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Wine Grape Response to Foliar Particle Film under Differing Levels of Preveraison Water Stress

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***Abstract*. We investigated how foliar application of kaolin particle film influenced diurnal leaf gas exchange, leaf water potential, yield, and berry maturity of a red ('Merlot') and white ('Viognier') wine grape (*Vitis vinifera* L.) cultivar under differing levels of water stress over two growing seasons (2005 and 2006) in the warm, semiarid climate of southwestern Idaho. Net diurnal stomatal conductance (g_S) was increased by particle film and the effect varied according to vine water status. Particle film delayed the onset of diurnal decline in g_S under mild water stress (leaf water potential ≈ –1.2 MPa) but had no influence on leaf gas exchange when vines were under greater water stress (leaf water potential ≈ –1.4 MPa). Correlation between soluble solids concentration and titratable acidity ('Viognier') and between berry fresh weight and yield ('Merlot') was higher with than without particle film, suggesting that particle film may attenuate the influence of other factors affecting expression of these traits. Particle film was associated with an increase in berry weight in 'Merlot' and with an increase in berry soluble solids concentration in 'Viognier', suggesting that the film may increase vine-carrying capacity. Midday leaf water potential throughout the growing season was not influenced by particle film. Fruit surface browning was observed on deficit-irrigated, particle film-treated vines on exposed clusters on the west side of the canopy, indicating that the film did not eliminate development of heat stress symptoms on fruit under the most extreme environmental conditions evaluated in this study.**

Deficit irrigation is a production tool used on wine grapes and other perennial fruit crops to manage vegetative and reproductive growth for enhancement of product quality or to increase water use efficiency. In white wine grapes, optimum balance between canopy size and crop load is achieved when the vine has sufficient leaf area to ripen the fruit without excessively shading leaves or clusters. In red wine grapes, deficit irrigation is used to manage canopy size as well as to alter berry phenolic components in the skin that are associated with wine quality (Castellarin et al., 2007; Kennedy et al., 2002). Vine water stress has its greatest influence on berry and canopy size during the early phases of berry development (Matthews and Anderson, 1988; Matthews et al., 1987) and this stage may also be influential on berry mass components (Roby et al., 2004; Roby and Matthews, 2004) and secondary metabolites associated with wine quality (Cortell et al., 2005; Hrazdina et al., 1984). Deficit irrigation regimes imposed before veraison (onset of fruit ripening) restrict vine vegetative growth and this reduction in growth permits higher canopy light transmission (Shellie, 2006). Cluster exposure to sunlight beneficially increases skin phenolics for wine production; however, a higher incidence of sunburned fruit has been observed under deficit irrigation in warm, semiarid production regions with high solar radiation (Spayd et al., 2002). Clusters directly exposed to solar radiation have been found to exceed ambient temperature by as much as 13 °C, and berry temperature in excess of 35 °C has been associated with a reduced amount of skin anthocyanin, the principle component in grapes responsible for wine color (Spayd et al., 2002).

One of the primary ways that wine grapes maintain positive leaf cell turgor during water deficit is by closing leaf stomata to restrict loss of water vapor through transpiration (Düring, 1987). The extent to which stomatal limitations reduce carbon dioxide uptake and photosynthesis depends on the uniformity, magnitude, and duration of stomatal closure (Düring, 1992). Reduction in stomatal conductance (g_S) under deficit irrigation has been observed on many wine grape cultivars under field conditions (Naor et al., 1994; Peña and Tarara, 2004; Schultz, 2003; Souza et al., 2005; van Zyl, 1987). In warm, arid production regions, deficit irrigation is easily implemented as a production tool; however, high ambient temperatures may render exposed fruit and leaves more susceptible to damage from solar radiation or heat, and reduced leaf gas exchange may deleteriously affect productivity or fruit maturity.

Foliar application of a white kaolin particle film has been shown to reduce stress by increasing foliage reflection of infrared (IR) radiation thereby reducing leaf and fruit tissue temperature in a number of crops, including soybean (*Glycine max*), cotton (*Gossypium lirsutum*), artichoke (*Cynara scolymus*), melons (*Cucumis melo*), peach (*Prunus persica*), apple (*Malus sylvestris* L.), pecan (*Carya illinoinensis*), and grapefruit (*Citrus paradisi* L.). This reduction in heat load is thought to be accomplished without restricting leaf gas exchange (Glenn et al., 2001). A leaf or fruit intercepts photosynthetically active radiation through the particle film, whereas the film reflects ultraviolet and IR radiation from the leaf or fruit surface (Glenn and Puterka, 2005). Kaolin particle film was found to increase water use efficiency in citrus (Jifon and Syvertsen, 2003) but decrease water use efficiency in apple (Glenn et al., 2003). In citrus, water use efficiency was increased without changing whole-tree water use or leaf transpiration, whereas particle film was associated with higher transpiration in apple under a temperate climate. An objective of this research was to determine whether foliar particle film increased leaf water potential and/or g_S in field-grown wine grapes under varying levels of vine water stress. The present study also measured the influence of the particle film on wine grape yield and berry maturity.

Materials and Methods

This study was conducted during the 2005 and 2006 growing season on own-rooted 'Merlot' (U.C. Davis Foundation Plant Services clone 1) and 'Viognier' (U.C. Davis Foundation Plant Services clone 1) planted in 1999 at the University of Idaho Parma Research and Extension Center in Parma, ID (latitude 43°49′N, longitude 116°56′W, elevation 750 m). Four replicate plots of eight vines per cultivar were oriented north to south on a 3% to 7% slope with northern aspect. Row by vine spacing was 2.7 × 2.1 m. Each vine was double-trunked with each

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trunk forming a unilateral, 1-m long cordon located 1 m above the soil surface. Cordon arms were spur-pruned (seven two-bud spurs per cordon) and shoots were vertically positioned using two sets of moveable wires. The soil type was a Turbyfill fine sandy loam (U.S. Dept. Agr., Soil Conservation Service, 1972). With the exception of irrigation scheduling and particle film application, vines were managed according to standard commercial practice, which included rowcover crop maintenance, weed removal, pesticide application, and nutrient management.

Particle film (Surround® WP; Engelhard Corp., Iselin, NJ) was applied to four consecutive vines in each plot just after fruit set (first week of July). The film was applied weekly for 3 weeks to the entire canopy at a concentration of 60 $g \cdot L^{-1}$ in 950 $L \cdot ha^{-1}$ using a backpack sprayer. The first application contained 1.3 $mL \cdot L^{-1}$ of a nonionic surfactant (a.i.: alkyl aryl polyethoxylates, R-11 Wilbur-Ellis). Subsequent applications did not contain a surfactant because the particle film residue from the first application facilitated foliar coverage and therefore served the function of a surfactant. The remaining four consecutive vines within each cultivar plot received no spray application. Supplemental water was provided to all plots by aboveground drip [two emitters (3.8 $L \cdot h^{-1}$) per vine]. The soil was irrigated to field capacity before budbreak and after leaf fall and as needed between budbreak and fruit set to maintain leaf water potential (Ψ_L) at midday above –1.0 MPa. Beginning at fruit set, half of the plots were deficit-irrigated with 35% of estimated crop evapotranspiration (ET_c) until veraison (berry softening and color change). After veraison, the percentage of ET_c was increased from 35 to 70 (35% to 70% ET_c). The remaining plots received 100% ET_c from fruit set to harvest. Vines were irrigated twice weekly and irrigation amount was calculated from reference evapotranspiration (ET_r) (U.S. Bureau of Reclamation Parma weather station, http://www.usbr.gov/pn/agrimet/wxdata.html) and a wine grape crop coefficient (Evans et al., 1993), which was increased from 0.2 to 0.7 over the season. Application efficiency was assumed at 100%.

Leaves sampled from vines with or without particle film in each plot were used to measure Ψ_L and leaf g_S. Ψ_L was measured weekly, beginning on day of the year (DOY) 200 and ending on DOY 278 at midday (up to 2 h after solar noon) on two fully exposed, mature leaves 2 d after an irrigation. Leaves were covered with a clear plastic bag before severing the petiole and the bagged leaf was immediately inserted into a pressure chamber (model 610; PMS Instruments, Corvallis, OR). The chamber was pressurized at 33 $kPa \cdot s^{-1}$ and balancing pressure recorded at the first appearance of moisture on the cut petiole. The weekly midday Ψ_L values were used to calculate the average Ψ_L for phenological periods corresponding to changes in irrigation regime (fruit set to veraison and veraison to harvest). g_S (LI-1600 Steady State Porometer; LI-COR, Lincoln, NE) and Ψ_L were measured in sequence every 3 h from predawn until evening in 2006 on a clear sunny day during the preveraison period (DOY 201) and 1 week after veraison (DOY 236). Ambient air temperature and relative humidity were also monitored on these days.

Yield and cluster number per vine were measured at harvest and used to calculate average cluster weight. Ten clusters from vines with or without particle film in each plot (five clusters from each side of the canopy) were used to visually inspect for sun scald, calculate average berry fresh weight, and measure must composition. Ten berries sampled from each cluster (two berries from four cardinal quadrants and center) were combined and weighed and the 100-berry weight used to calculate average berry fresh weight. The 10 clusters were passed through a hand-operated crusher, left overnight on the skins at 21 °C room temperature, and analyzed the next day for soluble solids concentration, pH, and titratable acidity as described by Shellie (2006). Crop load, expressed as the Ravaz index (Ravaz, 1903), was calculated by dividing yield per vine by pruning weight (measured each season).

Average weekly midday Ψ_L was analyzed each year by cultivar using analysis of variance appropriate for a split-plot design with particle film split within irrigation as the main effect (SAS version 8.02; SAS Institute, Cary, NC). Probability of significant difference among treatments was determined from an F test ($P < 0.05$). Diurnal values for Ψ_L and g_s were averaged over cultivars by irrigation amount for each of the two sampling days in 2006 and graphed with SE bars using Sigmaplot 2000 (version 6.1; SPSS, Chicago). Data describing berry and vine attributes were analyzed by cultivar using analysis of covariance with particle film as the main effect and yield per vine as the covariate (SAS version 8.02; SAS Institute, Cary, NC). Probability of significant difference ($P < 0.05$) was determined with a *t* test of least square means.

Results

Seasonal temperature and evaporative demand were higher in 2006 than 2005 (Table 1). Heat unit accumulation in 2006 exceeded the 80-year site average of 1487 growing degree days (Shellie, 2006) by 231 heat units, mostly attributable to unusually high accumulation early in the season (May), before bloom. Annual precipitation was 35 mm higher in 2005 than 2006 with 21 mm more rainfall accumulating in 2005 than in 2006 between 1 Apr. and bloom. Vines irrigated at 100% ET_c from fruit set until harvest were provided with 38% (2005) or 39% (2006) of total ET_r. Vines irrigated at 35% to 70% ET_c were provided with 55% (2005) or 50% (2006) less water than vines irrigated at 100% ET_c.

Particle film had no consistent influence on midday Ψ_L (Table 2; Fig. 1). Average preveraison (fruit set to veraison) midday Ψ_L was influenced by irrigation regime and was ≈0.4 MPa lower for vines under 35% to 70% ET_c than for vines irrigated at 100% ET_c with the exception of 'Merlot' in 2005 for which it was only 0.24 MPa lower. Preveraison midday Ψ_L of vines under 100% ET_c in 2005 was

Table 1. Growing degree days, reference evapotranspiration (ET_r), precipitation, and water provided to wine grape cultivars Merlot and Viognier trial plots in southwestern Idaho in 2005 and 2006.

	2005	2006
Growing degree days (°C)[z]	1511	1718
ET_r 1 Apr. to 31 Oct. (mm)[y]	1197.6	1281.7
Annual precipitation (mm)	284.7	249.4
1 Apr. to bloom (18 June)	104.7	83.6
Bloom to veraison (16 Aug.)	6.1	9.9
Veraison to harvest (27 Sept.)	1.3	10.9
Irrigation (mm)		
100% ET_c	344.6	402.1
35% to 70% ET_c	154.7	201.9

[z]Growing degree days 1 Apr. to 31 Oct. calculated by simple daily average, base 10 °C with no upper threshold, Northwest berry and grape degree-day calculator (http://pnwpest.org).
[y]Alfalfa reference crop (http://www.usbr.gov/pn/agrimet/sxdata.html).

Table 2. Mean square and average values from analysis of variance for weekly midday leaf water potential of Merlot and Viognier vines for phenological stages corresponding with irrigation at 100 or 35% to 70% crop evapotranspiration (ET_c) with or without particle film in 2005 and 2006.

	Merlot[z]				Viognier			
	Fruit set to veraison		Veraison to harvest		Fruit set to veraison		Veraison to harvest	
	2005	2006	2005	2006	2005	2006	2005	2006
Irrigation (I)	4.839*	13.709*	0.428	0.378	7.211*	12.613**	2.505	2.440
Particle film (PF)	0.275	0.533	0.528	0.001	0.060	0.032	0.006	0.160
I × PF	0.009	0.204	0.265	0.397	0.228	0.180	0.027	0.156
	Midday leaf water potential (MPa)[y]							
100% ET_c	–1.23	–0.97	–1.11	–0.71	–1.11	–0.96	–0.95	–0.68
35% to 70% ET_c	–1.47	–1.39	–1.14	–0.81	–1.57	–1.43	–1.04	–0.83

[z]*, **Significant at $P \leq 0.05$, 0.01, respectively. Mean square values 10^{-2}. Mean separation in columns by *t* test at $P \leq 0.05$.
[y]Values represent four measurements at each weekly sampling.

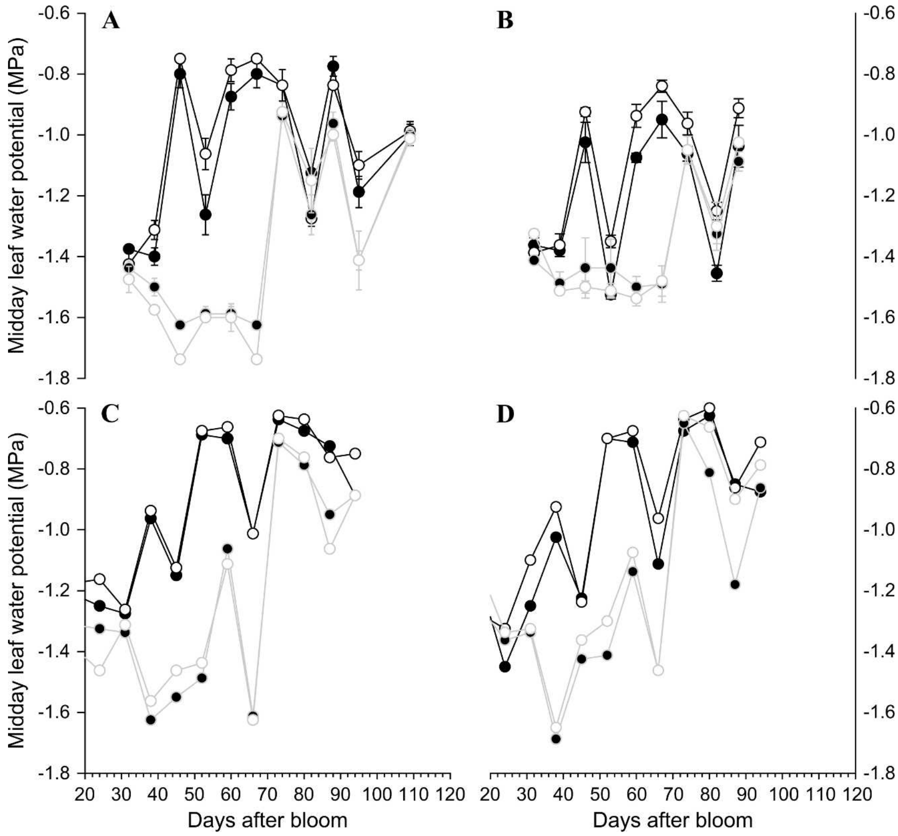

Fig. 1. Weekly midday leaf water potential of 'Viognier' (graphs **A** and **C**) and 'Merlot' (graphs **B** and **D**) in 2005 (graphs **A** and **B**) and 2006 (graphs **C** and **D**) under deficit irrigation (gray line) or well-watered (black line) with particle film (open circle) or without particle film (solid circle).

lower than the targeted value of –1.0 MPa (Greenspan, 2005), suggesting that these vines experienced water stress. Midday Ψ_L was similar between irrigation regimes during the postveraison period and higher than the preverasion period under both irrigation regimes. However, the increase from pre- to postveraison was greater (0.3 to 0.6 MPa) under 35% to 70% ET_c than under 100 ET_c (0.12 to 0.28 MPa). Midday Ψ_L was unaffected by an interaction between particle film and irrigation regime.

The irrigation regime for 35% to 70% ET_c was increased from 35% to 70% ET_c 1 week before postveraison diurnal Ψ_L and g_s measurements taken on DOY 236 (Fig. 2). Maximum ambient temperature on preveraison sampling DOY 201 reached 38 °C and exceeded that of DOY 236 by ≈8 °C. Maximum vapor pressure deficit on DOY 201 was 1 kPa higher than the 4.8 kPa maximum on DOY 236. Deficit-irrigated vines without particle film had lower g_s and Ψ_L than well-watered vines; however, all vines displayed a similar diurnal pattern (Fig. 2A–B). Daily maximum g_s for both irrigation regimes occurred at 0800 HR on DOY 201 and at 1100 HR on DOY 236 and corresponded with the daily minimum Ψ_L. Maximum g_s, of vines without particle film, was 50% lower under 35% to 70% ET_c compared with 100% ET_c preveraison but was similar postveraison for both irrigation regimes (Fig. 2A–B). Deficit-irrigated vines postveraison displayed lower g_s during the afternoon than the well-watered vines. A reduction in g_s signifies a reduction in leaf gas exchange and an increase in stomatal closure. Diurnal decline in g_s on both sampling days coincided with a Ψ_L lower than –1.2 MPa and ambient temperature and vapor pressure deficit near 28 °C and 4 kPa, respectively. The diurnal pattern for Ψ_L differed by sampling date as noted by an increase on DOY 201 at 1700 HR when ambient temperature was 37 °C compared with the sustained low level maintained throughout the afternoon on DOY 236.

The influence of particle film on g_s differed according to irrigation regime and day of sampling (Fig. 2C–D). Vines irrigated at 100% ET_c with particle film maintained higher g_s from 1100 to 1400 HR on DOY 201 than did vines without particle film, demonstrating a delay in the onset of the diurnal decline. However, on the same day, particle film had no effect on g_s for vines under 35% to 70% ET_c. On DOY 236, only vines under the 35 to 70 ET_c irrigation regime had higher g_s with particle film.

Particle film did not prevent development of sun scald on exposed clusters located on the west side of the canopy under the most severe water stress. Particle film increased by 7% the berry weight of 'Merlot' and by 11% the berry soluble solids concentration of 'Viognier' (Table 3). However, the average berry weight of 'Viognier' and the average soluble solids concentration of 'Merlot' berries were unaffected by particle film. Other components of yield (cluster weight and pruning weight) and berry maturity (pH and titratable acidity) were not influenced by particle film for either cultivar. 'Viognier' vines with particle film had a smaller range in berry soluble solids concentration at harvest than did vines without particle film. The correlation between soluble solids concentration and titratable acidity accounted for 79% of total variability for must titratable acidity in 'Viognier' vines with particle film but only 26% in vines without particle film (Fig. 3). Particle film influenced the percentage of total variation in harvest berry fresh weight explained by vine yield in 'Merlot' (Fig. 4). The correlation between yield per vine and berry weight in 'Merlot' accounted for 82% of total variability in berry fresh weight in vines with particle film but only 35% in vines without particle film.

Discussion

Cultivated wine grape is mesophytic and generally classified as ''drought-avoiding'' (Smart and Coombe, 1983), meaning that the vine has a limited ability to restrict water loss under drought conditions. Stomatal closure is a primary mechanism used by wine grapes to maintain positive cell turgor under water deficit. The relationship between soil moisture and midday Ψ_L varies among plant species, and wine grapes are similar to sunflower (*Helianthus annuus*) in that their midday Ψ_L varies according to soil moisture status. Other plant species such as maize (*Zea mays*) achieve and maintain similar values of midday Ψ_L under differing levels of soil moisture (Tardieu and Simonneau, 1998). The responsiveness of midday Ψ_L to soil moisture has been used to characterize stomatal behavior as anisohydric or isohydric and thought to be distinguished by differences in hydraulic conductance (Schultz, 2003) or by the degree to which Ψ_L influences stomatal control at a given level of chemical signal (Tardieu and Simonneau, 1998). The Ψ_L of anisohydric plants is thought to be an artifact of water flux and to have no direct controlling action on stomatal behavior (Tardieu et al., 1996).

The differing values of midday Ψ_L observed in this study for vines irrigated at 100% or 35% to 70% ET_c (Table 2; Fig. 2) support classification of the cultivars evaluated in this study as anisohydric. Leaf water potential declined during morning hours, whereas g_s increased demonstrating responsiveness of Ψ_L to water flux. The late afternoon increase in Ψ_L observed before but not after veraison may be associated with water flux from the fruit to the shoot. Berries have been shown to exhibit stronger daytime contraction before veraison than after veraison, and sensitivity of contraction to plant water status was much greater before than after veraison (Greenspan et al., 1994). Ripening-related physiological changes such as berry solute accumulation or apoplastic phloem unloading may inhibit the hydraulic flux

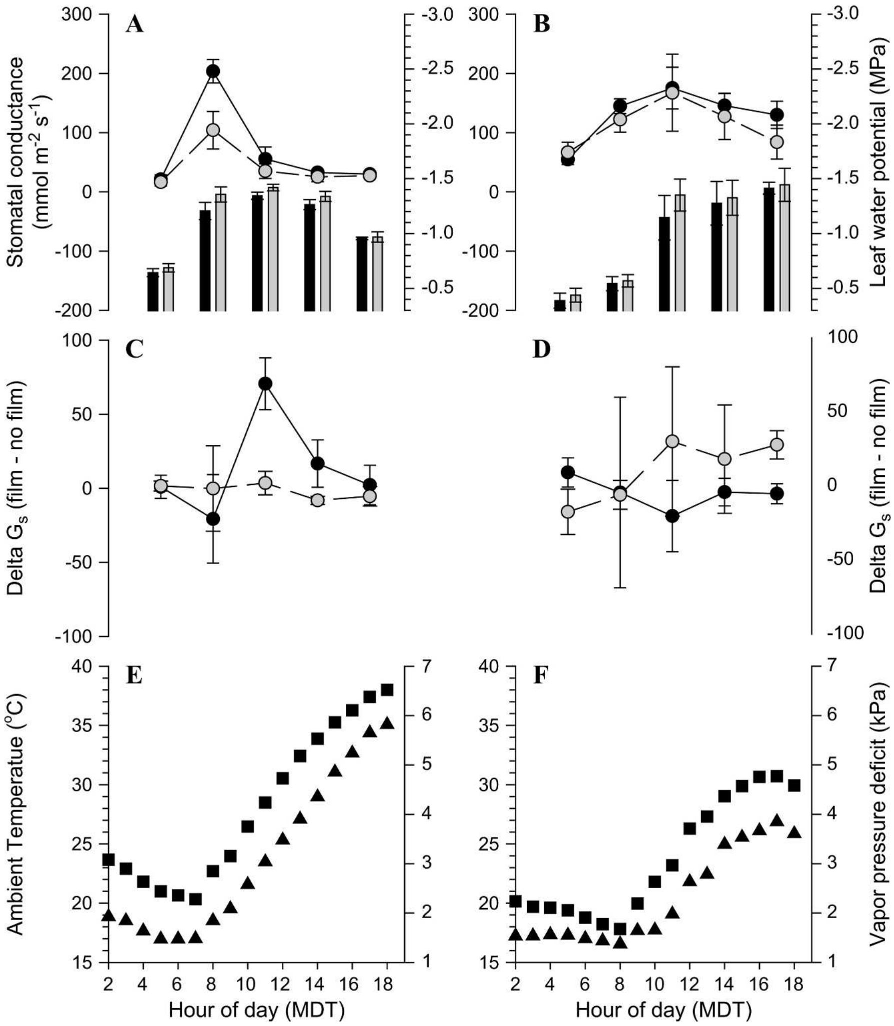

Fig. 2. Average values in 2006 for 'Viognier' and 'Merlot' pre- [day of year (DOY) 201, graphs **A, C**, and **E**] and postveraison (DOY 236, graphs **B**, **D**, and **F**). Graphs **A** and **B** show diurnal stomatal conductance (g_S) (circle) and leaf water potential (bar) of vines without particle film under well-watered (black) or deficit-irrigated (gray) conditions. Graphs **C** and **D** depict the difference in g_S between vines with particle film and vines without particle film under deficit (gray) or well-watered conditions. Graphs **E** and **F** present ambient temperature (square) and vapor pressure deficit (triangle) on the day of measurement. Error bars represent SES.

Table 3. Adjusted least square means for yield components and berry composition in 2005 and 2006 from analysis of variance by cultivar with yield per vine as covariate.

	Merlot		Viognier	
	Film	No film	Film	No film
Soluble solids (°Brix)	24.40 a	25.00 a	23.71 a	21.41 b
pH	3.64 a	3.63 a	3.26 a	3.18 a
Titratable acidity ($g \cdot L^{-1}$)	4.38 a	4.35 a	6.69 a	7.16 a
Berry weight (g)	1.18 a	1.10 b[z]	0.99 a	0.99 a
Cluster weight (g)	112.05 a	107.05 a	121.90 a	117.70 a
Pruning weight (kg $vine^{-1}$)	0.70 a	0.61 a	0.45 a	0.48 a
Ravaz index	5.74 a	6.37 a	13.16 a	12.32 a

[z]Mean separations by *t* test at $P \leq 0.05$ are within cultivar and row. Same letter within a cultivar row indicates no significant difference.

between fruit and shoot after verasion (Keller et al., 2006). Either one of these ripening-related changes could account for the sustained low afternoon levels of Ψ_L. The preverasion, late afternoon increase in Ψ_L while g_s remained low supports the hypothesis that Ψ_L does not directly control stomatal aperture. The diurnal pattern of g_s and Ψ_L observed in this study were similar to observations reported by others (Correia et al., 1995; Flexas et al., 1999; Loveys, 1984; Souza et al., 2005; van Zyl, 1987).

In this study, particle film had no consistent influence on Ψ_L but it delayed the onset of diurnal decline in g_s when vines were under mild water stress. A similar lack of influence of particle film on Ψ_L was reported for grapefruit (Jifon and Syvertsen, 2003) and for pecan (Lombardini et al., 2005). The increase in net diurnal leaf gas exchange observed in this study with particle film suggests potential for increased vine-carrying capacity. Particle film was associated with an increase in g_s in grapefruit and increased carbon uptake efficiency under high radiation and temperature stress, suggesting that photosynthesis was limited by g_s in leaves without particle film. The different cultivar response in berry components under particle film observed in this study could have been attributable to their different Ravaz index (yield: pruning weight) or the result of inherent cultivar differences in sensitivity or response to water stress. The Ravaz index for 'Viognier' exceeded the recommended range of 5 to 10 during both years of this study and was higher each year than 'Merlot'. If vine crop load in 'Viognier' was at or exceeded the capacity of the vine to ripen its fruit, then an increased net diurnal leaf gas exchange provided by the particle film could have increased leaf net sugar production and resulted in increased berry soluble solids concentration. A similar response may not have been apparent in 'Merlot' because its Ravaz index was within the expected range for adequate fruit ripening. An increase in red wine grape berry size could be desirable from a grower as well as a quality standpoint if there was a corresponding increase in skin phenolic concentration. Unfortunately, skin phenolic concentration was not evaluated in this study. Particle film was found to increase fruit size on apple trees when crop load was limited (Glenn et al., 2001) and to increase the soluble solids of some apple cultivars (Glenn and Puterka, 2005). The increase in net diurnal leaf gas exchange we observed with particle film under mild water stress suggests that particle film increased vine primary productivity under mild water stress.

An objective of this study was to measure whether particle film would indirectly increase Ψ_L through reduced g_s and whether this response would be similar under differing levels of vine water stress. The results from this study showed that particle film delayed the onset of the diurnal decline in g_s and this delay provided a net diurnal increase in leaf gas exchange. Particle film had no consistent influence on Ψ_L and the net diurnal increase in g_s was more apparent in well-watered than deficit-irrigated vines. The observed net increase in diurnal g_s and cultivar-specific responses to berry components suggested that particle film can increase vine-carrying capacity. Under the most extreme conditions evaluated in this study (high water stress, solar radiation, and ambient temperature), particle film did not eliminate visual symptoms of solar injury on the fruit surface at harvest.

The small increase in vine-carrying capacity and the persistent visual solar injury do not provide incentive for growers in warm, arid production regions with high solar radiation and vapor pressure deficit to apply particle film to wine grapes. It is, however, difficult to evaluate the potential benefit to

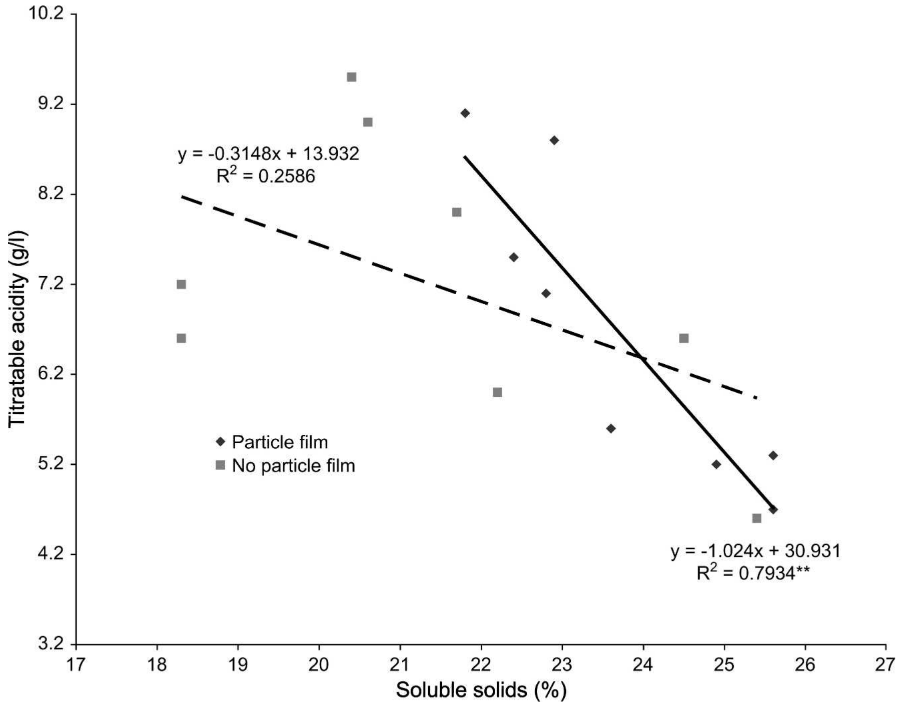

Fig. 3. Influence of particle film on the relationship between must titratable acidity and soluble solids concentration for 'Viognier' at harvest in 2005 and 2006.

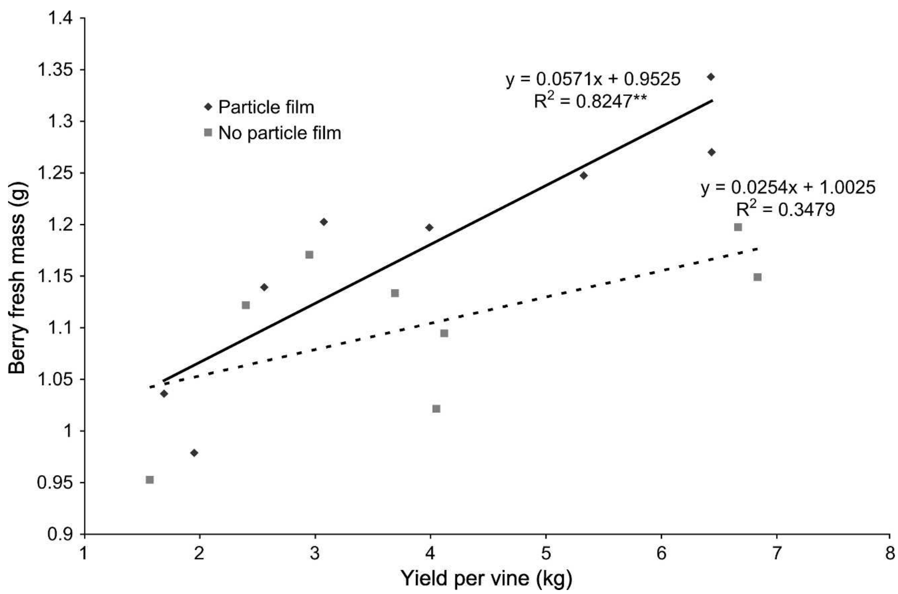

Fig. 4. Influence of particle film on the relationship between berry fresh weight at harvest and yield per vine for 'Merlot' in 2005 and 2006.

winemakers of the increased uniformity in harvest berry quality observed in vines with particle film. Winemakers need to determine the cost–benefit of obtaining more consistent fruit maturity (soluble solids concentration and titratable acidity) or stronger correlation between yield and berry size. The mechanism by which particle film appears to attenuate factors that influence wine grape maturity and yield warrants further investigation.

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