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Research Article

Impact of hail-netting on *Vitis vinifera* L. canopy microclimate, leaf gas exchange, fruit quality, and yield in a semi-arid environment

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Abstract

Hail events have the potential to destroy grapevine shoots, reduce yield, and inflict economic loss upon growers. As a result, many grape growers have adopted the use of hail-netting to mitigate potential vine damage. Although hail-netting has been observed to prevent hail damage, Texas High Plains grape growers have expressed concerns regarding effects hail-netting may have on vine canopy microclimate, grapevine health, fruit maturity, fruit quality and yield. Therefore, over three growing seasons (2018 – 2020), field-grown vines (*Vitis vinifera* L. 'Malbec' and 'Pinot gris') were exposed to hail-netting, or grown without hail-netting. Each growing season canopy microclimate, leaf gas exchange, fruit maturity, yield parameters, and vegetative growth were monitored. Netting reduced canopy air and leaf temperature and decreased canopy vapour pressure deficit. By modifying light infiltration and leaf temperature, hail-netting altered leaf gas exchange. In addition, gas exchange differences were found between cultivars. Although fruit pH and total acidity were not different at harvest, fruit maturity measurements revealed total soluble solid development was influenced by netting and cultivar. Vine cluster numbers were greater for vines without netting and yield parameters were generally lower for 'Malbec' vines. Pruning weights indicate decreased vegetative growth for hail-netting and

‘Pinot gris’ vines. Results suggest grape-growers' use of hail-netting may allow growers to achieve fruit production goals. However, when using hail-netting, growers should consider possible management modifications due to changes in vine physiology, fruit maturation, and harvest schedules.

Keywords

fruit maturity, shade, vine growth, vineyard management

Introduction

Within the State of Texas, the wine and grape industry accounts for approximately $20 billion of annual economic activity (National Association of American Wineries 2022). The Texas High Plains American Viticultural Area (AVA) is the second largest Texas AVA and encompasses an area of roughly 3.5 million ha in the semi-arid western region of Texas. In addition, the High Plains AVA accounts for the majority of grape growing area and produces more grapes than of any Texas AVA (United States Department of Agriculture 2021, Botezau et al. 2022). Grape-growing success of the AVA is due to a variety of climatic and geographical features (Hellman et al. 2011, Kamas 2017, Montague et al. 2020). With favourable soil conditions, low biotic stress factors (low instances of insect and disease pressure) and favourable climate (Hellman et al. 2011, Kamas 2017), the Texas High Plains AVA has gained a reputation for producing high yields and fruit with exceptional quality (Hellman et al. 2011).

Although the Texas High Plains AVA climate and soils are well suited for growing wine grapes, viticulturists encounter several abiotic challenges (Townsend and Hellman 2014, Kamas 2017, Montague et al. 2020). Geophysical challenges within the Texas High Plains include dangerous winter temperatures, late spring frosts, high wind speeds, thunderstorms, extreme temperature fluctuations, drought and damaging hail events (Townsend and Hellman 2014, Kamas 2017, Montague et al. 2020). Townsend and Hellman (2014) list hail as one of the main causes of crop loss within the Texas High Plains AVA. In addition, many growers report hail damage to irrigation and other equipment (Hillin et al. 2022). From 1955 to 2002, Schaefer et al. (2004) report 200 to 600 incidences of hail each decade within the Texas High Plains region. Data indicate hail events within the AVA peak in April (25 to 100 incidents each decade), diminish in July and decrease further in October (Schaefer et al. 2004). From 2007 to 2010, Cintineo et al. (2012) determined the Texas High Plains received between 0.75 and 1.5 hail days on average each year (Fig. 1).

Within the Texas High Plains AVA, April hail events coincide with grapevine budbreak and early shoot growth (Montague et al. 2020). As shoots from secondary buds contain fewer inflorescence primordia and produce fewer fruit clusters, damage to primary shoots from hail events may result in high yield losses (Sánchez and Dokoozlian 2005, Montague et al. 2020). For example, across four *V. vinifera* cultivars (‘Chardonnay’, ‘Tămâioasă Românească’, ‘Pinot noir’, and ‘Fetească Neagră’), Baniță et al. (2020) indicate a single

hail event reduced the number of primary shoots by nearly 90%. Due to fruit damage, increased instances of fungal disease, and leaf area loss, late-season hail events may also result in yield loss as well as reduced fruit quality and fruit maturation (Petoumenou et al. 2019). Furthermore, research suggests hail events have a wide range of effects on grapevine leaf area, fruit composition, and overall vine production (Petoumenou et al. 2019, Vitisphere 2022, Green 2023). Studies also indicate leaf defoliation damage may decrease vine leaf gas exchange and carbon assimilation which are subsequently associated with decreased carbohydrate production and storage, limited fruit set, and reduced yield and cluster weights (Intrieri et al. 2008, Basile et al. 2015). As current year grapevine carbohydrate production and storage are related to current year fruit production and quality, and correlated with winter hardiness and bud primordia production for the following growing season (Sánchez and Dokoozlian 2005, Keller 2020), decreased carbohydrate synthesis due to leaf area loss during the current growing season could lead to reduced yield, smaller clusters, decreased bud hardiness, and reduced vegetative growth the following growing season (Vanden Heuvel et al. 2004, Keller 2020).

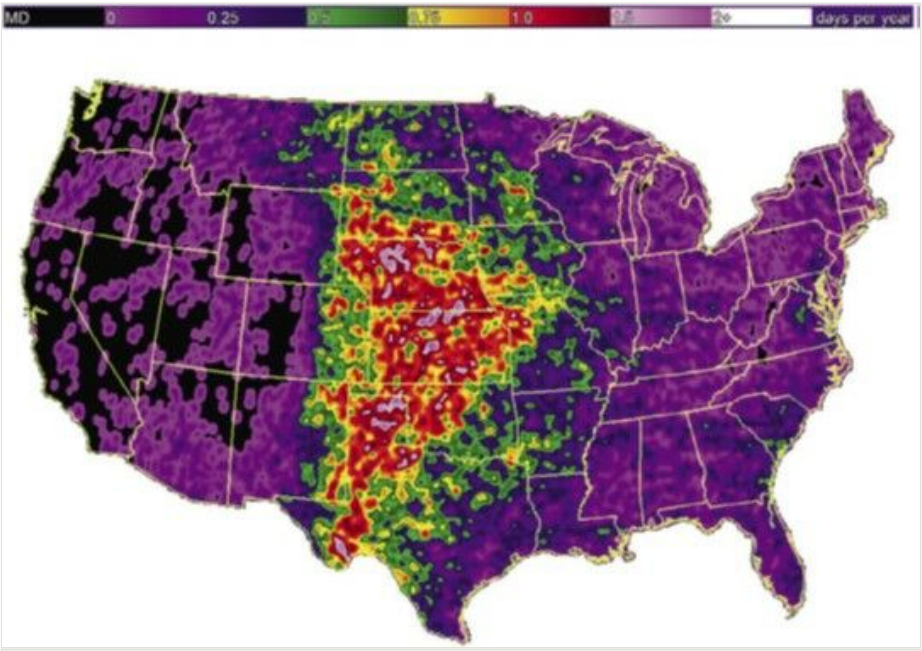

Figure 1. doi

Figure 1. Average annual hail days each year (2007 – 2010) throughout the continental United States (Cintineo et al. 2012).

In a variety of crops such as apples (*Malus domestica* L.), table and wine grapes (*Vitis* spp.), and citrus (*Citrus reticulata* L.), plastic mesh netting, placed on or above the plant's canopy, is widely adopted as a hail-preventative measure (Iglesias and Alegre 2006, Chorti et al. 2010, Wachsmann et al. 2014, Mupambi et al. 2018). Netting has also been utilied for an assortment of other purposes including pest control and selective shading to reduce leaf

or fruit temperature (McArtney and Ferree 1999, Shahak et al. 2008, Wachsmann et al. 2014, Mupambi et al. 2018). Protective nets take many forms with numerous mesh sizes, shading factors, colours, and netting placement in relation to the plant canopy (Cartechini and Palliotti 1995, Chorti et al. 2010, Mupambi et al. 2018). Relative to unnetted crops, netting has been observed to modify canopy microclimate conditions, such as changes in relative humidity (RH), wind speed, light quality, solar radiation infiltration, diminished air flow, and air temperature (Tair) (Iglesias and Alegre 2006, Mupambi et al. 2018).

The common form of hail-netting utilised by grape growers within the Texas High Plains AVA consists of a black, plastic mesh netting (mesh cells are 4 mm x 6 mm) secured around the sides of the vine canopy and covering the fruit zone (Suppl. material 1). Using nets similar to nets used within Texas High Plains vineyards, Iglesias and Alegre (2006) investigated the influence of hail-netting on apple ('Mondial Gala') canopy microclimate and fruit quality. They indicate trees with hail-netting had maximum above-canopy (below netting) photosynthetically active radiation (PAR) reduced by 25% compared to treatments without netting. They also report total soluble solids (TSS) within fruit under hail-netting was reduced 7-11% compared to control trees (Iglesias and Alegre 2006). Chorti et al. (2010) investigated hail-netting over seven-year-old, field-grown, vertically trained, cane-pruned 'Nebbiolo' grapevines. Microclimate under hail-netting was compared with microclimate of vines without nets. Compared to control vines, data indicate hail-netting decreased PAR received within the fruit zone and decreased berry temperature up to 3°C. Furthermore, Chorti et al. (2010) suggest decreased light and lower berry temperature under hail-netting contributed to reduced anthocyanin production, particularly during hot growing seasons. However, although delayed berry maturity was observed for fruit under netting, netting did not affect vine yield (Chorti et al. 2010). In addition, Cartechini and Palliotti (1995) investigated 'Sangiovese' wine grapes using three levels of mesh shading (100, 60, and 30% PAR) and found canopy microclimate conditions were altered with the use of nets. As PAR transmission decreased below netting, leaf temperature (Tleaf), leaf transpiration (E), instantaneous water use efficiency, and ambient vapour pressure deficit (VPD) also decreased (Cartechini and Palliotti 1995). Decreased PAR and other related microclimate factors were directly associated with decreased vine yield, cluster weight, and berry TSS (Cartechini and Palliotti 1995).

Due to the uncertainty of using mesh hail-netting on grapevines, Texas High Plains AVA growers expressed concerns regarding the influence hail-netting may have on vine canopy solar radiation infiltration, vine canopy microclimate conditions, fruit maturity, fruit quality, and yield. As the Texas High Plains AVA is known to have hot, semi-arid weather with high light intensity and increased wind speed (Townsend and Hellman 2014, Graff et al. 2022), grape growers within the AVA desired to know if changes to canopy microclimate conditions induced by hail-netting could provide enhanced canopy-growing conditions yet maintain current yield and fruit quality standards. If yield and fruit quality were positively influenced by hail-netting, costs associated with purchasing, installing, and moving hail-netting may be warranted. Therefore, this research evaluated the influence of hail-netting on vine microclimate, leaf gas exchange, yield, and fruit quality of two *V. vinifera* cultivars grown within the Texas High Plains AVA.

Methods and materials

Experiment site and set-up

Research was conducted within the Texas High Plains AVA in a commercial vineyard near Brownfield, TX (33°09'06.9"N 102°12'57.4"W). Vineyard soils consisted of deep, well-drained Patricia and Amarillo loamy sands with a slope of 0 - 3% (United States Department of Agriculture 2023). Adjacent blocks of *V. vinifera* L. 'Pinot gris' FPS 09.1 grafted on to 1103P rootstocks and own-rooted *V. vinifera* L. 'Malbec' FPS 04 were selected for the experiment. Vines of each cultivar were planted in 2009 and 2011, respectively. Vine by row spacing was 1.5 m x 3.0 m with an east-west orientation. Vines were bilateral cordon-trained (cordons established on a cordon wire 1.0 m above the soil surface), utilising vertical shoot positioning. Each cordon was spur-pruned with four to five spurs on each cordon, and two buds for each spur (Montague et al. 2020, Graff et al. 2022). Early in the 2018 growing season (after cordons were spur-pruned), two netting treatments were initiated for each cultivar: netted and non-netted (control) vines. Although numerous net colours and mesh sizes are available and canopy microclimate may be altered differently by colour of netting (Cartechini and Palliotti 1995, Chorti et al. 2010, Mupambi et al. 2018), for netted vines, black hail-netting was secured using two trellis catch wires placed 1.7 m above the soil surface. Selected netting was similar to netting commonly used by Texas High Plains AVA grape growers, and was 10 UV resistant, 1.0 m wide with 4 mm x 6 mm cells (Grupo Agrotecnologia Mexico, Colonia Tabacalera, Delegación Cuauhtémoc, México). To secure nets around the vine canopy (including the fruit zone), nets were secured to top trellis wires using factory provided clips. Hail nets were secured below the canopy using standard vineyard tying tape (Tie-It, E&E Industries, Lindsay, CA) (Suppl. material 1). Each growing season, hail-netting was installed immediately after final spring pruning (approximately mid-March) and removed 3 - 4 days prior to harvest. Although Texas High Plains AVA grape growers do not re-install netting post-harvest, to evaluate effects of post-harvest netting on vine physiology, netting was re-installed on vines 3 - 4 days post-harvest. Nets remained on vines until mid-October of each experiment year.

For each cultivar, vines were arranged in a randomised complete block design with three blocks within three adjacent vineyard rows. Within each block, there were six adjacent vines of each netting treatment. In addition, treatment vines were separated by six non-treatment guard vines within each block. Therefore, there were a total of 72 vines with 18 vines for each treatment x cultivar. Each experimental year, vines were irrigated and fertilised through a drip irrigation system, and the vineyard was managed by utilising viticulture practices standard for the Texas High Plains AVA (Townsend and Hellman 2014, Kamas 2017, Montague et al. 2020) and as determined by the vineyard manager.

Weather and canopy microclimate

Each growing season (1 April - 31 October), temperature and precipitation data were collected from a West Texas Mesonet weather station (West Texas Mesonet 2023), located

5.0 km from the experiment site. Seasonal growing degree day (GDD) heat unit accumulation was calculated for each experiment year using the following equation (Moyer et al. 2018):

$$GDD = \Sigma (Tmax + Tmin) / 2 – (Tbase)$$

where Tmax and Tmin are mean daily maximum and minimum temperatures, respectively and Tbase equals the base temperature for grapes (10°C). If a daily GDD calculation resulted in a negative value, the value was set to zero (Moyer et al. 2018).

To monitor PAR under netting treatments (‘Malbec’ vines only), one shortwave radiation sensor (LI-COR 200-SZ, LI-COR Biosciences Inc., Lincoln, NE) was positioned in a single vine block of each treatment. Each sensor was placed within the vine canopy (below hail-netting for the netting treatment) and remained exposed to full sun throughout the growing season. Moreover, near each PAR sensor, Tair and RH sensors (HygroVUE5, Campbell Scientific Inc., Logan, UT) were installed within the canopy at fruit level (1.0 m about the soil surface). For each netting treatment, PAR, Tair, and RH sensors were connected to a datalogger (CR10x or CR23x, Campbell Scientific, Logan, UT). Sensor measurements were taken every 60 seconds and means were calculated each hour. Each day of the growing season, hourly and daily means (PAR (Wm^{-2}), Tair (°C), RH (%), and total daily shortwave (MJ $m^{-2}s^{-1}$)) were calculated. Mean hourly VPD was calculated using saturated vapour pressure and ambient vapour pressure of hourly mean Tair and RH data (Jones 2013, Kar et al. 2021a).

Leaf Gas Exchange

Following procedures of Kar et al. (2021b), each growing season, two LI-6400 XT machines (LI-COR Biosciences Inc., Lincoln, NE) were utilised to measure mid-day (solar noon ± 1 hr) leaf gas exchange in netted and control vines. Beginning in May (when mature leaves were present) and continuing until October, leaf net photosynthetic rate (PN), stomatal conductance (gs), E, leaf to air vapor pressure deficit (LVPD), Tleaf, and incident PAR were measured on a bi-weekly basis. A 6400-02B red/blue LED light source and CO_2 mixer were affixed to each machine. To capture environmental light exposure conditions, chambers were placed on tripods and remained level (under the netting in the netted treatment) during each measurement (Suppl. material 2). Vine microclimate growing conditions were simulated during each measurement period by matching chamber light intensity to that of ambient light. Chamber CO_2 was sustained at 400 ppm. Prior to and several times during daily measurement periods, each cuvette was clamped to a nearby non-sample leaf. Tleaf and ambient VPD were observed and conditions within each chamber were then set to closely represent these conditions (Montague et al. 2020).

Each leaf gas exchange measurement day began with selecting one cultivar and randomly selecting a block of vines within the selected cultivar. Within this block, each LI-6400 XT machine measured one fully opened, recently matured (7^{th} to 9^{th} node from shoot tip), full sun, randomly selected leaf from each vine and treatment (Padgett-Johnson et al. 2003, Montague et al. 2020). One machine began measuring leaves from the first vine of the

treatment block and progressed through to vine 6. During the same time period, the other LI-6400 XT began measuring the last vine in the treatment block and progressed through to vine 1. Once measurements were completed on vines within the block, another block of vines was selected, and measurements were completed as described until leaf gas exchange had been measured on all vines of the cultivar. Therefore, leaf gas exchange was measured on each vine within one cultivar prior to measuring leaf gas exchange on the other cultivar. Every measurement date resulted in 36 leaf gas exchange measurements for each hail-netting treatment and cultivar.

Fruit Maturity

Each growing season, starting prior to veraison and continuing through harvest, fruit maturity was monitored as part of a weekly berry juice assay that included TSS, pH, and total acidity (TA). To estimate fruit maturity, 50 berries from each vine were selected. Berries were selected from the top, middle, and bottom of random clusters. Berries were transported to an off-site lab in zipper-locked bags placed on ice within a cooler (throughout harvesting, sampling, and processing, berries were separated by cultivar, vine number, and block). Juice was extracted from each sample using a benchtop stomacher (400Circulator, Seward Ltd., Worthing, W. Sussex, UK) and juice was poured into 50 ml centrifuge tubes (Falcon REF 352098 50 ml Polypropylene Conical Tube, Corning, Corning, NY). To extract juice from precipitating tissues, juice samples were centrifuged two times for five minutes at 6,000 revolutions minute^{-1} (VWR Clinical 200, Avantor Inc., Radnor, PA). In 2018 and 2020, juice was analysed by utilising a Foss WineScan wine analyser (WineScanTM, Foss Analytics, Hilerød, Denmark). In 2019, juice assays were performed using an ATAGO RX-5000α-Bev benchtop refractometer (ATAGO, Tokyo, Japan), and a Mettler Toledo SevenCompact S220 benchtop pH meter (Mettler-Toledo, Columbus, OH). Berries were considered to have reached harvest maturity when mean juice TSS (°Brix) of control samples measured 22° for ‘Pinot gris’ and 24° for ‘Malbec’ (Boulton et al. 1999, Moyer et al. 2018). Each year at harvest, 50 berries from each vine were sampled as described previously and subjected to similar procedures. Boulton (Boulton 1980a) defines titratable acidity as the number of protons recovered during titration with a strong base to a specified endpoint (pH of 8.2). In addition, Boulton (Boulton 1980a) defines total acidity as the number of protons which organic acids would contain if organic acids were undissociated. Therefore, titratable acidity will always be less than total acidity (Boulton 1980a). Total acidity in grape berry tissue is closely correlated with the sum of titratable acidity and with the potassium and sodium content of the juice (Boulton 1980b). Although the use of these terms (total acidity and titratable acidity) interchangeably is misleading (Boulton 1980a), numerous authors describe these as compatible terms (Winkler et al. 1974, Esteban et al. 2002). Therefore, within the context of this paper, total acidity and titratable acidity will be discussed as compatible terms (TA).

Fruit Harvest and Ravaz Index

At harvest, the number of clusters, mean cluster weight, mean berry weight, and total yield were measured for each vine (due to a miscommunication with the grower, ‘Pinot gris’

harvest data were not available for the 2018 growing season). Total individual vine yield was determined using a benchtop scale (ES50L, Ohaus Corporation, Parsippany, NJ). Mean cluster weight for each vine was determined as the ratio of vine total yield to vine total cluster number. Vine mean berry weight was calculated as the ratio of the berry weight sample to 50. Each winter (February through March), vines were pruned and pruning weights for each vine were determined using a hand-held, digital hanging scale (Brecknell ElectroSamson, Brecknell, Fairmont, MN). Ravaz Index for each vine was calculated as the ratio of total vine fruit yield from the previous season to vine pruning weight (Moyer et al. 2018, Graff et al. 2022).

Data Analysis and Statistics

Daily cumulative GDD and precipitation for each experiment year was plotted against day of the year for each growing season (Fig. 2). In addition, total GDD and total precipitation, maximum, minimum, and mean Tair and harvest dates are presented for each growing season (Table 1). The 2020 growing season appeared to be warmer and drier compared to 2018 and 2019 growing seasons (Table 1, Fig. 2). Therefore, because future climatic conditions are predicted to become warmer and drier (Venios et al. 2020), the 2020 growing season was selected as a representative year to demonstrate treatment microclimate conditions within vines. Specifically, for an 18-day period (26 July-12 August 2020), canopy total shortwave radiation, VPD, and Tair measurements were plotted against day of the year (Fig. 3).

Table 1.

Total growing degree day (GDD) accumulation, precipitation, minimum temperature, maximum temperature, mean minimum temperature, and mean maximum temperature from West Texas Mesonet weather station located in Brownfield, TX during the 2018, 2019, and 2020 growing seasons. In addition, harvest date for own-rooted *Vitis vinifera* 'Malbec' and 'Pinot Gris' 'vines grafted to 1103P rootstocks with or without hail-netting. Research conducted in a commercial vineyard located near 'Brownfield, TX.

			Temperature (°C)[z]				Harvest Date	
	GDD	Precipicaton			Mean	Mean		
Year	accumlation[y]	(cm)	Minimum	Maximum	minimum	maximum	'Malbec'	'Pinot Gris'
2018	2,704	39.6	-1.6	40.5	15.4	29.6	05-Sep	*
2019	2,650	32.3	-8.8	42.8	14.8	29.4	15-Sep	15-Aug
2020	2,831	7.7	-5.1	43.3	14.8	31.2	14-Aug	10-Aug

[z]Climate date from 1 Apr to 31 Oct.

[y]Growing degree day base 10.0°C.

[*]Fruit unavailable for harvest.

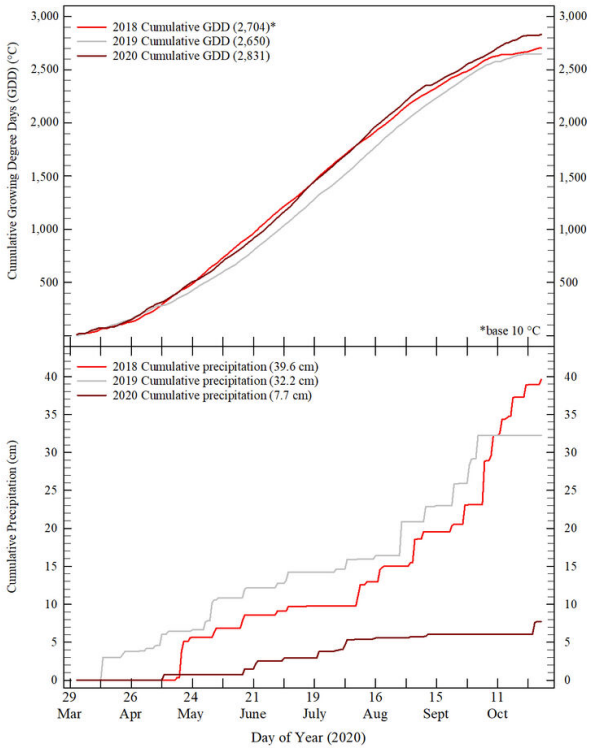

Figure 2. doi

Annual cumulative growing degree days (GDD) (A) and precipitation (B) in Brownfield, TX across the 2018, 2019, and 2020 growing seasons (1 April - 31 October).

Leaf gas exchange (PN, gs, E, LVPD, Tleaf, and incident PAR), yield, pruning weight, and Ravaz Index data for each growing season were exposed to analysis of variance by utilising a General Linear Models procedure appropriate for a randomised complete block design (SAS version 9.4, SAS Institute, Cary, NC). As interactions were not significant amongst years for each variable and means for each growing season yielded similar trends, data from each growing season were pooled. Pooled data were exposed to analysis of variance by utilising a General Linear Models procedure. If differences between means were detected, least squares means were subjected to Tukey-Kramer's procedure ($\alpha = 0.05$). In addition, despite variability in weather between years (Table 1, Fig. 2), fruit development and maturity data followed similar trends each growing season. Therefore, due to variations in vine phenology and harvest dates each year, for results and discussion purposes, statistical analysis of seasonal fruit development will also focus on the 2020 growing season as the representative year. Weekly 2020 seasonal fruit development and maturity data (TSS, pH, and TA) were analysed statistically as previously described. For weekly fruit development and maturity, analysis of variance indicated a treatment x cultivar

interaction. Therefore, TSS, pH, and TA treatment x cultivar means were plotted against day of the year for the 2020 growing season (Fig. 4).

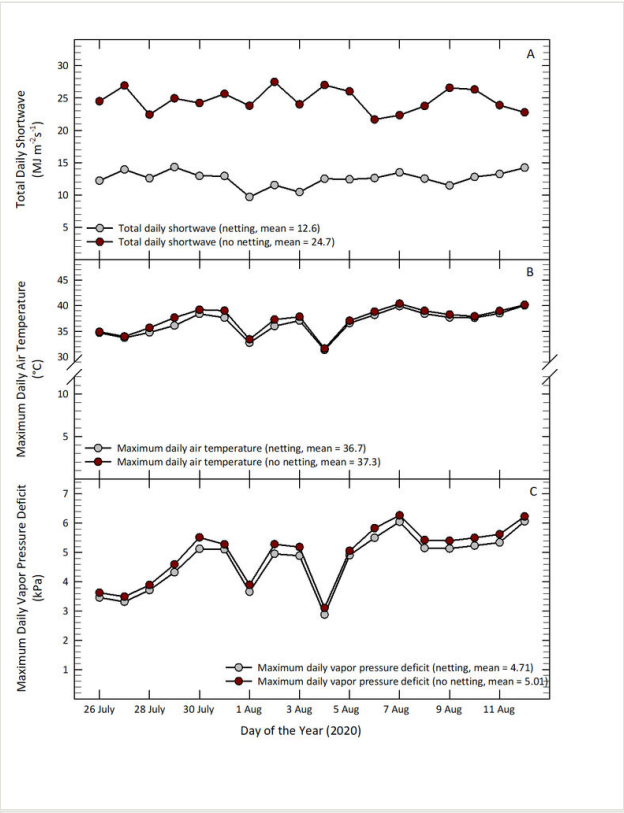

Figure 3. doi

Canopy total daily shortwave radiation (A), maximum daily air temperature (B), and maximum daily ambient vapor pressure deficit (C) below netted and non-netted treatments at vineyard in Brownfield, TX during the 18-day sample period during the 2020 growing season (26 July – 12 August).

Results

Weather and canopy microclimate

The 2020 growing season was warmer and drier than either the 2018 or 2019 growing seasons. When compared to the next warmest growing season (2018), 2020 had a 5% increase in cumulative GDD (Table 1, Fig. 2) . In addition, the 2020 growing season had 80% less precipitation than the next driest growing season (2019) (Table 1, Fig. 2). Vine canopy microclimatic conditions over the 18-day representative period in 2020 indicate an approximate 49% decrease in total daily shortwave radiation under the netted treatment.

Furthermore, compared to control vines, Tair and VPD appear to be lower under the hail-netting treatment (Fig. 3).

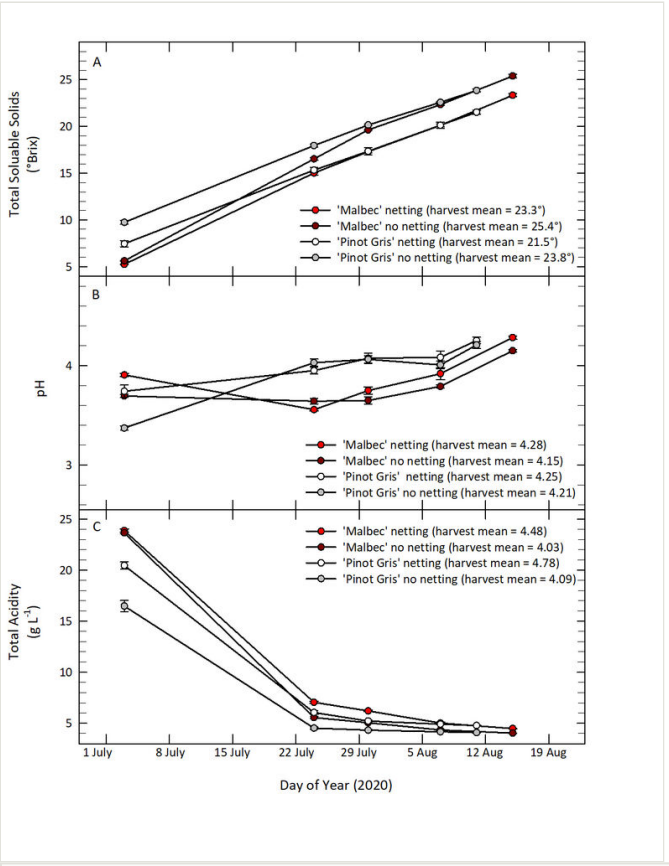

Figure 4. doi

Vitis vinifera 'Malbec' and 'Pinot gris' fruit quality measurements (total soluble solids (A), pH (B), and total acidity (C)) from fruit harvested below netted and non-netted hail-netting treatments within vineyard in Brownfield, TX across the 2020 growing season. Error Bars represent SE for each least squares cultivar x treatment mean (n = 24).

Leaf gas exchange

When compared to vines without hail-netting, data indicated a 25% reduction in PAR and a 0.5°C decrease in Tleaf for vines below hail-netting (Table 2). In addition, when comparing hail-netting to the control treatment, leaf gas exchange data indicate a 4% and 6% decrease in leaf PN and LVPD, respectively (Table 2). In contrast, compared to gs of control leaves, gs of leaves under netting was 6% greater. Leaf gas exchange data also indicated cultivar differences. For example, when compared to 'Malbec', 'Pinot gris' leaves were found to have greater PAR, Tleaf, LVPD, and E (Table 2).

Table 2.

Effect of hail-netting and cultivar on leaf photosynthetic rate, stomatal conductance, transpiration, leaf to air vapor pressure deficit (LVPD), leaf temperature, and photosynthetically active radiation (PAR) for own-rooted *Vitis vinifera* 'Malbec' and 'Pinot Gris' vines grafted to 1103P rootstocks. Research was conducted in a commercial vineyard in Brownfield, TX (data pooled from 2018, 2019, and 2020 growing seasons).

	Photosynthetic rate ($umolm^{-2}s^{-1}$)	Stomatal conductance ($molm^{-2}s^{-1}$)	Transpiration rate ($umolm^{-2}s^{-1}$)	LVPD (kPa)	Leaf Temperature (°C)	PAR ($W\ m^{-2}$)
Treatment						
No netting	10.9a[z]	0.171b	5.8	3.6b	34.2a	1,657a
Netting	10.5b	0.181a	5.8	3.4a	33.7b	1,243b
Cultivar						
'Malbec'	10.8	0.175	5.3b	3.4b	33.2b	1,373b
'Pinot Gris'	10.6	0.177	6.4a	3.7a	34.7a	1,527a
Significance[y]	P > F					
Treatment	0.0171	0.0066	0.9474	<0.0001	<0.0001	<0.0001
Cultivar	0.3434	0.5458	<0.0001	<0.0001	<0.0001	<0.0001
Treatment x Cultivar	0.8975	0.6928	0.6232	0.7156	0.7156	0.8816

[z]Least square means within columns noted by a different letter are different by Tukey-Kramer test (P ≤ 0.05).

[y]Total sample number equals approximately 3,900.

Fruit maturity

Fruit maturity measurements during the 2020 growing season indicate a number of differences between netting treatments and cultivars. TSS measurements indicate a delay in berry sugar development for netted treatments compared to non-netted treatments (Fig. 4). By time of harvest in 2020, TSS of berries under netting was less than TSS of non-netted berries. Furthermore, during the first measurement week, ‘Pinot gris’ berries displayed earlier sugar development compared to ‘Malbec’ berries (Fig. 4). However, as the season progressed, TSS was observed to be similar between cultivars. Differences in berry pH only occurred during the first measurement week when netted treatment fruit had greater pH when compared to fruit harvested from control vines. In addition, slight differences in fruit pH were observed between cultivars with ‘Pinot gris’ fruit having slightly greater pH than ‘Malbec’ fruit across much of the growing season (Fig. 4). In the first week of measurements, differences in fruit TA were observed between netting treatments and cultivars (Fig. 4). For ‘Pinot gris’, berries exposed to the control treatment displayed the

lowest TA. Although berry TA was greater for ‘Malbec’ when compared to ‘Pinot gris’, at this early observation date, treatment did not influence fruit TA of ‘Malbec’ berries (Fig. 4). As the 2020 growing season progressed, treatment and cultivar differences in fruit TA diminished, resulting in treatments and cultivars having similar harvest TA.

Fruit Harvest and Ravaz Index

Harvest of ‘Malbec’ vines occurred on 5 September, 15 September, and 14 August, in 2018, 2019, and 2020, respectively (Table 1). For the 2019 and 2020 growing seasons, ‘Pinot gris’ harvest occurred on 15 August and 10 August, respectively. For each cultivar, harvest was earliest in the 2020 growing season. Specifically, compared to the 2019 growing season, fruit harvest in the 2020 growing season was 5 days earlier for 'Pinot gris' and 32 days earlier for 'Malbec’ (Table 1). Compared to 2020, 'Malbec' fruit was harvested 22 days later in 2018 than in 2020. Pooled harvest data indicate treatment did not affect yield, cluster weight, or berry weight (Table 3). However, for vines under hail-netting, there was a 9% decrease for number of clusters harvested from each vine (Table 3). When compared to ‘Malbec’, yield, cluster number and cluster weight were greater for ‘Pinot gris’ vines. However, berry weight was similar across cultivars. Vine pruning weight pooled from each growing season was 13% greater for control vines when compared to hail-netting vines. In addition, vine pruning weight was 20% greater for ‘Malbec’ vines when compared to ‘Pinot gris’ vines (Table 3). Ravaz Index did not differ between netting treatments. However, Ravaz Index was 31% greater for ‘Malbec’ vines compared to ‘Pinot gris’ vines (Table 3).

Discussion

Weather and canopy microclimate

Based upon location, mean cumulative growing season GDD for the Texas High Plains AVA ranges from 2,028 to 2,653 (Hellman et al. 2011). Cumulative GDD for 2018 and 2020 growing seasons were recorded as greater than this mean. However, GDD for the 2019 season was within the AVA mean range (Table 1). The three-year period(2018 – 2020), mean growing season GDD (2,728) confirms air temperature during experiment years was generally greater than the Texas High Plains AVA mean annual air temperature for the same months. In addition, based upon location within the Texas High Plains AVA annual mean precipitation ranges from 41.4 to 63.7 cm (Hellman et al. 2011). Throughout each calendar year of the study, Brownfield, TX received 45.7, 40.1, and 12.6 cm of precipitation, respectively (West Texas Mesonet 2023). However, total precipitation within the 2018, 2019, and 2020 growing seasons (1 April – 31 October) totalled 39.6, 32.2, and 7.72 cm (Table 1, Fig. 2), respectively. Therefore, precipitation during each experiment year was less than mean annual precipitation. Weather during each experiment growing season was generally drier and warmer than mean annual weather data for the Texas High Plains AVA. In addition, weather data indicate great variability within and between growing seasons (Table 1, Fig. 2), which is typical for weather within the Texas High Plains AVA

(Kamas 2017, Graff et al. 2022) and is indicative of weather challenges faced by Texas High Plains AVA grape growers (Montague et al. 2020, Graff et al. 2022).

Table 3.

Effect of hail-netting or cultivar on pruning weight, yield, Ravaz Index, number of clusters harvested from each vine, cluster weight, and berry weight for own-rooted *Vitis vinifera* 'Malbec' and 'Pinot Gris' vines grafted to 1103P rootstocks. Research conducted in a commercial vineyard in Brownfield, TX (data pooled from 2018, 2019, and 2020 growing seasons).

	Pruning				Cluster	Berry
	weight	Yield	Ravaz	Clusters	weight	weight
	(kg)	(kg vine^{-1})	Index	vine^{-1}	(g)	(g)
Treatment						
No netting	0.38a[z]	3.76	10.76	78.31a	49.8	1.082
Netting	0.33b	3.5	11.82	71.11b	48.2	1.09
Cultivar						
'Malbec'	0.40a	3.40b	9.60b	70.51b	45.26b	1.087
'Pinot Gris'	0.32b	3.97a	13.88a	80.86a	54.45a	1.084
Significance[y]	P > F					
Treatment	0.0032	0.2305	0.2624	0.0353	0.6388	0.8533
Cultivar	<0.0001	<0.0001	<0.0001	<0.0001	0.0336	0.3564
Treatment x Cultivar	0.4807	0.4089	0.3844	0.4453	0.2158	0.6376

[z]Least square means within columns noted by a different letter are different by Tukey-Kramer test (P ≤ 0.05).

Protective hail- or shade-netting over various crops have been shown to decrease PAR intensity below netting (Vanden Heuvel et al. 2004, Iglesias and Alegre 2006, Chorti et al. 2010, Brglez Sever et al. 2020, Peavey et al. 2022). Extent of decreased PAR intensity below netting is related to netting material, mesh size, and distance of hail-netting placement above the plant canopy (Vanden Heuvel et al. 2004, Iglesias and Alegre 2006, Chorti et al. 2010, Brglez Sever et al. 2020). In the current study, over the 2020 18-day representative period, the mean daily total shortwave radiation was approximately 49% less under netting compared to vines without hail-netting (Fig. 3). In contrast, LI-6400 XT PAR sensors indicate light infiltration was reduced roughly 25% for vines under hail-netting compared to vines without hail-netting (Table 2). This discrepancy is likely the result of sensor placement in relation to vine canopy and netting, and timing of LI-6400 XT measurements. LI-6400 XT machines were placed on levelling tripods approximately 0.1 m below hail-netting (Suppl. material 2). Permanent, within-canopy sensors were placed such that levelled sensors were within the plant canopy (foliage never obstructed PAR from reaching sensors), but at a greater distance below hail-netting (approximately 0.5 m).

LI-6400 XT machines were used to estimate leaf gas exchange on nearly cloudless days and only during mid-day, when the sun is generally perpendicular (normal) or close to normal, in relation to LI-6400 XT PAR sensors. Due to the distance LI-6400 XT sensors were from the netting (0.1 m) and the orientation of the sun (zenith angle), it is likely less light was attenuated by hail-netting during LI-6400 XT measurements as compared to permanent PAR sensor measurements (Campbell and Norman 1998, Vanden Heuvel et al. 2004, Jones et al. 2009). Consequently, due to the distance of PAR sensors from netting, time of day, and sun zenith angle, compared to permanent PAR sensors, PAR intensity estimated by LI-6400 XT sensors was greater (Iland 2011).

Numerous studies indicate a decrease in canopy Tair is correlated with application of photo-selective or hail-netting (Cartechini and Palliotti 1995, Iglesias and Alegre 2006, Greer et al. 2011). Our results indicate during the 2020 18-day sampling period, mean canopy Tair below vines exposed to hail-netting was just 0.5°C lower compared to control vines (Fig. 3). Differences in netting placement and abiotic factors in our study compared to previous studies likely resulted in reduced Tair differences between the current and earlier trials. Previous studies which indicate decreased Tair under netting utilised nets that shaded not only plant canopies, but also surrounding soil surfaces. Cartechini and Palliotti (1995) placed nets on frames 2.0 m above grapevine canopies. Furthermore, Iglesias and Alegre (2006) utilised nets that covered the entire orchard and were supported by 5.0 m tall poles. Netting in the current study was placed directly on the plant canopy (Suppl. material 1). Therefore, soil surrounding vines was in full sun for a significant portion of each day. Sandy, light coloured, dry soils (similar to those present in the experiment vineyard) have shortwave reflectance (albedo) which results in high longwave radiation and sensible heat emittance (Campbell and Norman 1998, Montague and Kjelgren 2004, Montague and Bates 2015). Therefore, longwave radiation and sensible heat emitted by vineyard soil was likely absorbed by vine foliage and increased canopy Tair within canopies of all vines regardless of netting treatment (Montague and Kjelgren 2004).

Furthermore, within the current experiment, reduced canopy airflow likely affected Tair differences between netting treatments. Decreased canopy air movement has been observed in previous studies of hail- and photo-selective netting (Brglez Sever et al. 2020). Although not quantitively measured, in the current study when compared to control vine canopies, vine canopies below hail-netting were observed to be more compact in leaf and shoot structure (Suppl. material 3). Compactness of netted canopies occurred because nets restricted outward vine growth which resulted in leaves and shoots being confined. Therefore, it is likely both the netting itself and increased canopy density contributed to reduced airflow within vine canopies under hail-netting. Throughout several growing seasons, Chorti et al. (2010) evaluated Tair of control vines (no netting) relative to netting applied to ‘Nebbiolo’ grapevines. They suggest greater Tair for netted vines was greater than Tair of control vines due to reduced canopy airflow within netted vines. Therefore, in the current study, reduced airflow below hail-netting vines, whether initiated from nets or increased canopy density, likely contributed to reduced Tair differences between canopies of hail-netting and control vines. Within grapevines, increased Tair has been associated with smaller berries, increased berry sugar accumulation, and earlier grape ripening

(Chaves et al. 2010). Therefore, earlier harvest dates during the 2020 growing season are likely weather related. In addition, greater Tair has been associated with accelerated grapevine phenology (Chorti et al. 2010, Venios et al. 2020). Basile et al. (2015) found days between grape single flower separation stage and fruit set stage increased from 15 days in 2009 to 27 days in 2010. Authors attribute delayed phenology during the 2010 growing season to a 2.5ºC decrease in mean daily Tair. Budbreak, fruit set and veraison dates were not recorded in the current experiment. However, harvest dates occurred earlier in seasons with greater cumulative GDD and later within seasons with less cumulative GDD (Table 1).

During the 18-day sampling period within the 2020 growing season, a decrease in mean daily maximum VPD (≈ 0.3 kPa) was recorded under netting (Fig. 3). It is likely more compact canopies, reduced airflow, increased RH, and less light infiltration into vine canopies below hail-netting contributed to the decrease in VPD (Jones 2013, Montague and Bates 2015, Keller 2020). In their study evaluating three levels of shade netting above 'Sangiovese' grapevines, Cartechini and Palliotti (1995) show a decrease in VPD within each netting treatment. Measurements taken by LI-6400 XT machines indicated a 0.5°C decrease in Tleaf within vines below netting relative to control vines (Table 2). As Tair was slightly cooler under netting and only leaves exposed to full sun ambient light conditions were utilised during leaf gas exchange measurements, the decrease in Tleaf under netting treatments was likely instigated by decreased light infiltration under netting. In grapevines, Tleaf is closely correlated with leaf light exposure (Jones et al. 2009, Keller 2020). When evaluating effects of drought on different grapevine cultivars, Schultz (2003) and Schultz and Stoll (2010) found throughout the day, regardless of vine water status, Tleaf increased as leaf light exposure increased. At a given RH, saturation vapour pressure increases exponentially with increased Tair (Campbell and Norman 1998, Montague and Bates 2015). Consequently, VPD also increases as Tair rises. Therefore, it was expected that below netting as Tair decreased, VPD would likewise decrease (Montague et al. 2000, Montague and Kjelgren 2004) (Fig. 3).

Leaf gas exchange

Vine microclimate strongly influences foliage gas exchange (Düring 1987, Schultz and Stoll 2010, Keller 2020). In addition, research indicates foliage gas exchange may differ according to rootstock and scion cultivar (Düring 1994, Tomás et al. 2012). Furthermore, grape leaves alter PN, gs, and E in response to changes in vine water status, Tleaf, VPD, and PAR (Düring 1987, Vanden Heuvel et al. 2004, Schultz and Stoll 2010, Keller 2020). Compared to control vines, hail-netting vines had lower leaf PN and greater gs. In addition, as Tleaf decreased for vines under the hail-netting treatment, a decrease in LVPD was observed (Table 2). These results corroborate previous studies which indicate Tleaf and LVPD tend to follow similar daily diurnal curves with greatest values for each occurring at mid-day or later in the afternoon when Tair, VPD, and LVPD are greatest (Montague et al. 2000, Montague and Kjelgren 2004, Schultz and Stoll 2010). In the current study, decreased LVPD under netted treatments was associated with decreased Tleaf and a subsequent increase in gs. Numerous studies of woody plant foliage indicate that to reduce

leaf evaporative water loss as VPD and LVPD increase, many species (including numerous grape cultivars) will reduce leaf gs and E (Düring 1987, Montague et al. 2000, Schultz 2003 , Schultz and Stoll 2010). As hail-netting vines in this study were subjected to reduced Tleaf and LVPD compared to control vines, gs tended to be greater for netted vines compared to control vines (Table 2). This is contrary to previous studies investigating effects of netting on grapevine leaf-gas exchange. Cartechini and Palliotti (1995) exposed canopies of field-grown 'Sangiovese' grapevines to three levels of light intensity (100%, 60%, and 30% PAR). They explain gs declined in relation to the degree of shading. Martínez-Lüscher et al. (2020) placed nets with a 60% shading factor over the fruit-zone (including leaves) of field-grown 'Cabernet Sauvignon' grapevines. Their data indicate gs of leaves under nets was reduced when compared to gs of leaves exposed to full PAR. In the current study, it is likely leaf gs of vines exposed to hail-netting was greater than leaf gs of control vines because, even though PAR was lower under netted vines (Table 2), reduced diffuse radiation (Iland 2011) and PAR decreased Tleaf and LVPD under nets (Montague et al. 2000, Montague and Kjelgren 2004, Schultz and Stoll 2010, Keller 2020) such that leaf gs of netted vines had a stronger response to lower Tleaf and LVPD than to reduced light intensity (Keller et al. 2019).

For grapevines, leaf PN is strongly correlated to gs (Düring 1987, Gómez-Del-Campo et al. 2004, Keller 2020, Kar et al. 2021b). However, this relationship is often not linear (Gómez-Del-Campo et al. 2004) and may differ amongst cultivar and vineyard growing conditions (Düring 1987, Gómez-Del-Campo et al. 2004). Compared to vines below hail-netting, control vines exhibited greater leaf PN and lower gs (Table 2). Grape-leaf PN is highly dependent on exposure to PAR (Vanden Heuvel et al. 2004, Keller 2020). Therefore, in the current research, as PAR beneath hail-netting decreased, a subsequent decrease in PN was observed (Table 2). Greer et al. (2011) exposed grape leaves to 70% shade by placing netting above 'Semillon' grapevines and found daily maximum PN was 38% lower for netted treatments as compared to non-netted treatments. Moreover, Cartechini and Palliotti (1995) observed a comparable decrease in foliage PN of 'Sangiovese' vines under netting treatments. They report PN decline was correlated to intensity of leaf PAR exposure. Application of hail-netting and subsequent reduction in PAR in the current study resulted in similar trends. Based upon LI-6400 XT measurements, leaves of hail-netting vines received 25% less PAR compared to leaves with no hail-netting and leaf PN of hail-netting leaves was 4% lower compared to leaves of vines receiving full sun (Table 2). The lower degree of PN decrease in the current study as compared to previous research is likely related to netting shade factor differences, vine genotype, and microclimate (PAR, diffuse light, Tair, Tleaf, LVPD, and VPD) that varied between experiment conditions (Düring 1994, Jones et al. 2009, Schultz and Stoll 2010, Iland 2011).

Although leaf PN and gs for 'Malbec' and 'Pinot gris' did not differ, cultivar leaf gas exchange differences were observed. Compared to leaf gas exchange for 'Malbec' vines, Tleaf, E, and LVPD were greater for leaves of 'Pinot gris' vines (Table 2). As confirmed by Keller (2020), differences between cultivar leaf gas exchange is frequently genotype (cultivar) related and numerous authors (Montague et al. 2000, Schultz 2003, Gómez-Del-Campo et al. 2004, Santesteban et al. 2009, Chaves et al. 2010) show comparable results

for several grape cultivars. However, even though cultivar, vineyard location, and weather conditions may alter leaf gas exchange measurements (Schultz 2003, Keller et al. 2019, Keller 2020), in the current study, it is likely time of day when collecting leaf gas exchange data also impacted leaf gas exchange results. For most days, when leaf gas exchange data were measured, 'Malbec' leaf gas exchange was measured first and earlier in the day. Therefore, later in the day, 'Pinot gris' leaves were exposed to increased PAR, diffuse radiation, and greater Tair and VPD (Montague et al. 2000, Montague and Kjelgren 2004, Jones et al. 2009) (Table 2). As a result, when compared to 'Malbec' leaves, 'Pinot gris' leaves were exposed to greater light levels, and had greater Tleaf and LVPD (Table 2). However, although 'Pinot gris' leaves had greater LVPD than 'Malbec' leaves, PN and gs for 'Pinot gris' and 'Malbec' leaves were similar. Therefore, compared to leaves of 'Pinot gris', leaves of 'Malbec' appear to use available PAR more efficiently (maximise PN at lower PAR levels) (Vanden Heuvel et al. 2004). However, leaves of 'Pinot gris' display the capacity to maximise PN and E when exposed to more adverse microclimate conditions (greater PAR, Tair, VPD, Tleaf, and LVPD). Differing grape cultivar response to PAR, Tair, VPD, Tleaf, and LVPD has been noted by many authors (Santesteban et al. 2009, Zhang and Keller 2015, Keller et al. 2019) and is likely related to genotype and vineyard environment (Düring 1994, Schultz 2003, Schultz and Stoll 2010). Based upon results, as far as leaf gas exchange is concerned, it appears 'Pinot gris' vines are better adapted to the semi-arid West Texas AVA growing conditions than 'Malbec' vines. However, under lower PAR, Tleaf, and LVPD microclimates (such as under hail-netting), 'Malbec' leaf gas exchange appears to be more acclimatised.

Fruit maturity

Light interception within a grape canopy contributes to variability in fruit composition and maturity seen amongst clusters (Morrison and Noble 1990, Mullins et al. 1992). TSS measurements from 2020 indicated a delay in fruit development under hail-netting (Fig. 4). Such a delay in maturation is consistent with findings of Shahak et al. (2008) in which black netting was found to delay maturation of 'Red Globe' table grapes. Others (Morrison and Noble 1990, Cartechini and Palliotti 1995, McArtney and Ferree 1999, Chorti et al. 2010) reveal similar results. Reduced TSS in hail-netting fruit is likely due to decreased PN (Table 2) and lower carbohydrate transport from netted leaves when compared to leaves of control vines (Morrison and Noble 1990). Cartechini and Palliotti (1995) and Chorti et al. (2010) found a similar relationship amongst PAR, PN, and TSS development throughout experimental growing seasons, and TSS data in the current study concurs with their results (Table 2, Fig. 4). Although there is not a simple relationship between TA and pH (Keller 2020), reduced PAR incidence on grape foliage has been shown to influence grape-berry pH and TA. These results have been presented by several authors (Smart et al. 1985a, Morrison and Noble 1990, Mullins et al. 1992). Compared to control vines (no shade), Smart et al. (Smart et al. 1985a) demonstrate berry maturity (TSS, pH, and TA) were delayed when vine foliage was constrained into a smaller volume (increased shade) with bird-netting placed around mature 'Shiraz' vines. However, in agreement with current research, pH and TA were similar at harvest (Fig. 4). Morrison and Noble (1990) exposed field-grown, 12-year old 'Cabernet Sauvignon' vines to total shade (entire vine canopy

covered by shade), leaf shade (only foliage covered with shade), and control (no shade) treatments. Similar to previous results, berry TSS, pH, and TA differed from veraison to harvest. However, compared to control vines, at harvest 'Cabernet Sauvignon' fruit under shade treatments had lower TSS, but TA did not differ. Furthermore, unlike the current study, pH was greater for vines under shade treatments. Morrison and Noble (1990)and Smart et al. (1985b)demonstrate specific effects leaf shading may have on potassium accumulation in grape leaves and berries. They found greater potassium levels (correlated with greater pH) in foliage and berries with leaf shading. In addition, Morrison and Noble (1990) suggest the pathway of potassium movement from the soil to the berry during fruit ripening may be an indirect path through phloem transport from leaves, rather than a direct xylem translocation from roots to berry clusters. During the 2020 growing season, fruit maturity cultivar differences (Fig. 4) are likely attributed to response of genotype to weather and vine microclimate conditions (Schultz 2003, Gómez-Del-Campo et al. 2004, Santesteban et al. 2009, Keller et al. 2019). 'Pinot gris' is known to be an early season harvest cultivar, while 'Malbec' is considered to be a mid- to late season harvest cultivar (Keller 2020). Across numerous grape growing regions, greater Tair has been shown to increase berry TSS (Venios et al. 2020). Therefore, rapid berry development and early harvest of both cultivars observed in the 2020 growing season are likely due to increased Tair, Tleaf, and greater GDD (Table 1, Fig. 2). Nevertheless, in the current study, effects of leaf shading, Tair, Tleaf, and cultivar on berry maturation are likely a combination of direct and indirect effects and it is challenging to differentiate direct cause and effects in a field experiment setting (Morrison and Noble 1990).

Fruit harvest and ravaz index

Harvest of 'Malbec' vines occurred 5 September, 15 September and 14 August, in 2018, 2019, and 2020, respectively. Netting had no effect on harvest yield, cluster weight, or berry weight (Table 3). Lack of changes to berry weight is consistent with previous studies finding little or no impact of netting or fruit shading on berry size (Morrison and Noble 1990, Chorti et al. 2010). When using black shading nets, Chorti et al. (2010) found berry development, based on berry weight, to be slightly delayed in treatments shading the fruit zone early in the season, but also found berry weight to be unaffected at harvest. Light restriction during early stages of berry development is known to diminish berry size, likely due to the influence of decreased light on cell division or enlargement (Dokoozlian and Kliewer 1996). If berry development were delayed by this mechanism, similar berry weight at harvest may indicate a compensatory mechanism to increase fruit size later in berry development (Dokoozlian and Kliewer 1996).

Similar to the current study, Chorti et al. (2010) found netting placed over the fruit zone, no matter the time when season nets were installed, to have no impact on vine yield or cluster weight. This is contradictory to findings for other crops in which yield and fruit size decreased as shading factor increased (Iglesias and Alegre 2006, Peavey et al. 2022). In the current study, a decrease in cluster number for each vine was observed under hail-netting treatments (Table 3). Greater shoot light exposure during the previous growing season has been found to have a positive correlation on the number of inflorescences

produced in the current season (Sánchez and Dokoozlian 2005). Therefore, a decrease in cluster number for vines under netting may be attributed to diminished inflorescence production as a function of either decreased light exposure due to hail-netting or decreased light exposure due to increased canopy density within netted treatments. This theory is supported by findings of May et al. (1976) and Smart et al. (1990). Although there was no statistical decrease in yield or cluster weight within netted treatments (Table 3), yield for hail-netting vines was slightly less compared to yield of control vines. Decreased yield from each individual vine could be a concern for grape growers with large growing operations. Decreased production for each individual vine would extrapolate to large production (and economic) losses for a vineyard with many hectares. As vineyard profitability is based upon multiple factors, such as cultivar and number of vines, and hail risk is variable by location (Cintineo et al. 2012), whether loss of vineyard production induced by hail-netting is justified in order to eliminate crop loss due to potential hail damage should be assessed by each individual grower.

Ravaz Index may have limited application for winegrape growers (Matthews 2016), but is often utilised to evaluate vine balance and crop load (Reynolds and Vanden Heuvel 2009). For the many *V. vinifera* cultivars, a crop load between 5 and 10 is desirable. However, if ratios are greater than 12, vines are considered over-cropped (Bravdo et al. 1984, Bravdo et al. 1985). Over-cropping vines may delay fruit maturation, and compromise wine composition (reduced colour, TA, and proline concentration) (Bravdo et al. 1984, Bravdo et al. 1985, Reynolds and Vanden Heuvel 2009, Graff et al. 2022). However, vine balance is known to differ, based upon several factors including cultivar, climate, soil type, rootstock, and training system (Reynolds and Vanden Heuvel 2009, Scheiner et al. 2020, Graff et al. 2022). Results indicate control and vines below hail-netting had Ravaz Index ratios greater than 10, but no difference was found between netted and control vines (Table 3). Thus, vines of each treatment were likely over-cropped, but vine balance was not affected by application of netting. While Ravaz Index did not differ for netting treatments, pruning weight was lower for vines under hail-netting compared to control vines (Table 3). These results are in agreement with previous research (Martínez-Lüscher et al. 2020). For many grape cultivars, an increase in vine balance ratio is mainly related to an increase in vine yield and a decrease in vine cane weights (Reynolds and Vanden Heuvel 2009, Scheiner et al. 2020, Graff et al. 2022). However, hail-netting vines in the current study had lower pruning weights and similar yields compared to vines without nets (Table 3). Reduced vegetative growth and yield under hail-netting is likely related to decreased light intensity (PAR and diffuse radiation) and lower leaf PN for vines under hail-netting (Table 2) and, thus lower carbohydrate transport from leaves of hail-netting vines compared to leaves of control vines (Morrison and Noble 1990). The slight yield reduction for netted vines may also indicate vines compensated for reduced shoot growth (less leaf area) under netting with decreased fruit production (Greer et al. 2011). Grape cultivars vary greatly in their response to environmental conditions, including changes in leaf gas exchange, vegetative growth, and fruit productivity (Schultz 2003, Gómez-Del-Campo et al. 2004, Santesteban et al. 2009, Chaves et al. 2010, Keller et al. 2019). In addition, rootstock selection can influence vine-berry weight, cluster weight, yield, and shoot growth (Graff et al. 2022). Consequently, it is likely such responses resulted in the increase of Ravaz Index observed

for ‘Pinot gris’ vines compared to ‘Malbec’ vines (Table 3). With a mean Ravaz Index of 13.8 (Table 3), Ravaz Index for ‘Pinot gris’ vines (grafted to 1103P) was nearly 30% greater than Ravaz Index for ‘Merlot’ vines (own-rooted). In addition, ‘Pinot gris’ vines would be considered to be over-cropped (Bravdo et al. 1984, Bravdo et al. 1985). Thus, ‘Pinot gris’ vines may have experienced delayed fruit maturation and potentially compromised wine composition (Bravdo et al. 1984, Bravdo et al. 1985, Reynolds and Vanden Heuvel 2009, Graff et al. 2022). The Ravez Index difference between ‘Malbec’ and ‘Pinot gris’ vines would be attributed to increased pruning weights and decreased yields for ‘Malbec’ vines compared to ‘Pinot gris’ (Table 3) (Reynolds and Vanden Heuvel 2009, Scheiner et al. 2020, Graff et al. 2022). When considering the use of hail-netting, data indicate Texas High Plains AVA grape growers need a clear understanding of vine carbon allocation (source to sink relationship) and vine genotype for proper vine management and vineyard production (Petrie et al. 2000).

Conclusions

Hail events may inflict vine damage and yield loss and are a challenge for viticulture within the Texas High Plains AVA (Townsend and Hellman 2014). Therefore, many Texas High Plains AVA grape growers use black hail-netting to reduce possible vine damage due to hail events. As a result of hail-netting installation, this study indicates ‘Malbec’ and ‘Pinot gris’ vines that received hail-netting had a different canopy microclimate, leaf gas exchange, and fruit maturity when compared to vines that did not receive hail-netting. These changes were likely the result of reduced PAR and diffuse radiation incidence within the vine canopy and subsequent reduction in Tleaf. In addition, changes in canopy Tair, VPD, and LVPD are likely attributed to hail-netting vines having a more compact canopy. Furthermore, it is interesting to observe that, despite differences in weather each growing season (Table 1, Fig. 2), treatment and cultivar gas exchange (Table 2), harvest and growth (Table 3), and fruit quality (Fig. 4) data differences remained consistent between growing seasons. Therefore, despite variable weather each growing season, it appears High Plains AVA grape growers using hail-netting may rely on netting effects being stable from year to year. Besides preventing hail damage, hail-netting as installed for this experiment (Suppl. material 1) has been found by Texas High Plains AVA growers to provide a physical barrier which prevents biotic predators (birds and deer) from feeding on fruit. Taber (2002), Shahak et al. (2008) , and Pagay et al. (2013) report similar results. An additional benefit of hail-netting may be lower instances of fruit sunburn, reduced shot-berries, less wind scarring and berry decay (Shahak et al. 2008, Chorti et al. 2010, Martínez-Lüscher et al. 2020).

Besides delayed fruit maturity and yield concerns, hail-netting applied to grapevines may impose additional grower challenges. Taber (2002) reveals vines grow through and cling to netting and similar results were found in the current study (Suppl. material 1). Therefore, additional costs may be associated with vine pruning and netting removal. Canopies of netted treatments were observed to be more compact compared to canopies of non-netted vines (Suppl. material 3) and differences resulted in changes in canopy microclimate (Fig.

3). Such conditions have been related to increased incidence of fungal diseases (Carroll and Wilcox 2003, Valdés-Gómez et al. 2008, Keller 2020). Therefore, use of hail-netting may result in greater vineyard disease incidence. In addition, Vanden Heuvel et al. (2004) suggests shade leaves may reduce partitioning of photo-assimilates to permanent vine structures (roots, trunks, and stems) during the current growing season. Consequently, a vine's ability to withstand winter temperatures could be reduced and the vine would have fewer resources available for spring growth. McArtney and Ferree (1999) and Vanden Heuvel et al. (2002) confirm these results. When making vineyard management decisions in relation to use of hail-netting, information provided by this study and possible implications mentioned are critical considerations for Texas High Plains AVA and grape growers throughout the world (Vitisphere 2022, Green 2023). As greater numbers of grape growers consider use of hail-netting, information provided in this study will assist growers make informed vineyard management decisions.

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Author contributions

PH contributed original idea; PH, TM, and TR designed experiments; TR and TM completed experimental measurements; Statistical analysis provided by TM and TR; Graphs and tables supplied by TR and TM; Although each author provided manuscript comments and edits, TR and TM wrote manuscript; this paper represents a portion of the thesis submitted by TR for the MS degree in the Department of Plant and Soil Science at Texas Tech University.

Conflicts of interest

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References

- Baniță S, Sestraș A, Olteanu I, Călugăr A, Bunea CI (2020) The influence of hail and treatments with amino-acids on the fertility and biologic balance of grapevines. Romanian journal of Horticulture 1 (1): 111-118. https://doi.org/10.51258/rjh.2020.15
- Basile B, Caccavello G, Giaccone M, Forlani M (2015) Effects of early shading and defoliation on bunch compactness, yield components, and berry composition of Aglianico grapevines under warm climate onditions. American Journal of Enology and Viticulture 66 (2): 234-243. https://doi.org/10.5344/ajev.2014.14066
- Botezau A, Cook M, Crowley B, Dhingra A, Hillin D, Kamas J, Lewis J, Pontasch F, Scheiner J, Stein L (2022) Texas crush report and vineyard production survey. https://aggie-horticulture.tamu.edu/wp-content/uploads/sites/13/2023/01/Texas-Crush-Report-and-Vineyard-Production-Survey-Crop-Year-2021.pdf. Accessed on: 2023-6-16.
- Boulton R (1980a) The relationships between total acidity, titratable acidity and pH in wine. American Journal of Enology and Viticulture 31 (1): 76-80. https://doi.org/10.5344/ajev.1980.31.1.76
- Boulton R (1980b) The relationships between total acidity, titratable acidity and pH in grape tissue. Vitis 19: 113-120. URL: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://core.ac.uk/download/pdf/235693455.pdf
- Boulton R, Singleton V, Bisson L, Kunkee R (1999) Principles and Practices of Winemaking. Springer, New York. https://doi.org/10.1007/978-1-4757-6255-6
- Bravdo B, Hepner Y, Loinger C, Cohen S, Tabacman H (1984) Effect of crop level on growth, yield and wine quality of a high yielding Carignane vineyard. American Journal of Enology and Viticulture 35 (4): 247-252. https://doi.org/10.5344/ajev.1984.35.4.247
- Bravdo B, Hepner Y, Loinger C, Cohen S, Tabacman H (1985) Effect of crop level and crop load on growth, yield, must and wine composition, and quality of Cabernet Sauvignon. American Journal of Enology and Viticulture 36 (2): 125-131. https://doi.org/10.5344/ajev.1985.36.2.125
- Brglez Sever M, Tojnko S, Breznikar A, Skendrović Babojelić M, Ivančič A, Sirk M, Unuk T (2020) The influence of differently coloured anti-hail nets and geomorphologic characteristics on microclimatic and light conditions in apple orchards. Journal of Central European Agriculture 21 (2): 386-397. https://doi.org/10.5513/jcea01/21.2.2582
- Campbell G, Norman J (1998) An Introduction to Environmental Biophysics. Springer, New York. https://doi.org/10.1007/978-1-4612-1626-1
- Carroll JE, Wilcox WF (2003) Effects of humidity on the development of grapevine powdery mildew. Phytopathology® 93 (9): 1137-1144. https://doi.org/10.1094/phyto.2003.93.9.1137
- Cartechini A, Palliotti A (1995) Effect of shading on vine morphology and productivity and leaf gas exchange characteristics in grapevines in the field. American Journal of Enology and Viticulture 46 (2): 227-234. https://doi.org/10.5344/ajev.1995.46.2.227

- Chaves MM, Zarrouk O, Francisco R, Costa JM, Santos T, Regalado AP, Rodrigues ML, Lopes CM (2010) Grapevine under deficit irrigation: hints from physiological and molecular data. Annals of Botany 105 (5): 661-676. https://doi.org/10.1093/aob/mcq030
- Chorti E, Guidoni S, Ferrandino A, Novello V (2010) Effect of different cluster sunlight exposure levels on ripening and anthocyanin accumulation in Nebbiolo grapes. American Journal of Enology and Viticulture 61 (1): 23-30. https://doi.org/10.5344/ajev.2010.61.1.23
- Cintineo J, Smith T, Lakshmanan V, Brooks H, Ortega K (2012) An objective high-resolution hail climatology of the ontiguous United States. Weather and Forecasting 27 (5): 1235-1248. https://doi.org/10.1175/waf-d-11-00151.1
- Dokoozlian NK, Kliewer WM (1996) Influence of light on grape berry growth and composition varies during fruit development. Journal of the American Society for Horticultural Science 121 (5): 869-874. https://doi.org/10.21273/jashs.121.5.869
- Düring H (1987) Stomatal responses to alterations of soil and air humidity in grapevines. VITIS - Journal of Grapevine Research https://doi.org/10.5073/vitis.1987.26.9-18
- Düring H (1994) Photosynthesis of ungrafted and grafted grapevines: Effects of rootstock genotype and plant age. American Journal of Enology and Viticulture 45: 297-299. https://doi.org/10.5344/ajev.1994.45.3.297
- Esteban M, Villanueva M, Lissarrague J (2002) Relationships between different berry components in Tempranillo (*Vitis vinifera* L) grapes from irrigated and non-irrigated vines during ripening. Journal of the Science of Food and Agricultur 82: 1136-1146. https://doi.org/10.1002/jsfa.1149
- Gómez-Del-Campo M, Baeza P, Ruiz C, Lissarrague JR (2004) Water-stress induced physiological changes in leaves of four container-grown grapevine cultivars (*Vitis vinifera* L.). VITIS - Journal of Grapevine Research https://doi.org/10.5073/vitis.2004.43.99-105
- Graff E, Montague T, Kar S (2022) Secondary bud growth and fruitfulness of *Vitis vinifera* L. ‘Grenache’ grafted to three different rootstocks and grown within the Texas High Plains AVA. International Journal of Fruit Science 22 (1): 64-77. https://doi.org/10.1080/15538362.2021.1988809
- Green M (2023) Hailstorms blaze a trail of destruction through Provence. https://www.decanter.com/wine-news/hailstorms-blaze-a-trail-of-destruction-through-provence-503881/. Accessed on: 2023-6-16.
- Greer D, Weedon M, Weston C (2011) Reductions in biomass accumulation, photosynthesis in situ and net carbon balance are the costs of protecting *Vitis vinifera* ‘Semillon’ grapevines from heat stress with shade covering. AoB PLANTS 2011 https://doi.org/10.1093/aobpla/plr023
- Hellman EW, Takow EA, Tckakerian MD, Coulson RN (2011) Geographic information system characterization of four appellations in West Texas. Geoscience Canada 38: 6-20. URL: https://id.erudit.org/iderudit/geocan38_1ser01
- Hillin D, Scheiner J, Montague T, Ruland T (2022) Hail netting for vineyards. https://agrilifelearn.tamu.edu/s/product/hail-netting-for-vineyards/01t4x000007zC1vAAE. Accessed on: 2023-6-26.
- Iglesias I, Alegre S (2006) The effect of anti-hail nets on fruit protection, radiation, temperature, quality and probability of Mondial Gala apples. Journal of Applied Horticulture 08 (02): 91-100. https://doi.org/10.37855/jah.2006.v08i02.22

- Iland PG (2011) The Grapevine: From the Science to the Practice of Growing Vines for Wine. Patrick Iland Wine Promotions, Adelaide.
- Intrieri C, Filippetti I, Allegro G, Centinari M, Poni S (2008) Early defoliation (hand vs mechanical) for improved crop control and grape composition in Sangiovese (*Vitis vinifera* L.). Australian Journal of Grape and Wine Research 14 (1): 25-32. https://doi.org/10.1111/j.1755-0238.2008.00004.x
- Jones H, Serraj R, Loveys B, Xiong L, Wheaton A, Price A (2009) Thermal infrared imaging of crop canopies for the remote diagnosis and quantification of plant responses to water stress in the field. Functional Plant Biology 36 (11). https://doi.org/10.1071/fp09123
- Jones HG (2013) Plants and Microclimate: A quantitative approach to environmental crop physiology. 3rd. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511845727
- Kamas J (2017) Growing Grapes in Texas: From the commercial vineyard to the backyard vine. 2nd. Texas A&M University Press, College Station.
- Kar S, Montague T, Villanueva-Morales A (2021a) Measurement of photosynthesis in excised leaves of ornamental trees: a novel method to estimate leaf level drought tolerance and increase experimental sample size. Trees 35 (3): 889-905. https://doi.org/10.1007/s00468-021-02088-w
- Kar S, Montague T, Villanueva-Morales A, Hellman E (2021b) Measurement of gas exchange on excised grapevine leaves does not differ from *In Situ* leaves, and potentially shortens sampling ime. Applied Sciences 11 (8). https://doi.org/10.3390/app11083644
- Keller M, Martinez J, Hernádez-Montes E, Zhang Y, Chang BM (2019) Staying hydrated – Not easy when it's hot! GiESCO International Meeting: A Multidisciplinary Vision Towards Sustainable Viticulture, Greece, June 23-28, 2019. URL: https://www.giesco.org/article-21st-giesco-international-meeting-%E2%80%98a-multidisciplinary-vision-towards-sustainable-viticulture%E2%80%99staying-hydrated-%E2%80%93-not-easy-when-it%E2%80%99s-hot!11112-1070.html
- Keller M (2020) The Science of Grapevines. 3rd. Academic Press, San Diego.
- Martínez-Lüscher J, Chen CC, Brillante L, Kurtural SK (2020) Mitigating teat wave and exposure damage to "Cabernet Sauvignon" wine grape with partial shading under two irrigation amounts. Frontiers in Plant Science 11 https://doi.org/10.3389/fpls.2020.579192
- Matthews M (2016) Terroir and Other Myths of Winegrowing. Univeristy of California Press https://doi.org/10.1525/9780520962002
- May P, Clingeleffer PR, Brien CJ (1976) Sultana (*Vitis vinifera* L.) canes and their exposure to light. VITIS - Journal of Grapevine Research 14: 278-288. https://doi.org/10.5073/vitis.1975.14.278-288
- McArtney SJ, Ferree DC (1999) Shading effects on dry matter partitioning, remobilization of stored reserves and early season vegetative development of grapevines in the year after treatment. Journal of the American Society for Horticultural Science 124 (6): 591-597. https://doi.org/10.21273/jashs.124.6.591
- Montague T, Kjelgren R, Rupp L (2000) Gas exchange and growth of two transplanted, field-grown tree species in an arid limate. HortScience 35 (4): 763-768. https://doi.org/10.21273/hortsci.35.4.763

- Montague T, Kjelgren R (2004) Energy balance of six common landscape surfaces and the influence of surface properties on gas exchange of four containerized tree species. Scientia Horticulturae 100: 229-249. https://doi.org/10.1016/j.scienta.2003.08.010
- Montague T, Bates A (2015) Response of two field-grown maple (Acer) species to reduced irrigation in a high vapor pressure, semi-arid Climate. Arboriculture & Urban Forestry 41 (6): 334-345. https://doi.org/10.48044/jauf.2015.029
- Montague T, Graff E, Kar S (2020) Secondary bud gas exchange, growth, and fruitfulness of *Vitis vinifera* L. cultivars, 'Grenache' and 'Cabernet Sauvignon' grown on the Texas High Plains. Viticulture Data Journal 2 https://doi.org/10.3897/vdj.2.e60430
- Morrison JC, Noble AC (1990) The effects of leaf and cluster shading on the composition of Cabernet Sauvignon grapes and on fruit and wine sensory propertiess. American Journal of Enology and Viticulture 41 (3): 193-200. https://doi.org/10.5344/ajev.1990.41.3.193
- Moyer M, King J, Moulton G (2018) Evaluation of rootstocks on harvest metrics of 'Pinot noir clone 02A' wine grapes in maritime Western Washington. HortTechnology 28 (6): 830-835. https://doi.org/10.21273/horttech04170-18
- Mullins MG, Bouquet A, Williams LE (1992) Biology of the Grapevine. Cambridge University Press, Cambridge.
- Mupambi G, Anthony BM, Layne DR, Musacchi S, Serra S, Schmidt T, Kalcsits LA (2018) The influence of protective netting on tree physiology and fruit quality of apple: A review. Scientia Horticulturae 236: 60-72. https://doi.org/10.1016/j.scienta.2018.03.014
- National Association of American Wineries (2022) Texas Economic Impact Study 2022. https://wineamerica.org/economic-impact-study/texas-wine-industry/#:~:text=The%20study%20shows%20that%20the,detailed%20data%20for%20each%20state. Accessed on: 2023-6-16.
- Padgett-Johnson M, Williams LE, Walker MA (2003) Vine water relations, gas exchange, and vegetative growth of seventeen *Vitis* species grown under irrigated and nonirrigated conditions in California. Journal of the American Society for Horticultural Science 128 (2): 269-276. https://doi.org/10.21273/jashs.128.2.0269
- Pagay V, Reynolds AG, Fisher KH (2013) The influence of bird netting on yield and fruit, juice, and wine composition of *Vitis vinifera* L. OENO One 47 (1): 35-45. https://doi.org/10.20870/oeno-one.2013.47.1.1536
- Peavey M, McClymont L, Scalisi A, Goodwin I (2022) Netting of different shade factors affect light penetration, fruit and vegetative growth, yield and fruit quality in an Australian blush pear. Scientia Horticulturae 299 https://doi.org/10.1016/j.scienta.2022.111001
- Petoumenou DG, Biniari K, Xyrafis E, Mavronasios D, Daskalakis I, Palliotti A (2019) Effects of natural hail on the growth, physiological characteristics, yield, and quality of *Vitis vinifera* L. cv. Thompson Seedless under Mediterranean growing conditions. Agronomy 9 (4): 197-21. https://doi.org/10.3390/agronomy9040197
- Petrie PR, Trought MC, Howell GS (2000) Influence of leaf ageing, leaf area and crop load on photosynthesis, stomatal conductance and senescence of grapevine (*Vitis vinifera* L. cv. Pinot noir) leaves. VITIS - Journal of Grapevine Research31-36. https://doi.org/10.5073/vitis.2000.39.31-36
- Reynolds A, Vanden Heuvel J (2009) Influence of grapevine training systems on vine growth and fruit composition: A review. American Journal of Enology and Viticulture 60 (3): 251-268. https://doi.org/10.5344/ajev.2009.60.3.251

- Sánchez LA, Dokoozlian NK (2005) Bud microclimate and fruitfulness in *Vitis vinifera* L. American Journal of Enology and Viticulture 56 (4): 319-329. https://doi.org/10.5344/ajev.2005.56.4.319
- Santesteban LG, Miranda C, Royo JB (2009) Effect of water deficit and rewatering on leaf gas exchange and transpiration decline of excised leaves of four grapevine (*Vitis vinifera* L.) cultivars. Scientia Horticulturae 121 (4): 434-439. https://doi.org/10.1016/j.scienta.2009.03.008
- Schaefer JT, Levit JJ, Weiss SJ, McCarthy DW (2004) The frequency of large hail over the continuous United States. https://www.spc.noaa.gov/publications/schaefer/hailfreq.pdf. Accessed on: 2023-6-16.
- Scheiner J, Anciso J, Westover F (2020) Impact of training system on 'Blanc Du Bois' vegetative growth, yield components and fruit composition. Viticulture Data Journal 2 https://doi.org/10.3897/vdj.2.e53118
- Schultz HR (2003) Differences in hydraulic architecture account for near-isohydric and anisohydric behavior of two field-grown *Vitis vinifera* L. cultivars during drought. Plant, Cell & Environment 26 (8): 1393-1405. https://doi.org/10.1046/j.1365-3040.2003.01064.x
- Schultz HR, Stoll M (2010) Some critical issues in environmental physiology of grapevines: Future challenges and current limitations. Australian Journal of Grape and Wine Research 16: 4-24. https://doi.org/10.1111/j.1755-0238.2009.00074.x
- Shahak Y, Ratner K, Giller YE, Zur N, Or E, Gussakovsky EE, Stern R, Sarig P, Raban E, Harcavi E, Doron I, Greenblat-Avron Y (2008) Improving solar energy utilization, productivity and fruit quality in orchards and vineyards by photoselective netting. Acta Horticulturae 772: 65-72. https://doi.org/10.17660/actahortic.2008.772.7
- Smart RE, Robinson JB, Due GR, Brien CJ (1985a) Canopy microclimate modification for the cultivar Shiraz II. Effects on must and wine composition. VITIS - Journal of Grapevine Research 24: 119-128. https://doi.org/10.5073/vitis.1985.24.119-128
- Smart RE, Robinson JB, Due GR, Brien CJ (1985b) Canopy microclimate modification for the cultivar Shiraz I. Definition of canopy microclimate. VITIS - Journal of Grapevine Research 24: 17-31. https://doi.org/10.5073/vitis.1985.24.17-31
- Smart RE, Dick JK, Gravett IM, Fisher BM (1990) Canopy management to improve grape yield and wine quality – principles and practices. South African Journal of Enology & Viticulture 11 (1): 3-17. https://doi.org/10.21548/11-1-2232
- Taber MR (2002) Netting applications for agricultural bird control. Proceedings of the Vertebrate Pest Conference 20: 117-122. https://doi.org/10.5070/v420110192
- Tomás M, Medrano H, Pou A, Escalona JM, Martorell S, Ribas-Carbó M, Flexas J (2012) Water-use efficiency in grapevine cultivars grown under controlled conditions: effects of water stress at the leaf and whole-plant level. Australian Journal of Grape and Wine Research 18 (2): 164-172. https://doi.org/10.1111/j.1755-0238.2012.00184.x
- Townsend CG, Hellman EW (2014) Viticulture in Texas: the challenge of natural hazards. Journal of Wine Research 25 (4): 211-228. https://doi.org/10.1080/09571264.2014.967338
- United States Department of Agriculture (2021) National Agricultural Statistics Service 2020 Texas Wine Grape Varieties. https://www.nass.usda.gov/Statistics_by_State/Texas/ Publications/Current _News_Release/2021_Rls/tx-wine-grape-varieties-2020.pdf . Accessed on: 2023-6-16.

- United States Department of Agriculture (2023) Natural Resources Conservation Service Web Soil Survey. https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx. Accessed on: 2023-6-16.
- Valdés-Gómez H, Fermaud M, Roudet J, Calonnec A, Gary C (2008) Grey mould incidence is reduced on grapevines with lower vegetative and reproductive growth. Crop Protection 27 (8): 1174-1186. https://doi.org/10.1016/j.cropro.2008.02.003
- Vanden Heuvel JE, Leonardos ED, Proctor JT, Fisher KH, Sullivan JA (2002) Translocation and partitioning patterns of ^{14}C photoassimilate from light- and shade-adapted shoots in greenhouse-grown 'Chardonnay' grapevines (*Vitis vinifera* L.). Journal of the American Society for Horticultural Science 127 (6): 912-918. https://doi.org/10.21273/jashs.127.6.912
- Vanden Heuvel JE, Proctor JT, Fisher KH, Sullivan JA (2004) Shading affects morphology, dry-matter partitioning, and photosynthetic response of greenhouse-grown 'Chardonnay' grapevines. HortScience 39 (1): 65-70. https://doi.org/10.21273/hortsci.39.1.65
- Venios X, Korkas E, Nisiotou A, Banilas G (2020) Grapevine responses to heat stress and global warming. Plants 9 (12). https://doi.org/10.3390/plants9121754
- Vitisphere (2022) For the umpteenth time, hail causes 'carnage' across French wine regions. https://www.vitisphere.com/news-97040-for-the-umpteenth-time-hail-causes-carnage-across-french-wine-regions.html. Accessed on: 2023-5-18.
- Wachsmann Y, Zur N, Shahak Y, Ratner K, Giler Y, Schlizerman L, Sadka A, Cohen S, Garbinshikof V, Giladi B, Faintzak M (2014) Photoselective anti-hail netting for improved citrus productivity and quality. Acta Horticulturae 1015: 169-176. https://doi.org/10.17660/actahortic.2014.1015.19
- West Texas Mesonet (2023) https://www.mesonet.ttu.edu/. Accessed on: 2023-5-18.
- Winkler AJ, Cook JA, Kliewer WM, Lider LA (1974) General Viticulture. University of California Press, Berkeley. URL: https://www.ucpress.edu/book/9780520025912/general-viticulture
- Zhang Y, Keller M (2015) Grape berry transpiration is determined by vapor pressure deficit, cuticular conductance, and berry size. American Journal of Enology and Viticulture 66 (4): 454-462. https://doi.org/10.5344/ajev.2015.15038

Supplementary materials

Suppl. material 1: Hail-netting on vines doi

Authors: Montague
Data type: image
Brief description: Example of vineyard black hail-netting commonly used within Texas High Plains AVA. Netting is secured at top of canopy by utilising top wires and netting is secured below the canopy by utilising vineyard tying tape.
Download file (2.38 MB)

Suppl. material 2: Li-Cor-6400 machines below hail-netting doi

Authors: Montague
Data type: image
Brief description: Placement of LI-COR LI-6400 XT machines below hail netting for *in situ* gas exchange measurements.
Download file (1.43 MB)

Suppl. material 3: Compact canopy under hail-netting doi

Authors: Montague
Data type: image
Brief description: Grapevine canopy below hail-netting illustrating leaf orientation and canopy compactness instigated by netting's prevention of outward growth.
Download file (2.28 MB)