

# Performance of Early Fruit-Zone Leaf Removal in Cabernet Sauvignon and Merlot in an Arid Climate

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Cite this article:  
Moyer MM, Newhouse JM and  
Mireles MS. Performance of early  
fruit-zone leaf removal in Cabernet  
Sauvignon and Merlot in an arid  
climate. *Catalyst* 6:20-29.

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Manuscript submitted Sept 2021,  
revised Oct 2021, accepted Oct  
2021

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doi: 10.5344/catalyst.2021.21007

## Summary

**Goals:** Our goals were to evaluate how the timing of early fruit-zone leaf removal, done between prebloom and post-fruit set, influenced the risk of reduced fruit set, sunburn, and fruit quality in *Vitis vinifera* Cabernet Sauvignon and Merlot grown in the hot, arid, and irrigated region of eastern Washington State.

### Key Findings:

- Fruit set was reduced in *V. vinifera* Cabernet Sauvignon when fruit-zone leaf removal was completed during bloom. Prebloom and postbloom fruit-zone leaf removal did not reduce fruit set.
- Sunburn occurred on fruit on the westside of the canopy in both *V. vinifera* Cabernet Sauvignon and Merlot. Sunburn severity increased with later-timed fruit-zone leaf removal. Overall, the maximum severity of sunburn was 15% of the cluster surface area.
- Vintage had a greater effect on fruit quality than timing of leaf removal for both varieties. This emphasizes the need to make canopy management decisions that are informed by weather forecasts to achieve desired management goals.

**Impact and Significance:** Early fruit-zone leaf removal was traditionally avoided in eastern Washington, in favor of completing the practice after berries have reached pea-size. The later timing of leaf removal, however, can result in sudden exposure of the fruit during the typically warmest and sunniest time of the growing season. Results from this study show that many of the assumed risks associated with early fruit-zone leaf removal, such as extreme reduction in fruit set and sunburn, are not fully realized. This means that early fruit-zone leaf removal could be adopted in this hot, arid climate without a high risk of reduction in fruit quantity or quality.

**Key words:** abiotic stress, anthocyanins, canopy management, fruit exposure

## Overview

Canopy management in commercial vineyards is a practice that comes in many forms, with a variety of desired outcomes based on the production system. From more permanent approaches such as the choice of training systems, to more variable in-season approaches such as shoot manipulation or fruit-zone leaf removal, the intended result of canopy manipulation typically focuses on altering the canopy microclimate to influence either current year fruit quality and quantity, or subsequent season fruit quantity.<sup>1,2,3,4,5,6,7</sup>

Fruit-zone leaf removal, through its alteration of canopy architecture, can influence the canopy microclimate to where it reduces the favorability for disease development, particularly for powdery mildew (*Erysiphe necator*) and Botrytis bunch rot (*Botrytis cinerea*).<sup>8,9,10</sup> Historically performed near veraison, this technique removes leaves around clusters to improve sun exposure and increase air flow. Recent studies have focused on fruit-zone leaf removal earlier in the growing season (i.e., prebunch closure). The intent is that the earlier timing may reduce the risk of sunburn, reduce cluster compactness, and potentially

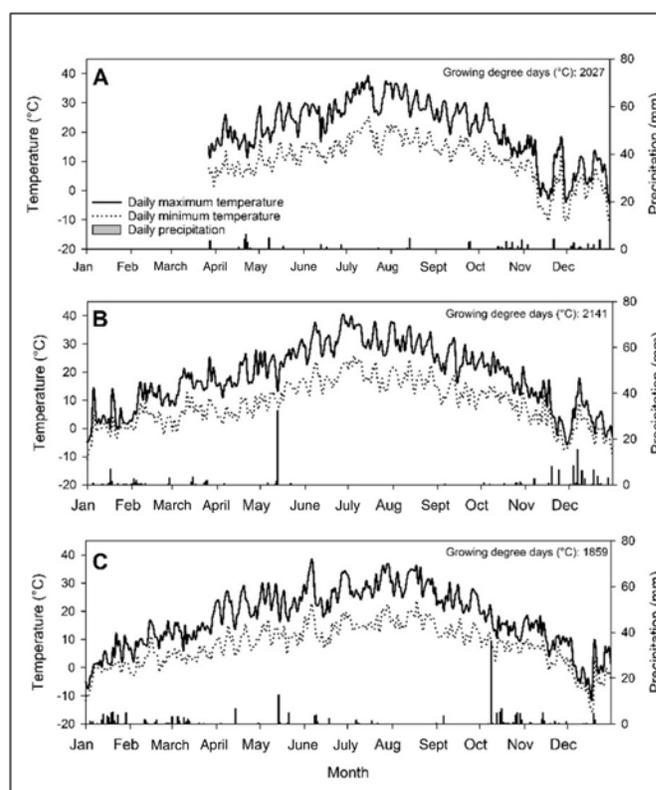
improve pest and disease management programs by improving spray penetrations during key periods of fruit development.<sup>4,7,11,12,13,14,15,16</sup> Fruit-zone leaf removal earlier than veraison can also help to reduce under-ripe flavors in red wine varieties (i.e., reduction of methoxypyrazines),<sup>6</sup> and enhance anthocyanin production during cool vintages.<sup>17</sup> These latter attributes related to alterations in fruit quality may be of greater importance to growers in arid climates, where disease pressure is often low and not the primary driver for the adoption of cultural practices in winegrape vineyards.<sup>18</sup>

Our past research has shown that early fruit-zone leaf removal is a viable option in white wine grapes in the warm arid conditions of eastern Washington State.<sup>13</sup> Still, the practice of early, complete fruit-zone leaf removal has not been widely adopted, likely driven by lack of mechanization ability. There are also perceived concerns related to increased sunburn, and reduction in both fruit quantity (fruit set) and quality when applied to winegrapes grown in a climate with notable hot and dry growing seasons. The project presented here was designed as a three-year demonstration trial to highlight how early fruit-zone leaf removal may influence yield and quality on two key red wine grape (*Vitis vinifera*) varieties in the region.

## Major Observations and Interpretations

**Weather description.** The 2014 vintage was considered slightly warmer-than-average and dry for the region, with a season total heat accumulation of 2027 growing degree days (GDD), and precipitation of 82.3 mm, with 54.4 mm falling between 1 April and 31 Oct (Figure 1A). The following vintage, 2015, was also considered warmer and dryer than average, with a drier and warmer vintage relative to the average, with a season total degree day accumulation of 2141 GDD, and the total annual precipitation of 141.7 mm, with 41.7 mm falling between 1 April and 31 Oct (Figure 1B). There was a notable rain event in mid-May, and no measurable precipitation in June, July, or August. The 2016 vintage had a near-average heat accumulation for the area, with slightly higher-than-average in-season precipitation. The season total degree day accumulation was 1859 GDD, with a total annual precipitation of 200.6 mm, with 119.1 mm falling between 1 April and 31 Oct (Figure 1C). There was measurable precipitation in June and July, which is uncharacteristic for the region, and notable precipitation events in October.

**Total leaf area removed during different times, and influence of leaf removal timing on dormant pruning weights.** In other studies, early fruit-zone leaf removal typically removed 20 to 39% of total canopy leaf area.<sup>19,20</sup> In our study, total area removed was higher (Figure 2), likely due to the overall smaller canopies maintained by Washington growers relative to general canopy sizes in other production regions. In Cabernet Sauvignon, leaf removal at prebloom removed ~50.5% and 48.9% of the foliage in 2015 and 2016, respectively (Figure 2A). In Merlot, leaf removal at prebloom in 2015 removed ~70.9% of the foliage, whereas in 2016 only 37.3% was removed (Figure 2B). Less than 40% of the total leaf area was removed for all remaining leaf removal timings in both varieties in both years. Total leaf area removed was not measured in 2014.



**Figure 1** Daily maximum and minimum temperatures, and precipitation, for the commercial vineyard in 2014 (A), 2015 (B), and 2016 (C) located in the Snipes Mountain American Viticultural Area in eastern Washington State, USA. Washington State University AgWeatherNet Snipes Mountain weather station was installed on 27 March 2014. (A) 2014 was considered a slightly-above-average temperature year, with consistent, low precipitation typical of the region. (B) 2015 was considered an exceptionally hot year, with a regional storm in late May which produced locally heavy rain. After that event, many of the remaining summer months (June, July, August, and September) did not have measurable precipitation. (C) 2016 was considered a relatively average year in terms of heat accumulation, with notable late-harvest rainfall for the region.

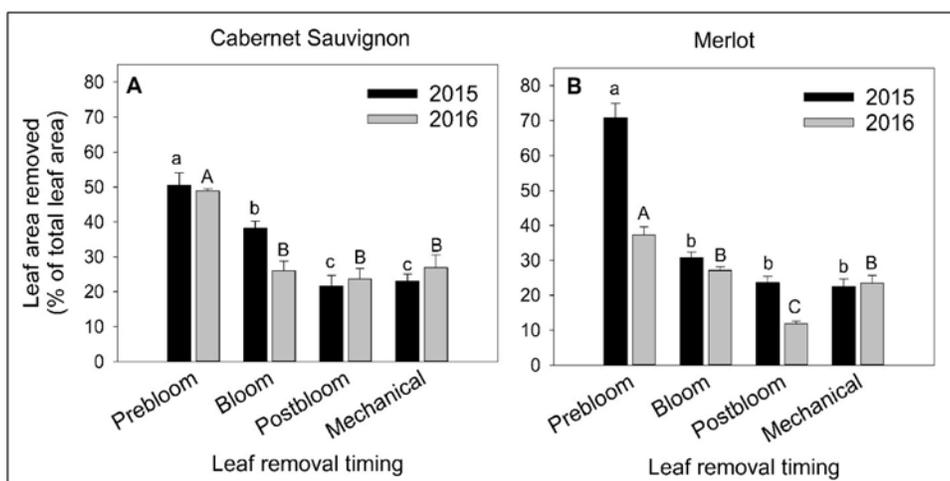
**Influence of vintage and leaf removal treatments on fruit set, berry size, and cluster weights.** A common concern relating to the adoption of early fruit-zone leaf removal is the potential effect it may have on yield. These effects can come in a variety of forms but are usually related to a reduction in fruit set or number of berries per cluster. However, these effects on yield are variable and often inconsistent, driven by specific combinations of leaf removal timing and severity, environmental conditions, management approaches, and variations in variety response.<sup>4,15,19,21,22</sup> In other words, a reduction in fruit set as a result of early fruit-zone leaf removal is not a universal response so it needs to be regionally considered.

In this trial, fruit set in Cabernet Sauvignon was influenced by both vintage and timing of leaf removal (but no interactive effects) (Table 1). Both 2014 and 2015 were very low fruit set vintages. Leaf removal at bloom resulted in a reduction in fruit set relative to no leaf removal (control), postbloom leaf removal, or mechanical leaf removal. Leaf removal at prebloom did not reduce fruit set relative to the control or postbloom timings, but fruit set was reduced relative to mechanical leaf removal. A similar response was seen for berry diameter; the 2014 and 2015 vintages had smaller berries, and the smallest diameter berries were associated with leaf removal at bloom. Berry and cluster weights in Cabernet Sauvignon were influenced by the interactive effect of vintage and leaf removal timing. For example, while the 2016 vintage had heavier berries and clusters, leaf removal at bloom reduced these weights, and this reduction in weight was exacerbated during the warmer 2014 and 2015 vintages. These interactive effects indicate that when available, current and forecasted weather conditions should be considered before the application of fruit-zone leaf removal because conducting the practice during an ex-

treme weather event, such as heat, may reduce certain yield parameters when performed during warmer-than-average vintages.

Fruit set in Merlot was not affected by vintage or timing of leaf removal, but both factors did influence berry and cluster size. In 2015, berries and clusters were smaller than they were in other years. Leaf removal at bloom in Merlot resulted in lighter berries when compared to the mechanical leaf removal treatment, but those same berries were not statistically lighter than the non-leaf removal control or other manual leaf removal timings. Merlot's consistency in yield component response (fruit set, berry size, cluster size) to the different timings of leaf removal, make it a good candidate for this practice.

**Influence of vintage and leaf removal timing on sunburn, fruit juice metrics, and skin phenolics.** Sunburn on fruit in Cabernet Sauvignon was influenced by the interaction of vintage and the side of the canopy on which fruit sunburn ratings were taken ( $p = 0.001$ ). Sunburn was also influenced by the interaction between the timing of leaf removal and the side of the canopy on which fruit sunburn ratings were taken ( $p = 0.004$ ; Figure 3A). In both 2015 and 2016, fruit on the western side of the vine had a higher average severity of sunburn than fruit on the eastern side of the vine (12.2% and 7.5% severity for 2015-West and 2016-West, respectively, versus 0.6% and 0.5% for 2015-East and 2016-East, respectively). However, in 2014, there was no difference in sunburn between fruit on either side of the vine (5.9% and 2.0% for 2014-West and 2014-East, respectively); this may likely be attributed to slightly larger canopies in the block in 2014 relative to the size the canopies were managed to in 2015 and 2016 (data not shown). Figure 3A shows the interactive effect with timing of leaf removal and the side of the canopy that sunburn was seen. Gener-



**Figure 2** Total leaf area removed at the time of fruit-zone leaf removal indicated for (A) *Vitis vinifera* Cabernet Sauvignon, and (B) *V. vinifera* Merlot grown in the Snipes Mountain American Viticultural Area in eastern Washington State, USA. Error bars are standard error. Different letters denote significant differences among treatment means at  $\alpha = 0.05$  using Tukey's honest significant difference test; lowercase letters are means separation within a variety for 2015; uppercase letters are means separation within a variety for 2016.

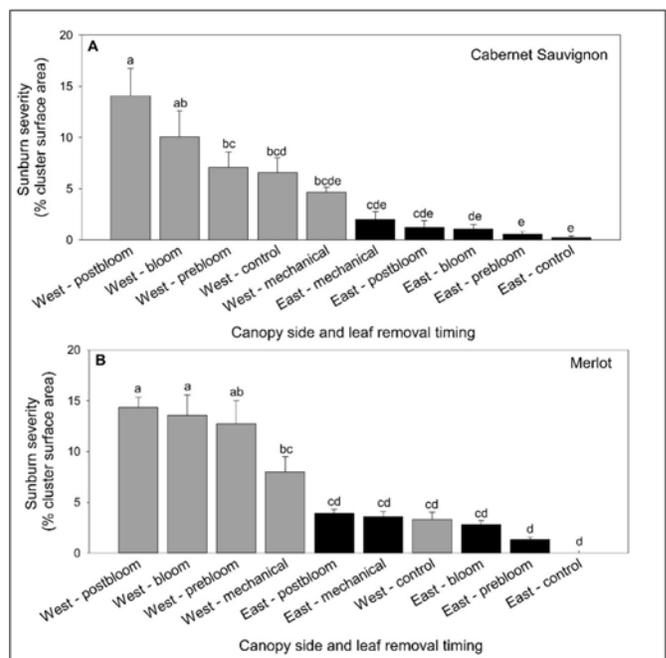
ally, sunburn was more severe for fruit on the western sides of the canopy; the later the timing of leaf removal, the higher the severity of sunburn. There was no interactive effect of vintage and timing of leaf removal ( $p = 0.44$ ), and there was no three-way interaction between vintage, leaf removal timing, or the side of the canopy from which fruit were rated ( $p = 0.61$ ).

**Table 1** Influence of year and leaf removal treatments on fruit set, berry size, and cluster weight on *Vitis vinifera* Cabernet Sauvignon and Merlot in Snipes Mountain American Viticultural Area in eastern Washington State, USA. Different letters denote significant differences among treatment means at  $\alpha = 0.05$  using Tukey's honest significant difference test.

Effect	Cabernet Sauvignon			
	% Fruit Set	Berry diameter (mm)	Berry weight (g)	Cluster weight (g)
<b>Year</b>				
2014	16.9% b	10.37 a	0.97 b	107.51 b
2015	17.8% b	10.29 a	0.83 c	102.78 b
2016	25.3% a	12.31 b	1.41 a	206.79 a
<i>p</i> value	<0.0001	<0.0001	<0.0001	<0.0001
<b>Leaf removal treatment</b>				
Control	22.5% ab	11.59 a	1.19 a	159.88 a
Prebloom	18.1% bc	11.26 a	1.10 ab	137.39 a
Bloom	14.6% c	9.82 b	0.96 c	88.61 b
Postbloom	20.9% ab	11.21 a	1.06 bc	170.12 a
Mechanical	23.7% a	11.11 a	1.03 bc	139.15 a
<i>p</i> value	0.0002	<0.0001	<0.0001	<0.0001
<b>Treatment × Year</b>				
<i>p</i> value	0.63	0.06	0.04	0.05
Effect	Merlot			
	% Fruit Set	Berry diameter (mm)	Berry weight (g)	Cluster weight (g)
<b>Year</b>				
2014	27.2%	12.1 a	1.53 a	158.18 b
2015	25.1%	11.2 b	0.99 b	114.29 c
2016	24.2%	12.4 a	1.52 a	197.72 a
<i>p</i> value	0.26	<0.0001	<0.0001	<0.0001
<b>Leaf removal treatment</b>				
Control	28.8%	11.89 ab	1.34 ab	156.21
Prebloom	25.1%	12.05 a	1.38 ab	175.14
Bloom	23.6%	11.16 b	1.22 b	131.46
Postbloom	24.1%	12.32 a	1.32 ab	152.85
Mechanical	25.9%	12.13 a	1.45 a	167.98
<i>p</i> value	0.25	0.0013	0.04	0.11
<b>Treatment × Year</b>				
<i>p</i> value	0.83	0.86	0.68	0.34

Sunburn in Merlot was only influenced by the interactive effects of timing of leaf removal and the side of the canopy from which cluster ratings were taken ( $p = 0.0005$ ) (Figure 3B) and was not influenced by vintage ( $p = 0.15$ ). As with Cabernet Sauvignon, Merlot fruit on the western side of the vines had the higher average sunburn severity ratings, and the later timing of leaf removal exacerbated sunburn severity (Figure 3B).

Differences in titratable acidity (TA), 3-isobutyl-2-methoxy-pyrazine (IBMP), and berry anthocyanin content in Cabernet Sauvignon (Table 2) were mostly driven by vintage, rather than by timing of leaf removal. This was also seen in Merlot (Table 3). The warmer years (2014, 2015) typically had lower TA, lower pH, and higher berry anthocyanins in both varieties. In Cabernet Sauvignon these warmer vintages also had reduced methoxy-pyrazines (Table 2). Interestingly, in Cabernet Sauvignon we saw lower skin tannins and phenolics in 2014 compared to 2016 (Table 2), but the opposite was true of Merlot for those two vintages (Table 3).



**Figure 3** Sunburn severity on clusters, rated from the eastside and westside of the grapevine canopy for the specified timing of fruit-zone leaf removal in both (A) *Vitis vinifera* Cabernet Sauvignon, and (B) *V. vinifera* Merlot, grown at a commercial vineyard in the Snipes Mountain American Viticultural Area in eastern Washington State, USA. Average sunburn severity of clusters on the western sides of the vines are shaded gray, and average sunburn severity of clusters on the eastern sides of the vines are shaded black for easier viewing. Error bars are standard error. Different letters denote significant differences among treatment means at  $\alpha = 0.05$  using Tukey's honest significant difference test.

The timing of leaf removal influenced total soluble solids and skin phenolics in Cabernet Sauvignon; leaf removal at bloom resulted in higher total soluble solids than postbloom mechanical leaf removal, and also had

higher skin phenolics than all other leaf removal timings. No leaf removal in Cabernet Sauvignon resulted in fruit with lower skin tannins compared to fruit from vines that underwent leaf removal at bloom or later. There was an

**Table 2** Influence of year and leaf removal timing on fruit quality at harvest in *Vitis vinifera* Cabernet Sauvignon in the Snipes Mountain American Viticultural Area in eastern Washington State, USA. Different letters denote significant differences among treatment means at  $\alpha = 0.05$  using Tukey's honest significant difference test. TA, titratable acidity; IBMP, 3-isobutyl-2-methoxypyrazine.

Effect	Soluble solids (Brix)	TA (g/L)	pH <sup>a</sup>	IBMP (ng/kg)	Berry anthocyanin (m/g fresh weight)	Skin tannins (mg/g)	Skin phenolics (mg/g)
<b>Year</b>							
2014	27.03 a	4.57 c	3.87 a	5.53 b	1.43 a	1.43 b	3.02 b
2015	26.28 a	5.47 b	3.67 b	6.96 b	1.08 b	1.60 a	3.92 a
2016	23.29 b	7.40 a	3.64 b	13.98 a	0.83 c	1.60 a	3.92 a
<i>p</i> value	<0.0001	<0.0001	0.0001	<0.0001	<0.0001	0.04	0.0002
<b>Leaf removal treatment</b>							
Control	25.50 ab	5.49	3.72	8.47	1.10	1.33 b	3.12 b
Prebloom	25.63 ab	5.77	3.73	9.12	1.11	1.46 ab	3.30 b
Bloom	26.16 a	5.99	3.67	7.74	1.16	1.66 a	4.78 a
Postbloom	25.53 ab	5.83	3.68	6.75	1.09	1.64 a	3.81 b
Mechanical	24.83 b	5.98	3.70	12.03	1.10	1.63 a	3.07 b
<i>p</i> value	0.05	0.18	0.42	0.20	0.96	0.006	<0.0001
<b>Treatment × Year</b>							
<i>p</i> value	0.73	0.86	0.04	0.63	0.22	0.53	0.11

<sup>a</sup>Statistical evaluation based on H<sup>+</sup>; presented as pH for ease of viewing.

**Table 3** Influence of year and leaf removal timing on fruit quality at harvest in *Vitis vinifera* Merlot. Different letters denote significant differences among treatment means at  $\alpha = 0.05$  using Tukey's honest significant difference test. TA, titratable acidity; IBMP, 3-isobutyl-2-methoxypyrazine.

Effect	Soluble solids (Brix)	TA (g/L)	pH <sup>a</sup>	IBMP (ng/kg)	Berry anthocyanin (m/g fresh weight)	Skin tannins (mg/g)	Skin phenolics (mg/g)
<b>Year</b>							
2014	25.51 a	3.86 b	3.94 b	11.12	1.02 a	1.15 a	2.84 b
2015	26.28 a	3.71 b	4.04 a	16.86	1.15 a	1.07 a	3.31 a
2016	22.99 b	7.42 a	3.79 c	12.85	0.76 b	0.78 b	1.89 c
<i>p</i> value	<0.0001	<0.0001	<0.0001	0.59	<0.0001	<0.0001	<0.0001
<b>Leaf removal treatment</b>							
Control	24.50	5.13 ab	3.93	25.15	0.88	0.99	2.42
Prebloom	25.49	5.38 a	3.94	11.85	1.01	1.01	2.74
Bloom	25.15	4.92 ab	3.93	8.80	1.05	1.08	2.86
Postbloom	29.97	4.68 b	3.94	6.75	1.02	0.99	2.76
Mechanical	24.49	4.86 ab	3.89	15.46	0.92	0.94	2.61
<i>p</i> value	0.15	0.02	0.48	0.12	0.14	0.74	0.31
<b>Treatment × Year</b>							
<i>p</i> value	0.89	0.06	0.60	0.91	0.47	0.62	0.73

<sup>a</sup>Statistical evaluation based on H<sup>+</sup>; presented as pH for ease of viewing.

interactive effect of vintage and timing of leaf removal on final fruit pH, but this was predominately driven by vintage (higher pH in 2014), with a subtle influence of very low pH in 2015 as a result of bloom leaf removal. In Merlot, fruit-zone leaf removal only influenced TA, where fruit from the postbloom leaf removal timing was lower in TA than fruit from vines that received leaf removal at prebloom.

These predominately vintage-driven responses in both varieties emphasize the much larger role of annual weather patterns on these basic fruit quality metrics in an arid climate like eastern Washington, compared to the minor effects that practices such as fruit-zone leaf removal may impart. Coupled with the yield response in the trial, this emphasizes the need to make weather (forecast)-informed vineyard management practice decisions, rather than simply applying practices such as fruit-zone leaf removal based on a traditional calendar schedule. If potentially detrimental weather events are predicted, management practices should be adjusted accordingly.

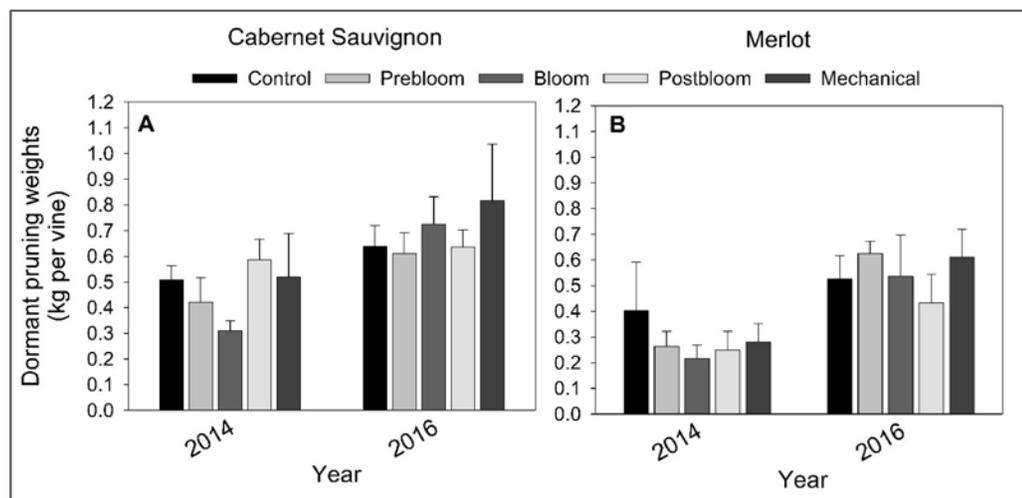
**Influence of leaf removal timing on dormant pruning weights.** In both 2014 and 2016, the timing of leaf removal did not influence dormant pruning weights (Figure 4) in either variety (Cabernet Sauvignon,  $p = 0.12$  and  $p = 0.56$ , respectively, for 2014 and 2016; Merlot,  $p = 0.67$  for both 2014 and 2016). In general, dormant pruning weights were less in 2014 than they were in 2016 (Figure 4). Pruning weights were not collected in 2015. For general context, average pruning weights (across all treatments) per linear meter of vine for Cabernet Sauvignon was 0.26 kg/m in 2014 and 0.38 kg/m in 2016. For Merlot, they were 0.16 kg/m in 2014 and 0.31 kg/m in 2016. Typically suggested optimal values are between 0.3 and 0.6 kg/m,<sup>23</sup> indicating the vines in this study had

lower vegetative growth than typically desired. Given the use of deficit irrigation to control canopy size (and cane diameter) in this production system, these lower-than-optimal values are not surprising because these index numbers were not developed using data from vineyards that practice controlled deficit irrigation.

## Broader Impact

Early fruit-zone leaf removal does not need to be considered as a cultural approach that can, or should, be applied across all managed acreage. Rather, it can be a tool that is deployed under specific situations to achieve a desired goal or set of goals. Those goals can range from alterations in attributes related to fruit quality (total soluble solids, TA, color, and/or tannins), to aiding disease management approaches. As with many practices, the adoption of early fruit-zone leaf removal needs to be placed into environmental context, both on the long-term (climate) and short-term (vintage) scale. In the study presented here, there were minimal overall negative effects of early fruit-zone leaf removal; however, leaf removal at bloom did result in reduced fruit set and berry size and increased skin tannins and phenolics in Cabernet Sauvignon. This highlights that when describing “early” in the concept of early fruit-zone leaf removal, specific phenological stages should be mentioned, because not all early timings are created equal.

When considering the environmental risks of fruit-zone leaf removal (whether early or late season) in a hot, arid climate like eastern Washington, the fear of sunburn on fruit is a driving factor for lack of application of the practice. This is understood, because sunburn is generally the result of both high temperatures and high sunlight exposure.<sup>24</sup> However, in a climate like eastern Washington, extreme heat events typically do not occur until mid-



**Figure 4** Dormant pruning weights in 2014 and 2016 of (A) *Vitis vinifera* Cabernet Sauvignon, and (B) *V. vinifera* Merlot vines that underwent fruit-zone leaf removal at different times. Vines were in a commercial vineyard in the Snipes Mountain American Viticultural Area in eastern Washington State, USA. Error bars are standard error. Leaf removal treatments did not statistically influence dormant pruning weights for either variety in the two years it was evaluated.

growing season (e.g., July), well after grapevine bloom for most varieties in the region. Thus, completing fruit-zone leaf removal earlier in the growing season when the risk of extreme heat is low, is the probable reason we saw a reduction in sunburn in those treatments (Figure 3). Shifting to earlier leaf removal likely also allows the developing fruit to potentially stave off severe sunburn through the accumulation of carotenoids and phenolic compounds.<sup>24</sup> In irrigated environments, viticulturists might be able to further reduce the risk of sunburn by adjusting their irrigation practices during heatwaves that occur postleaf removal; water stress through a reduction in transpiration can increase the risk of sunburn through increasing plant surface temperatures in direct sunlight. A practice such as early fruit-zone leaf removal can likely be adopted in most climates provided the practicing grower understands the abiotic factors that can influence its success. Growers should recognize that while their climate might be conducive for such a practice, specific weather patterns within the growing season (e.g., forecast heat waves) may require a shift in practice timing, degree of severity (i.e., total leaves removed), or follow-up mitigation strategies, such as adjustment to irrigation, to avoid plant damage.

The mechanization of leaf removal has predominately been done by machines that remove leaves by pulling them into shredding mechanisms. This approach is indiscriminate and works based on weight differences between leaves and ripening fruit; heavier fruit is less likely to be sucked into the blades than foliage. With the ease of mechanization of later leaf removal, the concept of returning to manual labor to perform early-season leaf removal results in a focus on the economics of manual labor,<sup>25</sup> especially in a tight labor market. Fortunately, newer leaf removal technologies, which remove leaves by pulsing high velocity air toward the canopy, have shown potential in mechanizing early fruit-zone leaf removal.<sup>7</sup> It is important to place the discussion of economics and labor into context. While mechanization may be a favored goal for large vineyard operations that struggle to maintain profitable business ventures in a challenging labor climate, it is not the primary goal for all grapegrowers. Particularly for smaller vineyard operations where the purchase of such mechanization equipment is not feasible, the integration of manual early fruit-zone leaf removal may be a practice that is worth considering to complement other fruit production goals. This might also hold true for those that have contractual obligations for non-mechanized activities in the vineyard.

The results of this three-year demonstration trial show that early fruit-zone leaf removal has a place in warm, arid climates with limited negative effects on fruit quality, and only minor effects on yield components. This information may prompt growers who are not currently practicing fruit-zone leaf removal to try it in their vineyards if they are struggling with canopy-environment related challenges (low fruit coloration, high disease pressure), or shift their practice to earlier in the growing season if they have experienced problems such as sunburn when conducting fruit-zone leaf removal later in the growing season.

## Experimental Design

**Vineyard description.** This trial was conducted in a commercial vineyard located west of Sunnyside, Washington, USA (46°18'N; 120°6'W) from spring 2014 to early winter 2016, for a total of three vintages. The soil at the site is a coarse-silty, mixed, superactive mesic Xeric Haplocambids (pedon: Wardon silt loam), with a 15 to 30% slope, as described on the United States Department of Agriculture's Natural Resources Conservation Service (USDA-NRCS) website (<https://soilseries.sc.egov.usda.gov/osdname.aspx>). One block each of *V. vinifera* Cabernet Sauvignon, field grafted onto a *V. vinifera* Syrah rootstock, and *V. vinifera* Merlot on own-root were used. Merlot and the Syrah rootstock were planted in 1999; Syrah was grafted-over to Cabernet Sauvignon in 2011. Rows are on a north-south orientation. Plant spacing were 2.7 m (between rows) × 1.8 m (between vines) in both vineyard blocks. Vines were trained to bilateral cordons, and annually pruned to two-bud spurs. Canopies were trained to a modified vertical shoot positioning with only a single, centered catchwire at ~40 cm above the fruiting wire. Irrigation was drip applied. In all years, water was applied by the cooperating grower to match (100%) evapotranspiration ( $ET_o$ ) rates until bloom. Postbloom irrigation was applied on biweekly irrigation sets to a regulated deficit of 80%  $ET_o$ . A final irrigation set was applied in October each year, prior to the termination of irrigation supply, to replenish the soil moisture profile. All other management practices (e.g., insect pest, disease, nutrient) were carried out per the cooperating grower's standard production practices.

**Weather data.** Weather data was collected using Washington State University's AgWeatherNet system (<http://weather.wsu.edu>). The Snipes Mountain weather station was used, located 3.3 km due east from the research site. Average daytime high and low temperatures and total precipitation data were recorded

at these stations, and GDDs (base of 10°C; 1 April to 31 Oct) and  $ET_0$  were calculated as described on the AgWeatherNet site. For 2014, weather data was only available starting on 27 March 2014, the date the station was installed.

**Leaf removal timing and approach.** Leaf removal was done either manually or mechanically using a Binger Seilzug Leaf Remover EB 490 (Binger Seilzug). For manual leaf removal, all leaves and lateral shoots from the base of each count shoot up to the secondary cluster were removed on both sides of the canopy. Mechanical leaf removal was on the east side of the vine canopy only per manufacturer's instructions; this side-limitation is because of the high temperatures common at the site and the general later timing of mechanical leaf removal. The different timing of leaf removal evaluated in this study were: (i) prebloom (rachis elongation) hand leaf removal, (ii) full bloom (50% of clusters at 50% capfall) hand leaf removal, (iii) approximately four weeks postbloom hand leaf removal, (iv) grower-timed postbloom mechanical leaf removal, and (v) no fruit-zone leaf removal. The timing of the postbloom hand leaf removal was adjusted to accommodate for labor-limiting temperature spikes, which are also conditions that are commonly associated with sunburn. These same avoidances are also generally considered by grower-producers in the area (i.e., limiting employee activities and canopy management activities when daily high temperatures exceed 35°C). The timing of the mechanical leaf removal ("industry control") was not determined based on vine phenology, but rather it followed the typical application schedule the cooperating grower usually uses for this practice, because it aligns with other on-farm activities. As a result, while the date of the mechanical leaf removal was similar between years, the phenological stage of the vine at the time of application was not. A summary of the dates at which leaf removal occurred across all three years is presented in Table 4.

The different timings of leaf removal (i.e., "treatments") were replicated four times in a randomized block design. Each treatment was applied to 30 vines in each replicate (10 vines per row, across three adjacent rows). The six center vines in the center row of each treatment replicate were used for data collection and observation, allowing a one-row buffer on either side of the treatment, and a two-vine buffer on either end of the observed vines in the center row. The same treatments were imposed on the same vines in all three years of the study.

**Fruit set, berry size, and cluster weights.** Fruit set was calculated for 12 clusters per treatment replicate, using the technique described by Komm and Moyer.<sup>13</sup> In

this technique, calyptra lost during the bloom period are collected in a fine mesh bag affixed to the inflorescence, and the total number of calyptra captured per cluster are compared to the total number of berries per cluster (for that same cluster) destructively counted at the start of veraison.

To determine cluster weight and berry size, additional clusters were collected near harvest: Cabernet Sauvignon, 21 Sept 2014, 27 Aug 2015, and 29 Aug 2016; Merlot, 15 Sept 2014, 19 Aug 2015, and 23 Aug 2016. Three clusters per treatment replicated were harvested, weighed, and then 20 individual berries per cluster were removed (60 berries per treatment replicate). Thirty of these berries were measured using a digital caliper (Electronic Digital Caliper #CO 030150, Marathon Watch Company) to assess berry diameter and then reserved for Brix, TA, and pH measurements (described below). The remaining 30 berries per treatment replicate (with pedicels intact) were then reserved for phenolic analysis, as described below.

**Fruit juice metrics, phenolics, IBMP, and sunburn.**

The 30 berries per treatment replicate that were reserved for Brix, TA, and pH measurements were crushed, and the resulting juice was used. Juice soluble solids were measured using a digital refractometer (Quick-Brix 60, Mettler-Toledo). Juice pH was measured using an electrode (InLab Versatile 413, Mettler-Toledo). Juice TA was measured and calculated as described by Iland et al. (2000).<sup>26</sup>

Berries reserved for skin phenolic analysis were processed as described by Komm and Moyer.<sup>13</sup> Tannin, phenolic, and anthocyanin measurements were done using protocols developed by Hagerman and Butler<sup>27</sup> and Har-

**Table 4** Vine phenological stage range in *Vitis vinifera* Cabernet Sauvignon and Merlot, and associated dates for fruit-zone leaf removal in this study. BBCH plant development stage as described by Lorenz et al.<sup>29</sup>

Timing of fruit-zone leaf removal	Year	Cabernet Sauvignon	Merlot
Prebloom: BBCH 55-57	2014	20 May	16 May
	2015	19 May	8 May
	2016	6 May	5 May
Bloom: BBCH 65	2014	9 June	3 June
	2015	28 May	26 May
	2016	17 May	16 May
Postbloom: BBCH 75	2014	9 July	9 July
	2015	24 June	22 June
	2016	13 June	13 June
Postbloom Mechanical: BBCH 73 to 79	2014	3 July	3 July
	2015	9 July	9 July
	2016	6 July	6 July
Control: No Leaf Removal	N/A	N/A	N/A

bertson et al.<sup>28</sup> IBMP was evaluated by randomly collecting 100 berries per treatment replicate, juicing berries, and sending juice samples to ETS Laboratories for analysis using their IBMP protocols. For Cabernet Sauvignon, berries were collected on 5 Sept 2014, 12 Aug 2015, and 21 Aug 2016. For Merlot, berries were sampled on 21 Aug 2014, 31 July 2015, and 21 Aug 2016.

Sunburn was rated as the percentage of cluster surface area displaying sunburn symptoms. Symptoms were rated on five clusters per treatment replicate per side (east or west) of the canopy. In 2014, sunburn was rated in both varieties on 18 Aug. In 2015, sunburn was rated on 19 and 25 Aug in Merlot and Cabernet Sauvignon, respectively, and in 2016, sunburn was rated on 22 and 29 Aug in Merlot and Cabernet Sauvignon, respectively.

**Total leaf area removed and dormant pruning weights.** Total leaf area removed was estimated by collecting 12 shoots per treatment replicate (per variety) from buffer vines directly next to data collection vines. These shoots were immediately collected after each specific leaf removal treatment timing and brought back to the lab to measure leaf area (LI-COR Area Meter model 3100, LI-COR, Inc.). Total leaf area per leaf on each shoot was measured; these were summed to estimate total leaf area per vine. To calculate leaf area removed, the area of the leaves located within the section of the shoot that would have experienced leaf removal was subtracted from the total leaf area for that shoot. Total leaf area removed was not estimated in 2014.

In both varieties, average dormant pruning weights were collected from five vines per leaf removal treatment replicate. Vines were pruned to two-bud spurs. Pruning weights were not collected in 2015 because of cooperating vineyard pruning prior to scheduled research pruning date. Dormant pruning weights from the 2014 growing season were collected on 4 March 2015. Dormant pruning weights from the 2016 growing season were collected on 20 Dec 2016.

**Statistical analysis.** The standard least-squares model platform in JMP (version 14.0.0, SAS Institute, Inc.) was used with year, treatment, and year × treatment interaction as fixed effects, and block as a random effect. Where significant differences were found, mean separation was performed using Tukey's honest significant difference test.

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