Kaolin Particle Film and Water Deficit Influence Red Winegrape Color under High Solar Radiation in an Arid Climate

Krista C. Shellie[1]* and Bradley A. King[2]

Abstract: The main and interactive effects of a kaolin particle film and water deficit on vine and berry attributes of winegrape cultivars Cabernet Sauvignon and Malbec were evaluated over three growing seasons in the warm, semi-arid climate of southwestern Idaho. Berry concentrations of total anthocyanins increased with increasing severity of water deficit in both cultivars in all three study years; however, the increase was accompanied by a decrease in berry fresh weight. An equal or greater increase in total anthocyanin concentration with greater berry fresh weight was achieved in two out of three years under less severe water deficit when particle film was applied to the vine canopy. Particle film influenced stomatal conductance and leaf temperature and response differed by vine water status and cultivar, suggesting that drought response influenced the effectiveness of the film. Under the climatic conditions of this study, the combination of particle film and mild water deficit provided the greatest net increase in anthocyanin concentration. The differences observed between cultivars in response to the particle film limit the applicability of our results to cultivars with similar response to drought as Cabernet Sauvignon and Malbec.

Key words: heat stress, radiation stress, temperature, drought, deficit irrigation

Red-skinned winegrape cultivars (*Vitis vinifera* L.) are often grown under a water deficit to control vine vigor and to enhance berry composition for red wine production (Ojeda et al. 2002, Roby et al. 2004, Basile et al. 2011, Ollé et al. 2011). Restriction of vegetative growth under water deficit increases the total amount of leaf and berry surface area exposed to solar radiation in the vine canopy (Shellie 2006). Stomatal closure is a primary response of the leaf to water deficit, and under warm field conditions with high solar radiation, water-deficit-related stomatal closure can increase canopy temperature and decrease canopy net transpiration and photosynthesis (Shellie and Glenn 2008, Glenn et al. 2010, Basile et al. 2011, Bowen et al. 2011). The primary mechanism of avoiding high radiation stress is transpiration in leaves and convection in berries (Smart and Sinclair 1976, Blanke and Leyhe 1988). The exposed berry's passive dependence on convective environmental conditions for heat transfer renders it vulnerable to high radiation stress.

Many studies in field and controlled environments have shown that color development in red-skinned grapes is sensitive to temperature and light (Kliewer 1977, Bergqvist et al. 2001, Spayd et al. 2002, Yamane et al. 2006, Sadras and Moran 2012). Low light conditions inhibited berry color development under temperatures optimum for anthocyanin biosynthesis (Kliewer 1977, Bergqvist et al. 2001). Under high light conditions, temperatures above 35°C compromised the accumulation of skin anthocyanins (Spayd et al. 2002). An increased incidence of heat and or solar injury has been observed in warm growing regions with high solar radiation when vines are maintained under a water deficit, particularly on western-facing fruit in north-south oriented rows and south-facing fruit on east-west oriented rows (Spayd et al. 2002).

Foliar application of clay-based particle films have been shown to mitigate radiation stress in a number of crops (Glenn and Puterka 2005). Kaolin-based particle films have high reflectance in the UV and infrared wavelengths. The white color and formulation of the film increases albedo on the fruit or leaf surface without impairing photosynthesis by reducing incident photosynthetically active radiation. Grapevines with particle film had cooler canopy temperatures and lower rates of stomatal conductance under nonlimiting soil moisture conditions; however, the magnitude of response to the film differed according to cultivar and severity of water deficit (Shellie and Glenn 2008, Glenn et al. 2010). Cultivars of *V. vinifera* differ in their response to drought (de Souza et al. 2005, Schultz 2003) and their inherently different mechanisms of stomatal control may influence the effectiveness of the particle film under drought conditions.

The red-skinned cultivars Cabernet Sauvignon and Malbec are widely grown in warm, arid regions with high solar radiation where sustained water deficits pose a risk for experiencing

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high radiation stress. The ability of a foliar particle film to alleviate berry exposure to high radiation stress under the above-mentioned field conditions has not been well characterized in either of these cultivars. The objective of this research was to determine whether a foliar application of particle film alleviated water-deficit-induced high-radiation stress during berry development in the winegrape cultivars Cabernet Sauvignon and Malbec. A secondary objective was to determine whether interactive effects between particle film and water deficit were similar in both cultivars.

Materials and Methods

The field trial was conducted in an experimental vineyard located at the University of Idaho Parma Research and Extension Center, Parma, ID (lat: 43′78°N; long: 116′94°W; 750 m asl) over three growing seasons (2007 to 2009). Soil type at the site was a fine sandy loam (Turbyfill series) with an available water-holding capacity of 0.14 cm/cm soil, pH 7.9, and 0.9% organic matter (USDA-NRCS 2009). The Turbyfill series is classified as a coarse-loamy, mixed, superactive, calcareous, mesic Xeric Torriorthent Entisol that formed in alluvium or lascustrine sediments on alluvial fans and terraces. Cabernet Sauvignon (clone 11) and Malbec (clone 6) planting material was obtained from Foundation Plant Services (University of California, Davis) as ungrafted, dormant-rooted cuttings and planted in 1997 in eight-vine panels with each of four replicate blocks containing three rows of 56 vines per row. Rows were oriented north-south with 2 × 2.7 m vine × row spacing. The vines were grown on their own roots and trained as double trunks, with each trunk forming one arm of a bilateral cordon. Vines were pruned to 16 buds per meter of row and shoots were trained to a single vertical plane on a vertically shoot-positioned trellis. Vineyard management reflected local commercial production practices including periodic application of herbicide, fungicide, and insecticide. Chemical and mechanical methods were used to keep alley and in-vine rows weedfree throughout the growing season.

The experimental design was a split, split-plot with cultivar main-plot panels randomly located within each replicate block. A standard or reduced amount of irrigation was supplied to half the number of vines in each cultivar main-plot and the particle film was applied to half the number of vines under each level of irrigation. All vines received the same treatment each successive growing season. The vineyard was equipped to irrigate with two lines of aboveground drip tubing (16 mm i.d.; Bowsmith, Exeter, CA) suspended 30 cm above the soil surface. One drip line contained in-line emitters with a flow rate of 1.9 L/hr and an emitter spacing of 1 m (two emitters per vine). The drip line with in-line emitters delivered an equal amount of water to all vines and was the only line used in irrigation events before bloom or after harvest. The purpose of the second drip line was to selectively deliver an additional amount of irrigation to subplots that received a standard amount of irrigation. This second drip line lacked in-line emitters and delivered water to vines under standard irrigation via punch-in emitters (flow rate of 3.8 L/hr) that were selectively spaced equidistant between the adjacent drip line's in-line emitter locations. Both drip lines were used during irrigation events between fruit set and harvest and three-fold more water was simultaneously delivered via the punch-in and in-line emitters to half the number of vines in each cultivar main plot.

All vines were supplied with a similar amount of water during any irrigation event before fruit set or after harvest by using only the in-line emitter drip line. A standard or reduced amount of water was first delivered simultaneously to vines throughout the period of berry development by using both drip lines during irrigation events. Irrigation duration at each event was calculated to supply vines under standard irrigation with 70% of their estimated full vine evapotranspiration (ET_c), which is a standard industry practice in the region (Keller et al. 2008). The standard irrigation treatment was intended to maintain a sustained water deficit throughout berry development. Vines under reduced irrigation were irrigated for the same duration as vines under standard irrigation, but the in-line emitter drip line provided 23% of ET_c. The duration of each irrigation event was calculated weekly using the 1982 Kimberly–Penman equation (Jensen et al. 1990) for well-watered alfalfa as reference crop and an on-site developed variable crop coefficient similar to that used by Keller et al. (2008). Values for reference evapotranspiration (ET_r) were obtained from a weather station located 3 km from the trial site (www.usbr.gov/pn/agrimet/wxdata.html). The amount of water delivered per block was measured by a flow meter during each irrigation event. The irrigation treatments were first applied during the 2006 growing season and data collection began in 2007.

A kaolin-based particle film (Surround WP; Engelhard Corp., Iselin, NJ) was applied just after fruit set (first week of July) to the entire canopy of half the number of vines in each irrigation subplot using the same method as Shellie and Glenn (2008). Vines not sprayed with particle film were left untreated as controls. The particle film was applied weekly for three weeks at a concentration of 60 g/L in 950 L/ha using a backpack sprayer. The first application contained a nonionic surfactant (R-II; Wilbur-Ellis Agribusiness, Kennewick, WA) at a rate of 1.3 mL/L. Subsequent film applications did not contain a surfactant because the particle film residue from the first application functioned as a surfactant.

The midday leaf water potential (Ψ_{md}) of two, fully expanded, exposed leaves from each subplot was measured weekly throughout berry development on the day preceding irrigation events using a pressure chamber (model 610; PMS Instruments, Corvallis, OR) as described by Turner (1988). Stomatal conductance (g_s) (LI-1600 Steady State Porometer; LI-COR, Lincoln, NE), leaf surface temperature (L1-1600 Steady State Porometer), and leaf water potential were measured on cloudless days pre- and postveraison on day of year 192 and 227 in 2007 and 207, 229, and 244 in 2009. Data were collected predawn, midmorning (10:00 MDT), and midday (14:00 MDT) in 2007 and predawn and midmorning in 2009.

Fruit was harvested when the must from a composite sample of clusters from replicate blocks had acquired a soluble solids (SS) concentration of ~24% and a titratable acidity (TA) of ~6 g/L. Ten clusters were collected from either side of the vine canopy on the day preceding harvest and used to calculate average berry weight by counting the number of berries in each cluster and dividing the weight of the cluster by the number of berries per cluster. A subsample of 100 berries was randomly selected from the 10-cluster sample and stored at -80°C until used for analysis of phenolics. All remaining berries from the 10-cluster sample were crushed, left at 21°C on their skins overnight, and analyzed the following day for SS (RE40; Mettler-Toledo, Columbus, OH), pH, and TA (716 DMS Titrino; Metrohm, Riverview, FL) as described by Shellie (2006). Analysis of berry total monomeric anthocyanins and total phenolics followed the method of Iland et al. (2004). Yield per vine was measured as the sum weight of clusters harvested per vine and the 10-cluster sample.

Berry composition and yield data were analyzed by cultivar and year using a mixed model with irrigation and particle film as fixed effects (SAS ver. 8.02; SAS Institute, Cary, NC). Differences between treatment means ($p \leq 0.05$) were detected using Tukey–Kramer adjusted t test. Annual cumulative growing degree days (GDD) were calculated as simple average daily temperature with no upper limit and a base threshold of 10°C using data from the weather station located 3 km from the trial site (www.usbr.gov/pn/agrimet/wxdata.html). Daily weather data from this site were also used to report annual precipitation, ET_r, weekly average maximum daily temperature, total direct solar radiation, and number of days per growing season with maximum temperature >35°C. Graphs and regression analyses were generated using SigmaPlot 11.2 (Systat Software, San Jose, CA).

Results

Growing season environmental conditions. Growing degree day heat unit accumulation (GDD) between 1 Apr and 31 Oct exceeded the 13-year site average by 13 and 5% in 2007 and 2009, respectively, and was similar to the 13-year site average in 2008 (Table 1). The number of days during the growing season with a daily maximum temperature >35°C was similar to the 13-year site average in 2007 but was half as frequent in 2009 and 71% less frequent in 2008. Daily average total direct solar radiation was similar to the 13-year site average in 2007 and 2008, but was 6% less than the site average in 2009. Growing season precipitation was similar to the site average during the three years of this study, but was lowest in 2008. ET_r was similar to the 13-year site average in 2008 and 2009, but was 8% higher than the site average in 2007. Irrigation amount under the standard treatment regime supplied 28, 21, and 34% of growing season ET_r in 2007, 2008, and 2009, respectively, and the reduced irrigation regime provided 46, 33, and 33% of the standard irrigation amount.

Daily solar radiation and maximum temperatures were highest between weeks 26 to 30, coinciding with the lag phase of berry development and the onset of veraison (Figure 1).

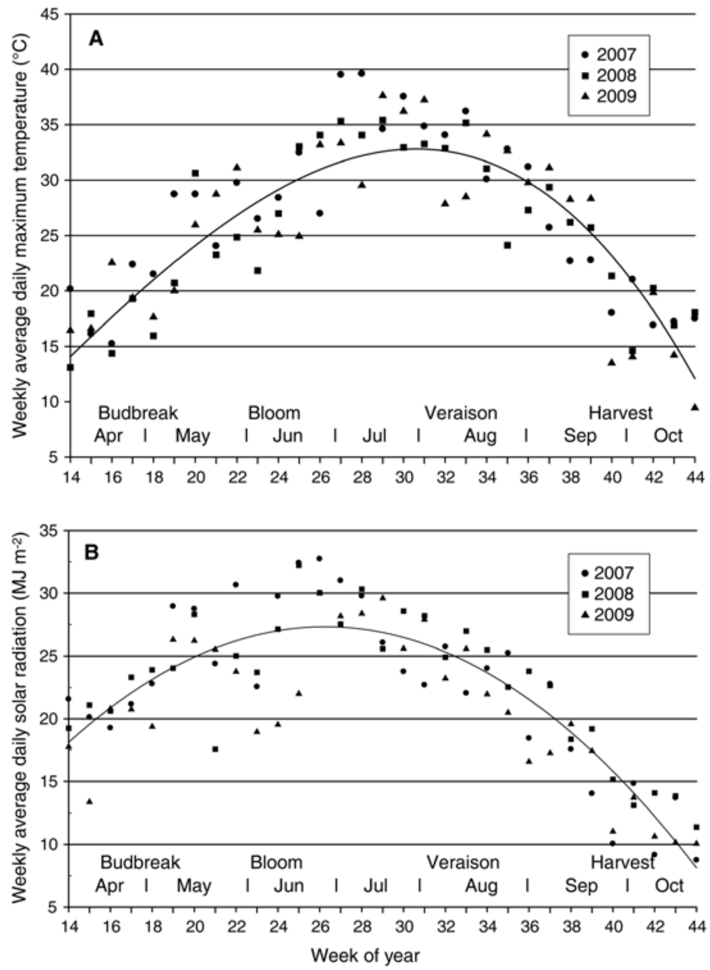

Figure 1 Weekly average daily maximum temperature (**A**) and total direct solar radiation (**B**) at Parma Agrimet weather station (www.usbr.gov/pn/agrimet/) (lat: 43°48´00”, long: 116° 56´00”, 702 m asl) during the 2007, 2008, and 2009 growing seasons. Line depicts the 3-year average value.

Table 1 Weather parameters 1 Apr through 31 Oct collected from Bureau of Reclamation Agrimet Parma, Idaho, weather station, and irrigation amount applied under standard and reduced treatment levels. Accumulated growing degree days were calculated from daily maximum and minimum temperature with no upper limit and a base temperature of 10°C.

Parameter[a]	2007	2008	2009	1994–2006
Accumulated GDD (°C)	1950	1725	1800	1720 ± 120
Days daily maximum temp >35°C	39	9	15	31 ± 12
Daily average total direct solar radiation (MJ m^{-2})	22.6	23.0	20.8	22.1 ± 0.8
Precipitation (mm)	97	63	111	100 ± 39
Alfalfa-based ET_r (mm)	1294	1276	1202	1195 ± 88
Standard irrigation (mm)	366	232	405	–
Reduced irrigation (mm)	170	77	135	–

[a]GDD: growing degree days; ET_r: reference evapotranspiration.

Weekly average daily maximum temperatures were highest in 2007. In 2008, daily maximum temperatures tended to be cooler than the 3-year average between bloom and veraison and warmer than average between veraison and harvest.

Leaf water potential and stomatal conductance. Particle film application had no consistent influence on Ψ_{md} in either cultivar under standard or reduced irrigation (Figure 2). However, vines under standard irrigation were maintained at a Ψ_{md} that was ~0.3 MPa higher than vines under reduced irrigation. The 3-year average of weekly values for Ψ_{md} under standard irrigation was -1.1 MPa in Cabernet Sauvignon and -1.0 MPa in Malbec and under reduced irrigation was -1.4 MPa in Cabernet Sauvignon and -1.3 MPa in Malbec. Application of particle film had no detectable influence on predawn or midmorning values of leaf water potential in either cultivar (data not shown).

The surface temperature of leaves with particle film was cooler than leaves without particle film on two out of five sampling dates in both cultivars and one additional sampling date (1 Sept) in Cabernet Sauvignon (Table 2). The greatest difference in temperature between leaves with or without particle film was 2.6°C in Cabernet Sauvignon and 1.2°C in Malbec and occurred on 26 July 2009. The smallest significant difference in temperature between leaves with and without particle film was 0.5°C in Cabernet Sauvignon and 0.3°C in Malbec and occurred on the warmest day of the five sampling dates (11 July 2007). The particle film had a similar cooling effect under either irrigation regime with the exception of Cabernet Sauvignon at the 14:00 hr sampling on 11 Jul 2007, where leaves were 0.5°C cooler with than without particle film under reduced but not standard irrigation. Leaf surface temperature in both cultivars was warmer under reduced than standard irrigation by ~3 (26 July) and 1°C (1 Sept) in 2009. Leaf temperature tended to be warmer under reduced than standard irrigation on other sampling dates, although temperature differences were not of statistical significance.

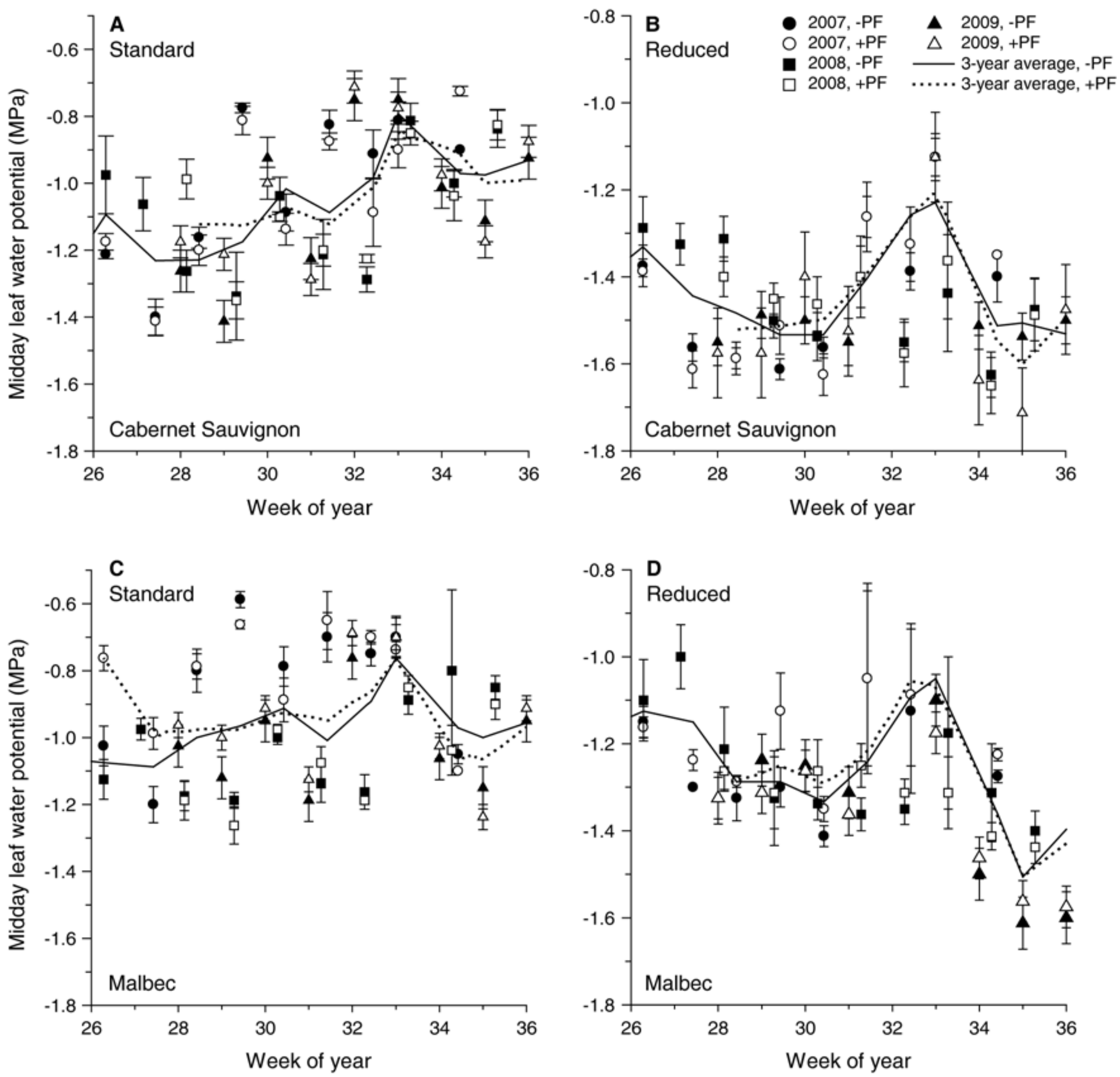

Figure 2 Weekly midday leaf water potential of Cabernet Sauvignon (**A**, **B**) and Malbec (**C**, **D**) under standard (**A**, **C**) or reduced (**B**, **D**) irrigation with (+) or without (-) foliar-applied, kaolin-based particle film (PF) during 2007, 2008, and 2009 growing seasons in Parma, Idaho. Symbols represent the mean value of eight leaves, and error bars are the standard error of the mean. Solid and dashed lines depict 3-year average values with (+PF) or without (-PF) particle film.

The effect of particle film on leaf stomatal conductance varied by cultivar and was influenced by irrigation regime (Table 2). In Cabernet Sauvignon, stomatal conductance tended to be lower in leaves with particle film. This trend was of statistical significance on 15 Aug 2007 when stomatal conductance was 17% lower in leaves with particle film, but not of statistical significance on July sampling dates in 2007 and 2009 when particle film decreased stomatal conductance by ~17 and 8%. In Malbec, the effect of particle film on stomatal conductance was influenced by irrigation regime in three out of five sampling dates. In Malbec, the stomatal conductance of leaves with particle film tended to be lower under reduced irrigation and higher under standard irrigation than leaves without particle film. The stomatal conductance of Malbec leaves with particle film was increased by 26 and 78% under standard irrigation (309 to 389 and 243 to 434 mmol/m^2/s) and decreased by 9 and 14% under reduced irrigation (29 to 26 and 103 to 88 mmol/m^2/s) in July 2007 and 2009, respectively. In August 2009, the stomatal conductance of leaves with particle film was decreased under reduced irrigation by 49% in Cabernet Sauvignon (361 to 185 mmol/m^2/s) and 46% in Malbec (382 to 206 mmol/m^2/s); however, under standard irrigation it was unaffected in Cabernet Sauvignon (336 to 338 mmol/m^2/s) and increased by 8% in Malbec (419 to 454 mmol/m^2/s). In both cultivars, stomatal conductance was ~ 50% lower under reduced than standard irrigation and differences were statistically significant on four out of five sampling dates.

Under standard irrigation, there was no apparent relationship in either cultivar between leaf surface temperature and stomatal conductance ($r^2 < 0.2$). However, under reduced irrigation, leaf temperature was correlated with stomatal conductance in both cultivars (Figure 3). Particle film attenuated the rate of decrease in stomatal conductance in response to increasing leaf surface temperature in Malbec but did not affect the rate of decrease in Cabernet Sauvignon.

Berry composition. Particle film had no detectable effect on the fresh weight of berries at harvest in Cabernet Sauvignon, but it increased the average berry fresh weight of Malbec from 1.24 to 1.42 g in 2007 and from 1.55 to 1.81 g under standard irrigation in 2009 (Table 3). Particle film had no detectable influence on juice titratable acidity in either cultivar. Particle film increased the soluble solids concentration of Cabernet Sauvignon under standard irrigation in 2007 from 21.9 to 23.9% but had no detectable effect under reduced irrigation in other years or on the cultivar Malbec.

Berries from vines under reduced irrigation had lower fresh weight and titratable acidity at harvest than berries from vines under standard irrigation in each year of the study, in both cultivars (Table 3). Reduced irrigation decreased berry fresh weight the greatest amount in 2007 and the decrease ranged from 13 to 23% in Cabernet Sauvignon and 18 to 32% in Malbec. The decrease in juice titratable acidity under reduced irrigation ranged from 21 to 33% in Cabernet Sauvignon and from 16 to 32% in Malbec over the three years of the study. Reduced irrigation increased the berry soluble solids concentration of Cabernet Sauvignon in two out of three years, from 22.9 to 23.5% in 2007 and from 22.8 to 24.0% in 2008, but had no effect on Malbec.

Berry anthocyanin concentration was highest in 2008 in both cultivars and was the only year in which the particle film

Table 2 Leaf surface temperature (LT) and stomatal conductance (g_s) of Cabernet Sauvignon and Malbec vines with (+) or without (-) a foliar coating of kaolin-based particle film (PF) that were irrigated with a standard (STD) or reduced (RED) amount of water (IRR) and measured pre- and postveraison at midmorning (10:00 MDT) or midday (14:00 MDT) during two growing seasons in Parma, Idaho.

	2007								2009					
	11 Jul				15 Aug				26 July		17 Aug		1 Sept	
	LT (C°)		g_s (mmol/m^2/s)		LT (C°)		g_s (mmol/m^2/s)		LT (C°)	g_s (mmol/m^2/s)	LT (C°)	g_s (mmol/m^2/s)	LT (C°)	g_s (mmol/m^2/s)
Time	10	14	10	14	10	14	10	14	10	10	10	10	10	10
Cabernet Sauvignon														
STD	31.3	38.1	296.2	227.5	26.7	32.4	221.0	182.1	29.1	301.4	24.6	336.9	24.3	288.5
RED	32.6	39.1	77.64	18.9	27.3	31.9	164.7	136.6	32.1	68.2	25.4	273.0	25.6	101.2
+PF	31.8	38.4	169.9	109.4	26.9	32.2	174.5	153.6	29.3	176.8	25.4	261.4	24.5	213.5
-PF	32.1	38.7	204.0	137.1	27.0	32.1	211.2	165.1	31.9	192.7	24.6	348.5	25.3	176.2
IRR	ns[a]	ns	*	*	ns	ns	ns	*	**	**	ns	ns	**	**
PF	**	**	ns	ns	ns	ns	**	ns	*	ns	ns	**	*	ns
IRR x PF	ns	*	ns	ns	ns	*	ns	ns	ns	ns	ns	**	ns	ns
Malbec														
STD	32.1	39.0	406.6	348.6	26.8	31.2	295.1	240.5	29.7	338.4	25.6	436.5	24.8	276.5
RED	31.0	37.7	85.4	27.5	27.3	32.2	195.0	183.9	32.3	95.6	26.0	293.9	25.5	148.0
+PF	31.3	38.2	270.1	207.4	27.0	31.8	224.5	191.7	30.4	261.1	25.7	330.2	24.9	234.6
-PF	31.8	38.6	221.9	168.7	27.1	31.6	265.6	232.6	31.6	173.0	25.8	400.2	25.5	189.9
IRR	ns	ns	**	*	ns	ns	ns	ns	**	**	ns	**	*	*
PF	*	*	ns	*	ns	ns	ns	ns	**	*	ns	ns	ns	ns
IRR x PF	ns	ns	ns	*	ns	ns	ns	ns	ns	**	ns	**	ns	ns

[a]*, **, and ns indicate significance at $p \leq 0.05$, $p \leq 0.01$, and not significant, respectively, from mixed model analysis of variance with mean separation of main effects within columns for each cultivar by Tukey-Kramer adjusted *t* test.

was not associated with an increase in anthocyanin concentration (Table 4). Particle film increased berry total anthocyanin concentration in 2007 and 2009 by 13 and 12% in Cabernet Sauvignon and by 36 and 11% in Malbec; however, response to the film differed according to irrigation amount and was not similar for both cultivars. In 2007, anthocyanin concentration in Cabernet Sauvignon was most increased by particle film under standard (19%) rather than reduced irrigation, but in Malbec the increase was highest under reduced (47%) rather than standard irrigation. In 2008, particle film had no main effect on anthocyanin concentration in either cultivar, but it had an interactive effect with irrigation amount in Cabernet Sauvignon, where it decreased anthocyanin concentration under reduced but not standard irrigation.

The effect of particle film on total berry phenolics was inconsistent among years and was influenced by irrigation amount (Table 4). In Cabernet Sauvignon, particle film increased total phenolics by 25% under standard irrigation in 2007, decreased total phenolics by 7% under reduced irrigation in 2008, and had no detectable effect in 2009. In Malbec, particle film increased total phenolics by 8% under reduced irrigation in 2009, decreased total phenolics by 6% under standard irrigation in 2007, and had no detectable effect in 2008.

Reduced irrigation increased anthocyanin concentrations and total phenolics in both cultivars in at least two out of three years. Reduced irrigation increased total anthocyanin concentrations from 15 to 17% in Cabernet Sauvignon and from 5 to 29% in Malbec and increased total phenolics from 4 to 9% in Cabernet Sauvignon and from 10 to 17% in Malbec.

Discussion

A key finding from this study was the increase in total anthocyanin concentration of berries from vines with particle film in two out of three years. This finding is of commercial

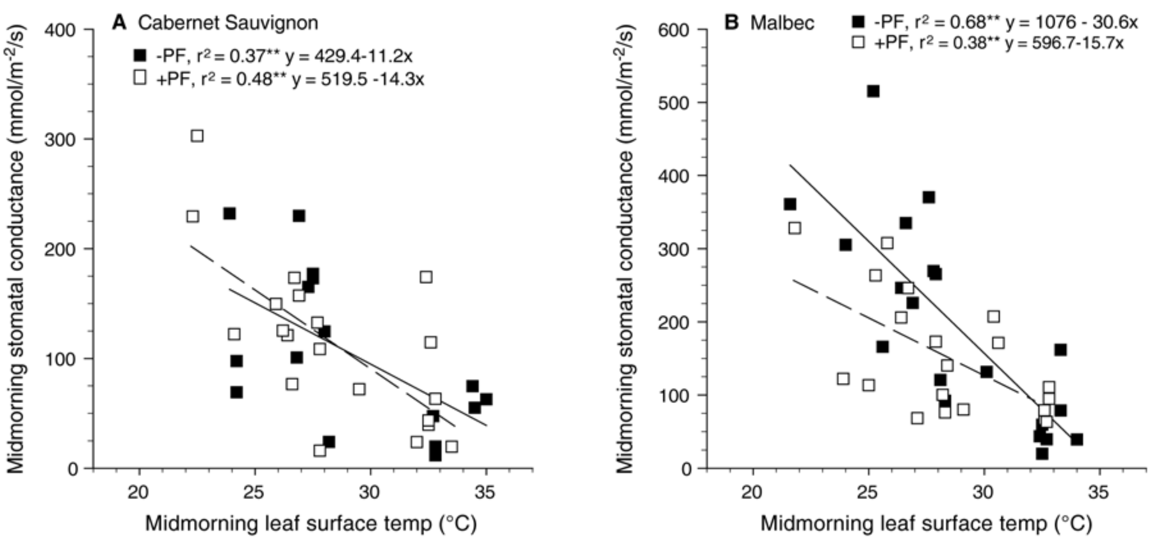

Figure 3 Relationship between leaf surface temperature and stomatal conductance at midmorning (10:00 MDT) in Cabernet Sauvignon (**A**) and Malbec (**B**) grown under reduced irrigation with (+PF, dashed line) or without (-PF, solid line) particle film. Data were collected during weeks 27 and 32 in 2007 and 30, 33, and 35 in 2009. Symbols represent individual vines (n = 4).

Table 3 Berry fresh weight and maturity at harvest in Cabernet Sauvignon and Malbec grown under standard or reduced irrigation, with or without a foliar applied, kaolin-based particle film, over three growing seasons in Parma, Idaho.

	Berry fresh wt (g)			Titratable acidity (g/L)			Soluble solids (%)		
	2007	2008	2009	2007	2008	2009	2007	2008	2009
Cabernet Sauvignon									
Full	1.06a[a]	1.04a	1.04a	5.25a	7.16a	3.92a	22.9a	22.8a	22.8a
Reduced	0.81b	0.91b	0.91b	3.93b	4.78b	3.11b	23.5b	24.0b	24.0b
Irrigation (I)	**	**	**	*	**	**	*	**	ns
Particle film (PF)	ns	ns	ns	ns	ns	ns	*	ns	ns
I x PF	ns	ns	ns	ns	ns	ns	**	ns	ns
Malbec									
Full	1.59a	1.68a	1.68a	7.03a	6.75a	4.51a	22.6a	24.8a	23.5a
Reduced	1.08b	1.37b	1.37b	4.80b	5.63b	3.81b	23.8a	25.4a	24.1a
Irrigation (I)	**	**	**	*	*	*	ns	ns	ns
Particle film (PF)	**	ns	ns	ns	ns	ns	ns	ns	ns
I x PF	ns	ns	*	ns	ns	ns	ns	ns	ns

[a]Within column treatment least square means followed by different letters are significantly different according to Tukey–Kramer adjusted *t* test at *,**, and ns, which indicate $p \leq 0.05$, $p \leq 0.01$, and not significant, respectively.

and economic interest because berry anthocyanin composition predetermines the color potential of the resulting red wine (Downey et al. 2006). We observed an increase in berry anthocyanin concentration in response to increased water deficit severity in both cultivars in each year of the study, but the water-deficit-induced increase in anthocyanin concentration was accompanied by a decrease in berry fresh weight and therefore a reduction in yield. An increase in berry anthocyanin concentration of equal or greater magnitude was achieved under less severe water deficit without an accompanying decrease in berry fresh weight in two out of three years when particle film was applied to the vine canopy. The greatest net production of anthocyanins in 2007 and 2009 was obtained when particle film was applied to vines under the standard irrigation regime. Berry anthocyanin concentrations in all treatments were greatest in 2008, which was also the coolest of the three study years and the only year in which the particle film did not increase berry anthocyanin concentrations.

The annual variability in effectiveness of the particle film to increase berry anthocyanin concentrations could be due to environmental influences on abiotic conditions that affect the physiological response of the berry to the film. The sensitivity of anthocyanin synthesis to light, temperature, and water relations has been well demonstrated (Kliewer 1977, Bergqvist et al. 2001, Spayd et al. 2002, Ojeda et al. 2002, Roby et al. 2004, Yamane et al. 2006, Downey et al. 2006, Castellarin et al. 2007, Ollé et al. 2011, Sandras and Moran 2012). Spayd et al. (2002) showed that temperature had a greater effect than light on anthocyanin concentrations; berry anthocyanin concentrations at maturity declined in relation to duration of berry exposure to temperatures ~35°C. The frequency of days with maximum temperatures >35°C was more similar to the 13-year site average in 2007 and 2009 and less frequent than in 2008 during the three years of our study. Total direct solar radiation was similar to the 13-year site average in every year of this study, but GDD accumulation was lowest in 2008. Yamane et al. (2006) found that the weeks surrounding lag phase and the onset of veraison were the stages of berry development when anthocyanin synthesis was most sensitive to temperature. Cohen et al. (2012) concluded that temperature events influenced anthocyanin concentrations more than the value of integrated seasonal temperatures when they observed no change in anthocyanin concentrations under compressed diurnal temperature ranges. The high temperature events of 2007 and 2009 during weeks 27 to 33 were of a magnitude expected to inhibit accumulation of anthocyanins and occurred at a stage of berry development considered sensitive to temperature. Berry temperature was not directly measured in this study. However, the magnitude and the phenological timing of extreme temperature events in 2007 and 2009 suggest that high temperature limited berry anthocyanin accumulation. The increased anthocyanin concentration in berries from vines with particle film in these years suggests that the particle film alleviated high radiation stress and provided a cooler canopy temperature that facilitated anthocyanin accumulation in the berry. The cooler temperature of leaves with kaolin-based particle film likely resulted from a reduction in absorbed incident radiation by the leaf due to the film's reflectance of infrared and ultraviolet radiation (Glenn et al. 2003). The high temperature events in 2007 and 2009 were of similar frequency as the 13-year site average, suggesting a high likelihood that the particle film would increase berry anthocyanin concentrations at this site in a majority of years.

Our findings that particle film had no consistent influence on Ψ_{md} were similar to the winegrape cultivars Viognier and Merlot (Shellie and Glenn 2008), grapefruit (Jifon and Syvertsen 2003), and pecan (Lombardini et al. 2005). The 3-year average for Ψ_{md} under standard and reduced irrigation in this study was similar to mild and severe levels of water deficit associated with increased berry anthocyanin concentration in Cabernet Sauvignon (Roby et al. 2004, Basile et al.

Table 4 Berry total monomeric anthocyanin and total phenolic concentration at harvest in Cabernet Sauvignon and Malbec grown under standard or reduced irrigation, with (+) or without (-) a foliar applied, kaolin-based particle film (PF), over three growing seasons in Parma, Idaho.

	Total monomeric anthocyanin (mg/g berry fresh wt)						Total phenolics (au)					
	Cabernet Sauvignon			Malbec			Cabernet Sauvignon			Malbec		
	2007	2008	2009	2007	2008	2009	2007	2008	2009	2007	2008	2009
Standard	1.10a[a]	1.22a	1.09a	1.13a	2.67a	1.80a	1.54a	1.49a	1.38a	1.22a	1.87a	1.54a
Reduced	1.07a	1.43b	1.25b	1.46b	2.81b	1.96b	1.60a	1.62b	1.51b	1.43b	1.92a	1.69b
+Particle film (PF)	1.15a	1.30a	1.24a	1.50a	2.74a	1.98a	1.63a	1.54a	1.46a	1.30a	1.88a	1.67a
-PF	1.02b	1.34a	1.11b	1.10b	2.73a	1.78b	1.51b	1.57a	1.42a	1.34b	1.92a	1.56b
Standard, +PF	1.19a	1.23a	1.16b	1.25b	2.69a	1.89b	1.66a	1.52a	1.40a	1.18a	1.87a	1.58bc
Standard, -PF	1.00b	1.20a	1.03a	1.02a	2.64a	1.72a	1.41b	1.46a	1.35a	1.26b	1.88a	1.50c
Reduced, +PF	1.11a	1.38b	1.32c	1.74c	2.79a	2.07b	1.60a	1.57ab	1.52b	1.43c	1.90a	1.76a
Reduced, -PF	1.04b	1.49c	1.19b	1.18b	2.83a	1.85b	1.61a	1.68b	1.49ab	1.43c	1.95a	1.63b
Irrigation (I)	ns	**	**	**	**	**	*	**	**	**	ns	**
PF	**	ns	**	**	ns	**	**	ns	ns	*	ns	**
I x PF	**	**	ns	**	ns	ns	**	**	ns	*	ns	*

[a]Within column treatment means followed by different letters are significantly different according to Tukey-Kramer adjusted *t* test at *,**, and ns, which indicate $p \leq 0.05$, $p \leq 0.01$, and not significant, respectively.

2011). Water deficit has been shown to induce transcription of regulatory genes in the flavonoid pathway (Castellarin et al. 2007).

The differences between cultivars in their response to particle film on stomatal conductance and leaf temperature observed in this study suggest that the film's effectiveness as a reflective antitranspirant was influenced by inherent differences in response to drought. Stomatal control mechanisms remain poorly characterized but are known to differ among cultivars of winegrape (Schultz 2003). Differences in response of stomatal conductance to particle film were also observed between the cultivars Viognier and Merlot (Shellie and Glenn 2008).

The inconsistent and cultivar-specific influence of the particle film on berry soluble solids observed in this study was similar to other findings (Glenn et al. 2010, Shellie and Glenn 2008). Concentration of soluble solids is less responsive to environmental conditions than anthocyanins (Dai et al. 2011, Sadras et al. 2007), which could explain why the particle film had an inconsistent influence on the concentration of soluble solids relative to anthocyanins. Sadras and Moran (2012) exposed vines with and without a water deficit to continuous, artificial elevation of ambient temperature and concluded that high temperature lowered the ratio of anthocyanin to soluble solids due a delay in the onset of anthocyanin accumulation. Sugar accumulation signals up-regulation of the biosynthetic pathways for anthocyanins (Solfanelli et al. 2006). Yamane et al. (2006) found that high temperature inhibited transcriptional induction of the anthocyanin biosynthetic pathways, and Mori et al. (2007) identified additional factors, such as enzymatic degradation, that contributed to decreased anthocyanin concentrations under high temperature. We observed an 8.7% increase in anthocyanin to soluble solids ratio in 2008 in Cabernet Sauvignon vines with particle film. Ratio mean values of vines with particle film were higher in both cultivars under both irrigation regimes in all other years, but the increased values were not of statistical significance. Without knowing the ratio of anthocyanin to soluble solids during the ripening process, it is difficult to speculate why neither particle film nor water deficit influenced the anthocyanin to soluble solids ratio in this study. It is possible that a treatment influence was not detected in this study because high temperature events were of an occasional rather than continuous occurrence.

Conclusions

Results showed that net total anthocyanin production can be increased under warm ambient growing conditions with high solar radiation by a combination of foliar particle film and vine water deficit, but many questions remain unanswered about the nature of this relationship. Water deficit alters the composition and structure of the anthocyanins, and the influence of particle film on composition and structure of anthocyanins was not evaluated in this study. Our findings show that the film was effective at the single rate and application method evaluated. There may, however, be other rates or methods of application that are more or less effective than the application evaluated in this study. In this study, the particle film was applied to the entire vine canopy, and berries sampled at maturity were obtained from eastern and western exposure aspects that were pooled for compositional analysis. Particle film effectiveness may be influenced by vine exposure aspect since ambient temperatures are warmest after solar noon. Knowing whether exposure aspect influenced film effectiveness could identify a more efficient application method than what was evaluated in this study. The differences we observed between cultivars in response to the particle film indicate that applicability of results from this study should be limited to cultivars with similar drought response as Cabernet Sauvignon and Malbec.

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