, shape, color, or sunburn severity of berries between fruit zone heights. Results showed that 40% of sampled berries exhibited moderate to severe symptoms of sunburn. The appearance of sunburn lesions on the berry surface correlated with changes in hue and maximum chlorophyll fluorescence, but not with the concentration of soluble solids. In general, greater concentrations of volatile terpenes were associated with more severe symptoms of sunburn in berries, and linalool showed the clearest response to sunburn damage.

Conclusions and significance

Contrary to previous research, our results indicate that moderate levels of berry sunburn induce positive changes in the aromatic profile of berries. However, the high incidence of berry sunburn found in the present study highlights the significant vulnerability of traditional farming systems to high solar radiation and thermal stress.

Key words: climate change, dryland vineyards, terpenes, thermal stress, *Vitis vinifera* (L.)

Introduction

Fresh fruit sunburn is a critical issue affecting the quality of horticultural commercial production. For instance, sunburn in apples can reduce marketable yield by as much as 20% (Wünsche et al. 2001). Recent technical reports claim that sunburn is the leading cause of apple "packouts," affecting more than 50% of harvested fruit in some years (Schmidt 2018). However, there is a lack of knowledge about the effect of sunburn on table and wine grape production (Greer and La Borde 2006).

The symptoms of sunburn in grape berries depend on several factors, such as variety, stage of development, and the presence of abiotic stress. Nevertheless, sunburn damage in grapevines exhibits clear physical symptoms in berry skins, which includes the degradation of chlorophyll and other photosynthetically active pigments (i.e., anthocyanins and carotenoids), the appearance of brown lesions, and the development of a shiny surface due to epicuticular wax crystalline structure losses (Greer et al. 2006). Moreover, sunburn-induced damage to the skin may increase the risk of berry dehydration due to a greater permeability of the cuticle to water loss (Bondada and Keller 2012).

From a commercial perspective, sunburn reduces the cosmetic value of berries, which may affect the vineyard's profitability. In Australia, winegrapes can be categorized as low-quality fruit if sunburn damage is identified in the winery (Gambetta et al. 2021). Although there is a lack of information about the effect of sunburn on wine quality, some markets consider the presence and severity of sunburn damage in the fruit to be a relevant defect. In Chardonnay, wines made with berries affected by sunburn tended to be more bitter, darker, and slightly less aromatic than those made with healthy berries, but no chemical analyses were provided (Greer and La Borde 2006). Traditionally, the presence of sunburn in fruits has been associated with air temperatures above 40°C.

[1]Facultad de Agronomía, Departamento de Producción Vegetal, Universidad de Concepción, Chile; [2]Facultad de Ciencias Agronómicas, Departamento de Agroindustria y Enología, Universidad de Chile, Chile; [3]Agricultural Research Service, U.S. Department of Agriculture, Davis, CA, USA; [4]Department of Enology and Viticulture, University of California, Davis, CA, USA.

*Corresponding author (arcalderon@udec.cl; tel: + 56 42 220893; fax: + 56 42 2208700)

Submitted April 2023, accepted Oct 2023, published Nov 2023

However, recent studies have detected the appearance of sunburn lesions in berry skins from clusters exposed for five hours to air temperatures from 24 to 30°C and to solar radiation levels ~2.7 MJ/m^{2}hr (Rustioni et al. 2014). These results indicate that berry sunburn can be induced at ambient temperatures considerably lower than those usually thought (Greer and Weedon 2013).

The interaction of the physiological, morphological, and biochemical characteristics of the fruit with the phenological stage, cultivar, and adaptability to environmental conditions determines the incidence and severity of sunburn damage in berries (Gambetta et al. 2021). Highlighting the role of fruit exposure to sunlight as a key determinant of sunburn in grape berries, Chorti et al. (2010) reported that removing leaves from the fruit zone at fruit set resulted in the highest level of sunburn damage in berries (37.5% of sunburn damage). Fruit overexposure is more often found in low-vigor vines (Romboli et al. 2017) or when shoots are severely trimmed during ripening (Diago et al. 2012).

The Itata valley is one of the few wine regions in Chile where vines are bush-trained and not irrigated during the whole growing season (Serra et al. 2017). In the bush training system, vines are not arranged in a permanent support structure, and vegetation appears discontinuously along the row (Freeman et al. 1992). This cultural management may be a key factor in obtaining unique wines that are representative of the Itata region, as bush-trained Chenin blanc vines have been found to produce berries with high pH but low soluble solids concentration and titratable acidity (Reynolds and Vanden Heuvel 2009). Nevertheless, the bush training system may increase the risk of sunburn on berries because clusters are very close to the warm soil during ripening (Freeman et al. 1992). Muscat of Alexandria is one of the most important cultivars in the Itata valley, accounting for >80% of the total planted area in Chile (SAG 2021). Muscat of Alexandria wines exhibit very characteristic fruity and floral aromas due to high concentrations of terpenes such as linalool, geraniol, and nerol (Black et al. 2015). In the Itata valley, the bush-trained Muscat of Alexandria vines often show low vigor, and clusters are exposed to maximum daily temperatures as high as 35°C for several weeks (Pascual et al. 2017). As global warming models predict a drastic increase in air temperature (up to 4°C) and evapotranspiration in the Chilean central valley in the most pessimistic scenario (Bambach et al. 2021), Muscat of Alexandria vines (especially under dry-farmed conditions) may be more vulnerable to sunburn. Due to the lack of scientific evidence that sunburn damage affects the chemical composition of the berry, a study was conducted to physically and chemically characterize berry sunburn in traditionally-farmed Muscat of Alexandria vineyards, using skin color as an objective measure of sunburn severity.

Materials and Methods

Study site

Six commercial nonirrigated and bush-trained vineyards (*Vitis vinifera* L.) of cv. Muscat of Alexandria, each representative of the traditional viticultural management of the Itata valley (Serra et al. 2017), were selected in 2018 and 2019 from several locations in the Ñuble Region, Chile. Traditional viticultural management includes mechanical weeding, minimal agrochemical application, and hand pruning. Fruit quality determinations, including berry sunburn characterization, were carried out at two fruit zone height classes (high, in which the fruit zone was 50 cm from the soil; and low, in which the fruit zone was between 2 and 10 cm from the soil) (Figure 1). The sampled vineyard blocks were very small, covering an area between 0.01 and 0.08 ha. Vines were planted at various spacing in different years, and all were >50-years-old (Table 1). The soils of Itata valley are derived mainly from the Chilean Coastal Range, exhibiting clay textures with drainage limitations. The study area is characterized by a Mediterranean climate and corresponds to a warm temperate climate with winter rains (663.7 mm/year) and dry summers, according to Köppen's classification (Ciren 2019). Daily values of maximum air temperature, solar radiation, and minimum relative humidity were obtained from the Nueva Aldea weather station

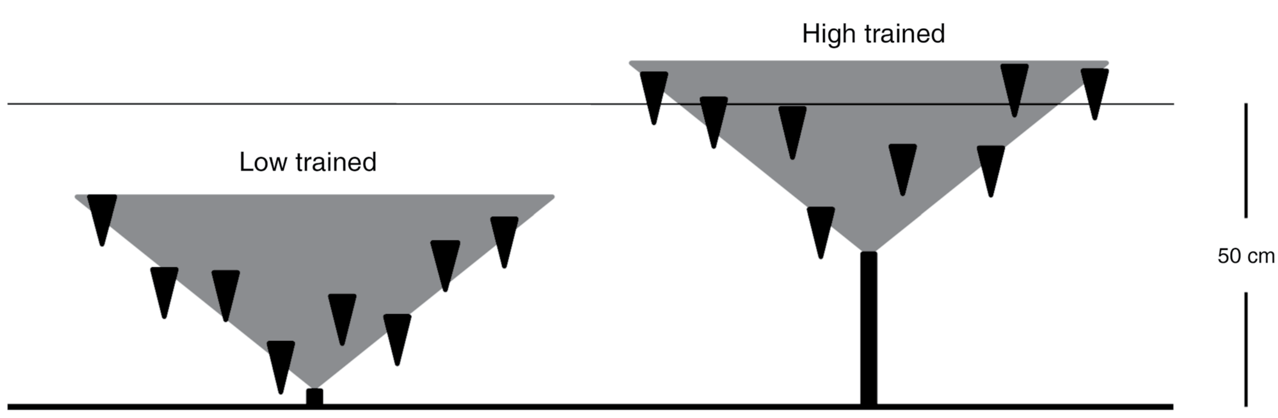

Figure 1 Bush training system in bush-trained Muscat of Alexandria vines under nonirrigated conditions in the Itata valley, Chile. Vines were trained at two heights from the soil (high, 50 cm; low, 2 to 10 cm) during the 2018 and 2019 seasons.

(Inia-Agromet weather network) (36°39′S; 72°27′W), which is located ~10 km from the sampled area, from 1 Oct to 30 April in 2018 and 2019.

Vegetation indices

Two vegetation indices (VI), the normalized difference vegetation index (NDVI) (Equation 1) and the enhanced vegetation index (EVI) (Equation 2), were chosen to estimate vineyard "greenness" at veraison (mid-January) and harvest (last week of March) each season. Satellite images were obtained from the Landsat 8 (30-m pixel) and processed using Google Earth (Gorelick et al. 2017). The atmospheric correction of the images was performed using a Level-1 precision processor, and each VI was calculated using the following equations:

$$\mathrm{NDVI} = \frac{(NIR-RED)}{(NIR+RED)} \quad \text{(Eq. 1)}$$

$$\mathrm{EVI} = 2.5\ \frac{NIR-RED}{(NIR+6\ RED+7.5\ BLUE)+1} \quad \text{(Eq. 2)}$$

Fruit characterization

The harvest time in each vineyard was determined when the average soluble solids concentration of a 200-berry sample reached between 21 and 23 Brix. One day before commercial harvest, all clusters (between 15 and 25 clusters per vine) were collected from three randomly selected vines per vineyard. Because the average vineyard size was less than 0.1 ha (328.3 m^2) (Table 1), the sampling protocol consisted of taking all clusters from at least 3% of the study vineyard, as suggested by Hamilton and Coombe (1992) for small vineyards (<1 ha). A variance component analysis for the concentration of soluble solids (i.e., the ripeness index used in this study) conducted one year prior to this work (2017) showed that the variability among clusters from the same vine was 144% higher than among vines from the same vineyard (data not shown), statistically justifying harvesting more clusters from the same vine rather than fewer clusters from a larger number of vines. Each cluster was counted and individually weighed using an analytical scale (2.0 kg ± 0.01 g) to obtain yield estimates. The yield per vine was calculated as the sum of all the cluster weights. A composite five-berry sample was manually taken from a top (two berries), middle (two berries), and bottom position (one berry) on each cluster (total of five berries per cluster) to estimate sunburn severity in berries based on a visual assessment of skin appearance, where 1 = healthy and green-colored berries; 2 = healthy and amber-colored berries; 3 = moderate damage with light brown lesions; 4 = severe damage with dark brown lesions; 5 = very severe damage with black lesions (Figure 2). The skin hue was measured in each sampled berry using a portable colorimeter (CR-10 Plus, Konica-Minolta). Color readings were carried out at the center of the skin lesion in berries visually affected by sunburn (sunburn severities 3, 4, and 5). After color determinations, the soluble solids concentration and berry size were measured in each berry with an optical refractometer (Atago Hand Refractometer, Atago) and a digital caliper, respectively.

Maximum chlorophyll fluorescence (*Fm*) was measured at harvest using a portable fluorimeter (Pocket Pea, Hansatech Instruments) in three berries per class of sunburn severity (n = 15). *Fm* was measured in berries covered with adapted fiberoptic probes and maintained in total darkness for 30 min. Fluorescence readings were made after exposing the berries to saturated light conditions (4000 μmol/m^2sec for 0.8 sec). Measurements were made at the fruit center for healthy berries (severities 1 and 2) and at the center of the lesion for sunburn-damaged berries (severities 3, 4, and 5).

The determination of volatile aromatic compounds was performed for three classes of sunburn severity (1, 3, and 5) that were collected and kept at -20°C until chemical

Table 1 Location, plant spacing, five-year average, soil characteristics, block size, and row orientation of vineyards that exhibited two fruit zone heights (high, 50 cm; low, 2 to 10 cm) in bush-trained Muscat of Alexandria vines.

Feature	High fruit zone			Low fruit zone		
	Vineyard 1	Vineyard 2	Vineyard 3	Vineyard 1	Vineyard 2	Vineyard 3
Latitude	-36.861	-36.845	-36.798	-36.851	-36.846	-36878
Longitude	-72.464	-72.448	-72.449	-72.452	-72.435	-72.452
Plant spacing (m)	1.2 x 1.5	1.4 x 2.8	2.5 x 1.2	2 x 1	1.5 x 1	1.5 x 1
Five-year average yield (ton/ha)	21.1	11.4	13.1	31.9	13.8	18.4
Soil taxonomy	Fine, kaolinitic, isomesic Ultic Palexeralfs family (Alfisol)	Coarse loamy, mixed, thermal Fluvaquentic Haploxerolls family (Mollisol)	Coarse loamy, mixed, thermal Fluvaquentic Haploxerolls family (Mollisol)	Fine loamy, mixed, thermal Fluvaquentic Eutrochrepts family (Inceptisol)	Fine, kaolinitic, isomesic Ultic Palexeralfs family (Alfisol)	Fine, kaolinitic, isomesic Ultic Palexeralfs family (Alfisol)
Soil texture	Clayey	Sandy clay	Loamy clay loam	Loam	Clayey	Clayey
Block size (m^2)	250	340	764	325	194	100
Row orientation	SW-NE	N-S	N-S	N-S	N-S	SW-NE
Other notes	Slope 8-15%	Slope <5%, may flood in winter	Slope <5%, water table close to one meter	Slope <5%, imperfect drainage	Slope >15%.	Slope >15%

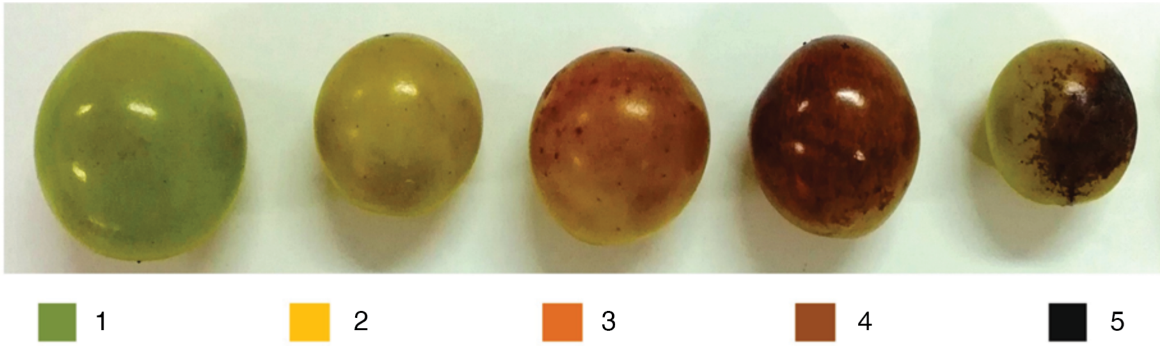

Figure 2 Scale used for the visual evaluation of skin appearance in berries from bush-trained Muscat of Alexandria vines under nonirrigated conditions in the Itata valley, Chile. 1 = Green berries (healthy); 2 = amber berries (slight); 3 = damage with skin browning (moderate); 4 = damage with dark browning (severe); 5 = damage with cell death (black skin) (very severe).

analysis. For determination of volatile aromatic compounds, grapes were defrosted at ambient temperature for over 40 min, and the seeds were removed. Afterward, three grapes were crushed in a 50-mL Falcon tube using an Ultra-TurraxTM homogenizer for 1 min. Then, 3.75 g of the sample was placed in a 20-mL glass vial, and 3.75 of milliQ water and 10 µL of 4-methyl-2-pentanol (0.75 mg/L) (used as an internal standard) were added. For the extraction and analysis, the methodology employed in Ubeda et al. (2017) was followed. The extraction was carried out in an MPS Autosampler (Gerstel), incubating the vial for 20 min at 45°C with agitation at 500 rpm. Then, the selected solid-phase microextraction fiber was a 2-cm 50/30-µm carboxen/divinylbenzene/polydimethylsiloxane (Supelco) placed into the headspace of the vial for 40 min. Afterward, the desorption was carried out in the injector in the splitless mode for 3 min with a transfer line temperature of 280°C. A 7890B Agilent gas chromatography system coupled to an Agilent 5977 quadrupole inert mass spectrometer with a DB Wax capillary column (60 m × 0.25 mm, 0.25 µm film thickness) (J&W Scientific) was used to perform the gas chromatography analysis. Helium was used as the carrier gas at a flow rate of 1 mL/min. The program of the oven was: 35°C for 1 min, followed by an increase to 130°C at 4.5°C/min with holding for 3 min, an increase to 180°C at 2.5°C/min, and then an increase to 230°C at 5°C/min with holding for 1 min. The electron ionization mass spectra were recorded in scan mode at 70 eV in the range of 35 to 300 amu. The mass spectrometry Chemstation software (Agilent Technologies) was used for the recording and processing of the data. Identification of the compounds was done by employing authentic standards when available, as well as by comparing the mass spectra obtained from each molecule with the reference spectra of the NIST 98 software library (only considering compounds identified with a match score >900%) and with the data from the literature. Compounds were treated as tentatively identified when they were only identified by the software. The data were expressed as the relative area with respect to 4-methyl-2-pentanol (internal standard). The relative concentration was calculated by dividing the peak area of the target ion of each compound by the peak area of the target ion of the internal standard (Ubeda et al. 2020).

The standard compounds used in this study for identification and quantification of volatile compounds were supplied by Sigma-Aldrich, including hexanal, (E)-2-hexenal, benzaldehyde, hexanol, benzyl alcohol, linalool, β-citronellol, nerol, and geraniol. Sodium chloride and 4-methyl-2-pentanol (internal standard) were purchased from Merck.

Experimental design and statistical analysis

This study was replicated three times in each of two consecutive years (2018 and 2019) and analyzed as a completely randomized design, where each vineyard with a fruit zone height was considered a replicate. Each replicate was randomly selected from several bush-trained vineyards under dry-farmed conditions with high and low fruiting zones. Means of various fruit parameters were analyzed by analysis of variance (ANOVA), and differences ($p < 0.05$) were subjected to Fisher's least significant difference means separation test. All statistical procedures were carried out using SAS-Studio 9.4 software (SAS Institute, Inc.).

Results

At anthesis, solar radiation ranged between 15 and 20 MJ/m^2 in both seasons (Figure 3A). Close to veraison, solar radiation reached the maximum seasonal levels of ~30 MJ/m^2 in both seasons. Thereafter, a progressive decrease in solar radiation was observed, reaching values similar to those measured at anthesis. Weekly averages of maximum air temperatures never exceeded 35°C, and reached the highest seasonal values around veraison (90 days after anthesis) (Figure 3B). From budbreak to harvest (October to March), there were 63 and 41 days with maximum air temperatures above 30°C in the first and second seasons, respectively.

Vines with high and low fruit zones exhibited similar VIs (EVI and NDVI near 0.6) between veraison and harvest. There was a slight decrease in both VIs during ripening (~10%), but differences were only detected in the second season (Table 2). There were no differences in yield per vine, number of clusters, and cluster weight between fruit

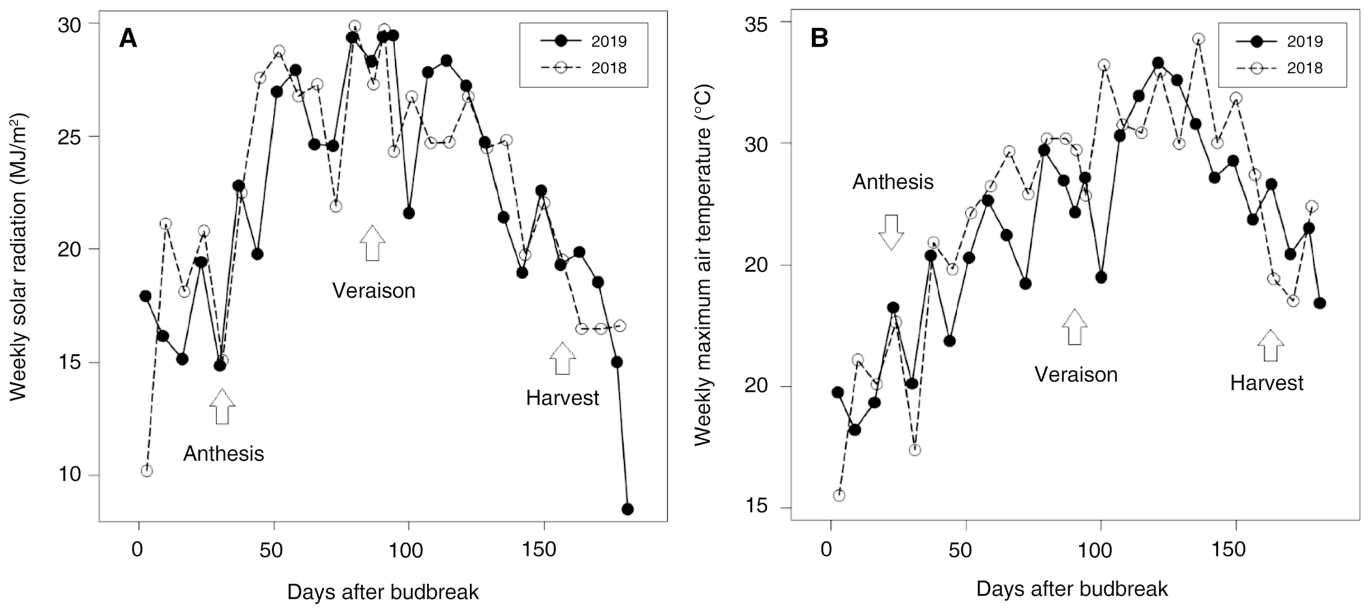

Figure 3 Weekly averages of solar radiation (**A**) and maximum air temperature (**B**) recorded at noon (1200 to 1500 hrs) from 1 Oct to 30 March in the 2018 and 2019 seasons at the Nueva Aldea agrometeorological station, Ñuble Region, Chile.

zone heights (Table 3). Although the yield per vine was similar in both seasons, the cluster number was significantly lower in 2017. However, the cluster weight was 19% higher in 2017. All clusters were harvested near 21 Brix each season. Differences in fruit height did not lead to differences in soluble solids concentration, berry diameters, or skin hue. The polar diameter of the berry was slightly higher than the equatorial diameter (10%) in both seasons. The hue of berry skins was 29.2% higher in the first season (104.9 in 2017 and 74.17 in 2018). The average severity of berry sunburn was near 2.2 in both seasons, with similar levels of severity between fruit zone heights. The combined incidence of moderate and severe sunburn was nearly 40% in both seasons (Figure 4A and 4B).

There was a quadratic relationship between skin hue and soluble solids concentration (R^2 = 0.59, $p < 0.05$) in berries from clusters that exhibited various levels of sunburn incidence (Figure 5). The hue variation was not associated with changes in the soluble solids concentration for sunburned berries, regardless of the damage severity. By contrast, healthy berries showed higher total soluble solids (TSS) as the hue decreased. There was a strong linear relationship between the *Fm* and the color parameter hue (R^2 = 0.72; $p <$ 0.0001) for berries that represented five visual categories of sunburn damage (Figure 6). Thus, the more severely damaged berries were associated with the lowest values of *Fm* and hue, while healthy berries exhibited higher values of *Fm* and hue.

No significant season-by-severity interaction was detected in the present study, which is why pooled data are presented for sunburn severities and seasons. The ANOVA showed no differences in the concentration of the analyzed volatile aromatic compounds among sunburn severities (Table 4). Total terpenes in berries affected by moderate sunburn were three-times higher than in "healthy" berries.

Table 2 Normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI) of vineyards that exhibited two fruit zone heights (high, 50 cm; low, 2 to 10 cm) in bush-trained Muscat of Alexandria vines at veraison and harvest during the 2018 and 2019 seasons.

	NDVI		EVI	
	2018	2019	2018	2019
Phenological stage				
Veraison	0.69	0.66 a[a]	0.68 a	0.62 a
Harvest	0.66	0.62 b	0.59 b	0.55 b
Height of the fruit zone				
High	0.68	0.64	0.64	0.61
Low	0.67	0.64	0.63	0.56

[a]Different letters indicate significant differences between columns at 95% confidence level (least significant difference). n = 3.

Table 3 Yield components and fruit quality parameters at two fruit zone heights (high, 50 cm; low, 2 to 10 cm) in bush-trained Muscat of Alexandria vines during the 2018 and 2019 seasons.

Yield components	Fruit zone height		Season	
	High	Low	2018	2019
Production per plant (kg)	4.4	3.2	3.8	3.8
Number of clusters per plant	19.9	14.9	15.9 b[a]	18.8 a
Cluster weight (g)	217.7	196.0	224.5 a	189.2 b
Berry quality				
Soluble solids concentration	20.2	21.2	20.6	20.8
Pole diameter (mm)	19.0	17.8	18.3	18.5
Equatorial diameter (mm)	16.5	15.7	16.0	16.3
Skin hue	96.7	82.4	104.9 a	74.2 b
Sunburn severity	2.28	2.23	2.39	2.13

[a]Different letters indicate significant differences between columns at 95% confidence level (least significant difference). n = 3.

A two-fold decrease in total terpenes was observed in severely sunburned berries compared with moderately sunburned berries. The total concentration of terpenes was two times higher in severely sunburned berries than in "healthy" berries. The orthogonal contrast analysis showed that the concentration of linalool in healthy green berries was 60% lower than in sunburned berries (Figure 7). The concentration of volatile aromatic compounds tended to be higher in 2019, but differences were only detected for linalool, geraniol, and *trans*-2-hexenal. Thus, the average concentration of these three compounds together in 2018 was five-times lower than in 2019 (17.5 versus 105.6 μg/L, respectively). The exception was the β-citronellol, which was 64% lower in 2019.

Discussion

Despite differences in fruit zone height, the concentration of soluble solids was similar for all vines, reaching a technical

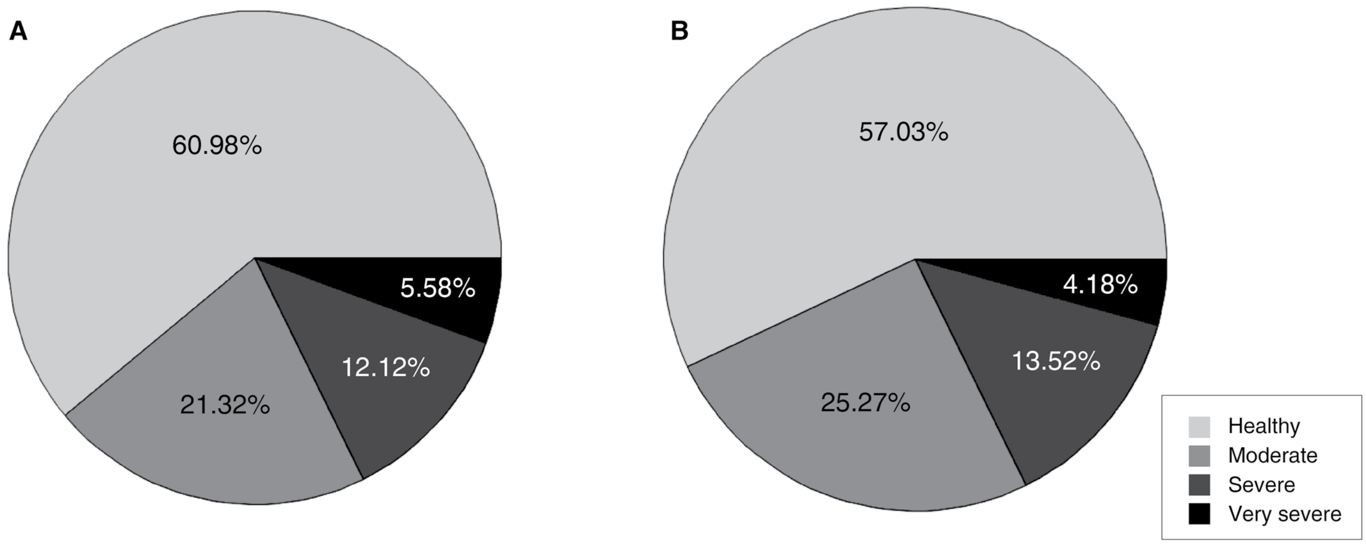

Figure 4 Percentage of berries from bush-trained Muscat of Alexandria vines under nonirrigated conditions in the Itata valley, Chile, showing different categories of sunburn damage (healthy, berries without lesions; moderate, faint reddish-brown lesions; severe, clear brown lesions; very severe, dark brown lesions) for the 2018 (**A**) and 2019 (**B**) seasons.

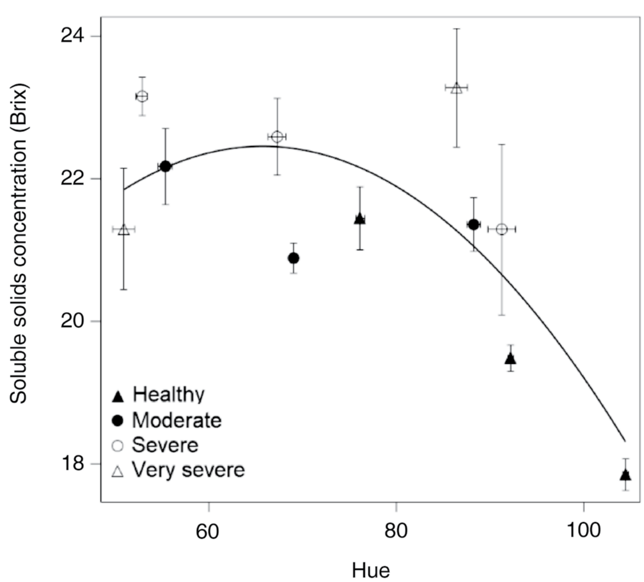

Figure 5 Quadratic relationship between nine hue categories and soluble solids concentration (Brix) at harvest time (end of March) of berries that were visually categorized by sunburn severity (healthy, berries without lesions; moderate, faint reddish-brown lesions; severe, clear brown lesions; very severe, dark brown lesions) in bush-trained Muscat of Alexandria vines under nonirrigated conditions in the Itata valley, Chile ($-0.0028 x^2 + 0.36x + 10.5$; $R^2 = 0.59$; $p \leq 0.05$; n = 11). Error bars represent ±1 standard error of the mean.

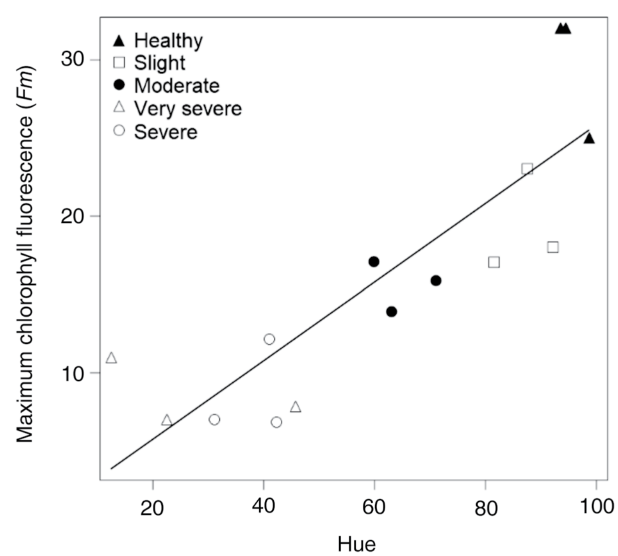

Figure 6 Linear relationship between hue and maximum chlorophyll fluorescence (*Fm*) in skins of berries that were visually categorized by sunburn severity (healthy, berries without lesions; slight, faint reddish-brown lesions; moderate, faint reddish-brown lesions; severe, clear brown lesions; very severe, dark brown lesions) in bush-trained Muscat of Alexandria vines under nonirrigated conditions in the Itata valley, Chile at harvest time (5 April) ($0.25 x + 0.72$; $R^2 = 0.72$; $p \leq 0.0001$; n = 15).

maturity appropriate for producing dry white wines from the Muscat of Alexandria cultivar (~21 Brix). These results were somewhat unexpected because clusters at the low fruit zone were closer to the warm soil, which may have stimulated berry dehydration and TSS increase in bush-trained vines. In the Itata valley, Pascual et al. (2017) reported that clusters from bush-trained Muscat of Alexandria vines were exposed to high air temperatures (>30°C) at least 30% of the time during the growing season. The lack of differences in soluble solids concentration between fruit zone heights was also observed for the remaining fruit quality parameters and yield components. This indicated that fruit zone height had no effect on the reproductive growth behavior of bush-trained vines even under nonirrigated conditions.

The high percentage of sunburn damage found in this work (>40%) supports the hypothesis that air temperatures <40°C may be sufficiently high to induce sunburn in grape berries, as the maximum air temperature in the study area was rarely >35°C. In the present study, maximum solar radiation exceeded 2.5 MJ/m^2hr from anthesis to harvest (for ~125 days), whereas maximum air temperatures were >30°C later in the season from veraison to harvest (for ~50 days). This means that both air temperature and sunlight intensity were sufficiently high to induce sunburn only throughout the ripening period. During ripening, grape berries have almost no evaporative cooling, as fruit transpiration rates are the lowest of the season (Greenspan et al. 1996). Clusters directly exposed to solar radiation can be several degrees above the air temperature (as much as 12°C) (Spayd et al. 2002). In low-vigor vines, fruit is usually overexposed to environmental conditions, and sunburn damage in berries is frequently found at harvest (Romboli et al. 2017). In general, the Muscat of Alexandria vines from the Itata valley exhibit small canopies and low interception ratios of solar radiation at the fruit zone (~50% of ambient photosynthetic photon flux density at 30 cm above the ground) (Pascual et al. 2017). In the present study, pruning weights averaged ~0.4 kg/vine (data not shown), which is 70% lower than those registered in moderately vigorous vines from the Itata valley

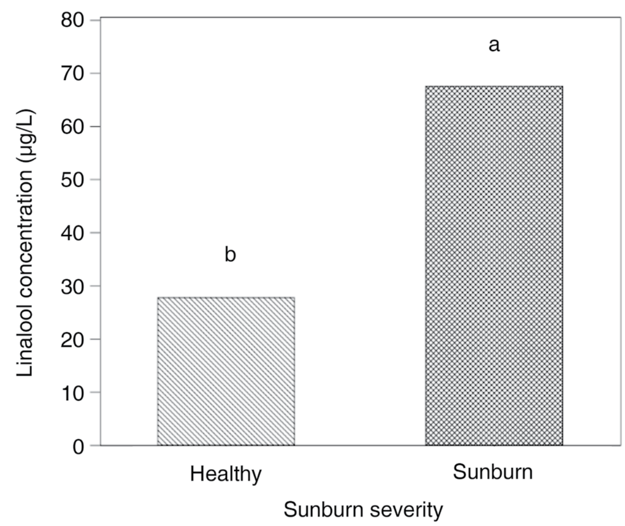

Figure 7 Orthogonal contrast analysis for linalool concentration in healthy (light-gray bar) and sunburned (dark-gray bar) berries of bush-trained Muscat of Alexandria vines under nonirrigated conditions in the Itata valley, Chile, in 2018 and 2019. Different letters indicate significant differences at a 95% confidence level (least significant difference). n = 6 to 12.

Table 4 Main and total volatile compounds concentration at harvest in berries from bush-trained Muscat of Alexandria vines under nonirrigated conditions in the Itata valley, Chile. Sampled berries were visually categorized by sunburn severity (healthy, berries without lesions; moderate, faint reddish-brown lesions; severe, clear brown lesions). Data are expressed in relative area (abundance) with respect to the internal standard.

Volatile aromatic compounds	Sunburn severity			Seasons	
	Healthy	Moderate	Severe	2018	2019
	Hue (90 to 100)	Hue (55 to 75)	Hue (30 to 45)		
Terpenes (g/L)					
Linalool	27.9	94.8	74.3	29.8 b[a]	108.9 b
α-Terpineol	2.5	23.0	26.1	17.2	54.7
β-Citronellol	31.9	62.1	63.2	98.1 a	35.6 b
Nerol	5.3	59.6	33.1	21.7	130.8
Geraniol	13.4	103.1	23.8	14.1 b	172.0 a
Total	91.0	322.6	220.5	180.9	502.0
Alcohols (g/L)					
Hexanol	8.6	25.2	18.0	13.6	21.7
Benzyl alcohol	99.9	212.6	241.6	241.8	148.1
Total	108.5	237.8	259.6	255.4	169.8
Aldehydes (g/L)					
Benzaldehyde	11.2	9.6	14.9	34.10	16.9
Trans-2-hexenal	20.6	10.5	19.9	8.74 b	36.0 a
Total	31.8	20.1	34.8	42.84	52.9

[a]Different letters indicate significant differences between columns at 95% confidence level (least significant difference). n = 6.

(Hidalgo et al. 2017). The study found a consistent reduction in the VIs tested in this study (EVI and NDVI) between veraison and harvest, reflecting a progressive decline in variables that are related to fruit exposure, such as canopy density and plant water status. NDVI and EVI have been correlated with leaf area index (Kang et al. 2022) and midday stem water potential (Helman et al. 2018). However, the lowest values of both VIs were only representative of moderate levels of abiotic stress in grapevine, which explains why, in this study, vines exhibited high yield components for bush-trained vineyards (Baeza et al. 1999) and Muscat of Alexandria vines (Avilez Cofré 2005).

The visual assessment of sunburn severity used in this study based on the physical appearance of skin lesions reflected physical and biochemical changes associated with the effect of environmental stress conditions and fruit ripening. The linear regression analysis indicated that more severe levels of sunburn induced changes in skin hue that were related to reductions in chlorophyll fluorescence, measured as *Fm*. In grape berries, severe oxidative stress can generate irreversible damage in skin chloroplasts, causing chlorophyll degradation and hence, lower emission of fluorescence (Müller et al. 2001, Rustioni et al. 2014). However, the *Fm* values measured in this study were considerably lower than those previously reported for sunburn in grape berries (Greer et al. 2006) and other fruit crops (Wünsche et al. 2001). This finding indicates that fruit from the Itata valley was probably exposed to particularly high levels of oxidative stress, which may explain the higher percentage of sunburn damage (~40%) compared with previous studies (e.g., Greer et al. [2006] found sunburn damage percentages of 5 to 15% for Chardonnay vines in Wagga Wagga, Australia).

The regression analysis between skin hue and soluble solids concentration showed that sunburn-affected berries tended to exhibit higher TSS than healthy berries, which corresponds with the common belief that the occurrence of sunburn accelerates maturity. It has been suggested that the loss of the crystalline structure of the epicuticular wax of sunburn-affected berries may enhance fruit dehydration and increase the soluble solids concentration compared with healthy berries (Muganu et al. 2011). However, the concentration of soluble solids remained near 22 Brix in berries affected by sunburn, regardless of the visual severity of the damage. This may indicate that fruit dehydration is relevant to raise the soluble solids concentration in berries only at moderate severities of sunburn, as there was no increase in TSS for severely damaged berries. For healthy berries, the soluble solids concentration linearly increased from 15 to 21 Brix as hue values decreased from 100 to 70, reflecting the well-known connection between sugar accumulation and chlorophyll degradation in skins during the ripening of white grapevine cultivars. By contrast, berries affected by sunburn exhibited no change in soluble solids concentration (22 Brix), regardless of sunburn severity. The cessation of the TSS increase in berries occurred when the skin hue was near 65, as the inflection point of the quadratic regression between skin hue and TSS was equal to 0 at that value of hue. The linear regression analysis between hue and *Fm* indicated that hue values near 60 were associated with moderate visual symptoms of sunburn. This suggests that a hue of 60 in berry skins may be used as a color index to harvest the fruit in Muscat of Alexandria vines, as no gain in the soluble solids concentration and alcohol is expected at hue values below 60, which are associated with severe levels of sunburn.

The concentration of terpenes in grapes is generally high in areas that exhibit elevated air temperatures and solar radiation because these volatile compounds exhibit plant thermoprotective and antioxidant functions (Joubert et al. 2016). Our results showed that the concentration of several volatile compounds, as well as of total terpenes, tended to be higher in berries affected by sunburn, despite the lack of differences among sunburn severities. The exception was linalool, which had a concentration that was 1.5-fold higher in sunburn-affected berries compared with healthy berries. Linalool is one of the most relevant terpenes that characterize the aromatic profile in Muscat of Alexandria wines; therefore, our findings suggest that the occurrence of sunburn in berries is not necessarily negative for winemaking. The higher concentration of linalool in sunburn-affected berries may respond to a faster biosynthesis of this aromatic compound due to microclimate conditions that induce the appearance of sunburn, specifically sunlight intensity at the fruit zone after veraison, as reported by Belancic et al. (1997). In berries shaded during ripening, linalool has not been detected in the fruit at harvest, unlike other terpenes that have been distinguished in low concentrations (Friedel et al. 2016). In another study, the concentration of glycosylated linalool in sunlight-exposed berries gradually increased during ripening when previously shaded clusters were re-exposed to sunlight (Zhang et al. 2017). Conversely, higher concentrations of linalool have been found in severely defoliated Muscat of Alexandria vines (Pascual et al. 2017). In the biosynthesis process of linalool, there is a light-dependent decarboxylation phase that does not exist in the synthesis of other terpenes (Belancic et al. 1997), which may explain the lack of differences for the remaining volatile compounds analyzed in this study. Because no differences in linalool concentration were found among severities of sunburn, induction of severe sunburn does not appear to be necessary to improve the aromatic profile in Muscat grapes. The lowest concentration of volatile terpenes was detected in the first season, which coincided with the highest number of days above 35°C from veraison to harvest. Elevated air temperatures (>35°C) may increase the anaerobic respiration rate of berries, inducing the synthesis of reactive oxygen species and affecting the monoterpene synthesis pathway (Jiang et al. 2015).

Conclusions

Global warming is expected to increase maximum air temperatures and the frequency of heat waves across the world's wine regions. This may increase the incidence and severity of sunburn damage in grapes, especially in vineyards affected by a combination of temperature, radiation, and water stress. In the present study, visual symptoms of sunburn were apparent in as much as 40% of the analyzed fruit. This may be attributed to the overexposure of clusters from the bush-trained vines to environmental conditions, rather than to the existence of particularly extreme weather conditions. Despite the common belief that sunburn reduces wine quality, our results showed that moderate levels of sunburn may be positive for grapes used for the production of aromatic wines, in which the concentration of volatile terpenes plays a key role in defining wine quality. However, no gain in technical maturity or aromatic profile was observed when sunburn was severe or very severe, which highlights the importance of monitoring sunburn incidence and severity during ripening.

Acknowledgments

We gratefully acknowledge the funding provided by the "Centro de Extensión Vitivinícola del Sur", "Programa de Magíster en Ciencias Agronómicas" Facultad de Agronomía, Universidad de Concepción, Chile, and "Cooperativa Agrícola y Vitivinícola Cerro Negro - Quillón Ltda (COOVICEN).

ORCID

Ignacio M. Serra 0000-0002-5903-4884
Álvaro Peña-Neira 0000-0003-1605-4241
Nicolás Bambach 0000-0002-5060-8781
Arturo Calderón-Orellana 0000-0001-6647-7125

Citation

Ibarra I K, Serra IM, Peña-Neira Á, Bambach N, Puentes P and Calderón-Orellana A. 2023. Sunburn and its relation to maturity and concentration of aromatic compounds in bush-trained Muscat of Alexandria vines. Am J Enol Vitic 74:0740037. DOI: 10.5344/ajev.2023.23022

References

Avilez Cofré PG. 2005. Distintos manejos en el cv. Moscatel de Alejandría destinado a mejorar la producción y calidad como uva de mesa. Thesis, Universidad de Concepción, Chile. http://repositorio.udec.cl/handle/11594/7975

Baeza P, Bartolomé MC, Sotés V, Ruiz C and Lissarrague JR. 1999. Diferencias en la superficie foliar de cuatro sistemas de conducción de la vid y sus consecuencias en el desarrollo y la producción. Invest Agr Prod Prot Veg 14:173-190.

Bambach NE, Rhoades AM, Hatchett BJ, Jones AD, Ullrich PA and Zarzycki CM. 2021. Projecting climate change in South America using variable-resolution Community Earth System Model: An application to Chile. Int J Climatol 42:2514-2542. DOI: 10.1002/joc.7379

Belancic A, Agosin E, Ibacache A, Bordeu E, Baumes R, Razungles A et al. 1997. Influence of sun exposure on the aromatic composition of Chilean Muscat grape cultivars Moscatel de Alejandría and Moscatel rosada. Am J Enol Vitic 48:181-186. DOI: 10.5344/ajev.1997.48.2.181

Black CA, Parker M, Siebert TE, Capone DL and Francis IL. 2015. Terpenoids and their role in wine flavour: Recent advances. Aust J Grape Wine Res 21:582-600. DOI: 10.1111/ajgw.12186

Bondada BR and Keller M. 2012. Not all shrivels are created equal-Morpho-anatomical and compositional characteristics differ among different shrivel types that develop during ripening of grape (*Vitis vinifera* L.) berries. Am J Plant Sci 3:879-898. DOI: 10.4236/ajps.2012.37105

Centro de Informacion de Recursos Naturales (Ciren). 2019. Comuna Quillón, Recursos Naturales. https://www.sitrural.cl/wp-content/uploads/2020/03/Quillon_rec_nat.pdf

Chorti E, Guidoni S, Ferrandino A and Novello V. 2010. Effect of different cluster sunlight exposure levels on ripening and anthocyanin accumulation in Nebbiolo grapes. Am J Enol Vitic 61:23-30. DOI: 10.5344/ajev.2010.61.1.23

Diago MP, Ayestarán B, Guadalupe Z, Poni S and Tardáguila J. 2012. Impact of prebloom and fruit set basal leaf removal on the flavonol and anthocyanin composition of Tempranillo grapes. Am J Enol Vitic 63:367-376. DOI: 10.5344/ajev.2012.11116

Freeman MR, Tassie E and Rebbechi MD. 1992. Training and trellising. *In* Viticulture Volume 2: Practices. Coombe BG and Dry PR (eds.), pp. 42-65. Winetitles, Adelaide, Australia.

Friedel M, Frotscher J, Nitsch M, Hofmann M, Bogs J, Stoll M et al. 2016. Light promotes expression of monoterpene and flavonol metabolic genes and enhances flavour of winegrape berries (*Vitis vinifera* L. cv. Riesling). Aust J Grape Wine Res 22:409-421. DOI: 10.1111/ajgw.12229

Gambetta JM, Holzapfel BP, Stoll M and Friedel M. 2021. Sunburn in grapes: A review. Front Plant Sci 11:604691. DOI: 10.3389/fpls.2020.604691

Gorelick N, Hancher M, Dixon M, Ilyushchenko S, Thau D and Moore R. 2017. Google Earth Engine: Planetary-scale geospatial analysis for everyone. Remote Sens Environ 202:18-27. DOI: 10.1016/j.rse.2017.06.031

Greenspan MD, Schultz HR and Matthews MA. 1996. Field evaluation of water transport in grape berries during water deficits. Physiol Plant 97:55-62. DOI: 10.1111/j.1399-3054.1996.tb00478.x

Greer DH and La Borde D. 2006. Sunburn of grapes affects wine quality. Aust NZ Grapegrower Winemaker 506:21-23.

Greer DH and Weedon MM. 2013. The impact of high temperatures on *Vitis vinifera* cv. Semillon grapevine performance and berry ripening. Front Plant Sci 4:491. DOI: 10.3389/fpls.2013.00491

Greer DH, Rogiers SY and Steel CC. 2006. Susceptibility of Chardonnay grapes to sunburn. Vitis 45:147-148

Hamilton RP and Coombe BG. 1992. Harvesting of winegrapes. *In* Viticulture Volume 2: Practices. Coombe BG and Dry PR (eds.), pp. 302-327. Winetitles, Adelaide, Australia.

Helman D, Bahat I, Netzer Y, Ben-Gal A, Alchanatis V, Peeters A et al. 2018. Using time series of high-resolution planet satellite images to monitor grapevine stem water potential in commercial vineyards. Remote Sens 10:1615. DOI: 10.3390/rs10101615

Hidalgo M, Henríquez R, Merino R, Chandía A and Serra I. 2017. Effect of shoot orientation on vegetative growth, yield parameters and berry composition in grapevine (*Vitis vinifera* L.). *In* Proceedings for the IX International Symposium on Grapevine Physiology and Biotechnology. Pinto M (ed.), pp. 11-16. La Serena, Chile. DOI: 10.17660/ActaHortic.2017.1157.2

Jiang J-M, Lin Y-X, Chen Y-Y, Deng C-J, Gong H-W, Xu QZ et al. 2015. Proteomics approach reveals mechanism underlying susceptibility of loquat fruit to sunburn during color changing period. Food Chem 176:388-395. DOI: 10.1016/j.foodchem.2014.12.076

Joubert C, Young PR, Eyéghé-Bickong HA and Vivier MA. 2016. Field-grown grapevine berries use carotenoids and the associated xanthophyll cycles to acclimate to UV exposure differentially in high and low light (shade) conditions. Front Plant Sci 7:786. DOI: 10.3389/fpls.2016.00786

Kang Y, Gao F, Anderson M, Kustas W, Nieto H, Knipper K et al. 2022. Evaluation of satellite leaf area index in California vineyards for improving water use estimation. Irrig Sci 40:531-551. DOI: 10.1007/s00271-022-00798-8

Muganu M, Bellincontro A, Barnaba FE, Paolocci M, Bignami C, Gambellini G et al. 2011. Influence of bunch position in the canopy on berry epicuticular wax during ripening and on weight loss during postharvest dehydration. Am J Enol Vitic 62:91-98. DOI: 10.5344/ajev.2010.10012

Müller P, Li X-P and Niyogi KK. 2001. Non-photochemical quenching. A response to excess light energy. Plant Physiol 125:1558-1566. DOI: 10.1104/pp.125.4.1558

Pascual GA, Serra I, Calderón-Orellana A, Laurie VF and López MD. 2017. Changes in concentration of volatile compounds in response to defoliation of Muscat of Alexandria grapevines grown under a traditional farming system. Chil J Agric Res 77:373-381. DOI: 10.4067/S0718-58392017000400373

Reynolds AG and Vanden Heuvel JE. 2009. Influence of grapevine training systems on vine growth and fruit composition: A review. Am J Enol Vitic 60:251-268. DOI: 10.5344/ajev.2009.60.3.251

Romboli Y, Di Gennaro SF, Mangani S, Buscioni G, Matese A, Genesio L et al. 2017. Vine vigour modulates bunch microclimate and affects the composition of grape and wine flavonoids: An unmanned aerial vehicle approach in a Sangiovese vineyard in Tuscany. Aust J Grape Wine Res 23:368-377. DOI: 10.1111/ajgw.12293

Rustioni L, Rocchi L, Guffanti E, Cola G and Failla O. 2014. Characterization of grape (*Vitis vinifera* L.) berry sunburn symptoms by reflectance. J Agric Food Chem 62:3043-3046. DOI: 10.1021/jf405772f

Schmidt T. 2018. Apple Sunburn 101. Washington State Tree Fruit Association. http://treefruit.wsu.edu/article/apple-sunburn-101/

Serra I, Castillo P, Hidalgo M, Fuentealba O, Cerda R and Salazar F. 2017. Itata valley: How traditional farming and geomorphological characteristics can became from a limiting factor to key factor in competitiveness. *In* Proceedings for the Fifth International Congress on Mountain and Steep Slope Viticulture. pp. 19-27. Conegliano, Italy. https://www.cervim.org/d/102/atti-completo-orali.pdf

Servicio Agrícola y Ganadero (SAG). 2021. Catastro vitícola nacional 2020. Santiago, Chile. https://hdl.handle.net/20.500.12650/71180

Spayd SE, Tarara JM, Mee DL and Ferguson JC. 2002. Separation of sunlight and temperature effects on the composition of *Vitis vinifera* cv. Merlot berries. Am J Enol Vitic 53:171-182. DOI: 10.5344/ajev.2002.53.3.171

Ubeda C, Gil i Cortiella M, Del Barrio Galán R and Peña-Neira A. 2017. Influence of maturity and vineyard location on free and bound aroma compounds of grapes from the País cultivar. S Afr J Enol Vitic 38:201-211. DOI: 10.21548/38-2-1546

Ubeda C, Gil i Cortiella M, Villalobos-González L, Gómez C, Pastenes C and Peña-Neira A. 2020. Ripening and storage time effects on the aromatic profile of new table grape cultivars in Chile. Molecules 25:5790. DOI: 10.3390/molecules25245790

Wünsche JN, Greer DH, Palmer JW, Lang A and McGhie T. 2001. Sunburn - The cost of a high light environment. Acta Hort 557:349-356. DOI: 10.17660/ActaHortic.2001.557.46

Zhang E, Chai F, Zhang H, Li S, Liang Z and Fan P. 2017. Effects of sunlight exclusion on the profiles of monoterpene biosynthesis and accumulation in grape exocarp and mesocarp. Food Chem 237:379-389. DOI: 10.1016/j.foodchem.2017.05.127