Manipulating the Postharvest Period and Its Impact on Vine Productivity of Semillon Grapevines

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Abstract: Trials were established in four Semillon hot-climate vineyards to determine the importance of the postharvest period for vines grown under different cropping levels and management practices. Two sites were chosen in high-yielding, furrow-irrigated vineyards in the Riverina region, and two in lower-yielding, drip-irrigated vineyards in the neighboring Hilltops region of New South Wales, Australia. Treatments were imposed over two consecutive seasons to alter either the length or the effectiveness of the postharvest period at each site. Complete defoliation at harvest to eliminate carbon assimilation during the postharvest period decreased yields by up to 21% relative to the control vines after one season and by 50% after two seasons of treatment. Extending the length of the postharvest period by early crop removal over two consecutive seasons increased yields by 48% when fruit was retained to commercial maturity in the third year. Vegetative growth responded similarly, and vine balance was not altered by any treatment. Berry sugar concentration at harvest was highest for previously defoliated vines and lowest for vines with an extended postharvest period. Treatments were less effective at the Hilltops vineyards, where lower yields and water availability may have reduced the importance of the postharvest period. Leaf damage or leaf spray applied after harvest did not impact vine productivity. Results suggest that adequate postharvest recovery is crucial for maintaining the productivity of high-yielding grapevines and that vineyards could be managed after harvest to manipulate vegetative growth and yield in the following season.

Key words: crop load, crop removal, leaf removal, postharvest, vigor, vine balance, yield components, *Vitis vinifera*

The length and effectiveness, in terms of nutrient uptake, storage reserve accumulation, and cold acclimation, of the vegetative postharvest period of grapevines varies with climate, crop load, and canopy condition. Crop load influences harvest date and vine reserve accumulation during crop maturation (Koblet et al. 1996) and therefore the time remaining until leaf fall. Most vineyards in Australia, particularly in the hot, irrigated inland regions, are harvested by machine. Physical leaf damage and juice splashing inflicted by mechanical harvesters may curtail the effectiveness of the postharvest period because of partial or severe defoliation. Other vineyard management practices after harvest may also alter the capacity of the vine to acquire nutrients and replenish storage reserves. Such variation has implications for canopy and fruit development in the following season.

The postharvest period is important for root growth and nutrient uptake in irrigated vineyards in hot climates (Conradie 2005), but much less so in cooler regions (Schreiner 2005). Sufficient late-season nitrogen uptake and reserve accumulation (Bates et al. 2002) is essential, since early nitrogen demand in spring cannot be met by root uptake (Cheng and Xia 2004). A considerable portion of a vine's carbohydrate reserves also may be accumulated after harvest if conditions permit (Williams 1996). Assimilate supply to the roots is more important in autumn than in summer, and autumn-stored assimilates also have higher translocation rates to the shoots in spring (Yang and Hori 1979). Mobilization of carbohydrate reserves in spring is crucial for new shoot growth and flower development until photosynthesis becomes the primary source of carbon. Therefore, the postharvest period may be important in determining vine vigor and productivity in the following season.

Vine reserve status at harvest determines the importance of reserve accumulation in the remaining part of the growing season. Despite grapes being a major sink, assimilates and nutrients can also be stored in the permanent structure during berry development (Miller et al. 1997). The capacity for reserve replenishment seems to increase after midberry ripening (Candolfi-Vasconcelos et al. 1994, Koblet et al. 1996). Loss of photosynthetically

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active leaf area or excessive crop loads may deplete storage reserves (Candolfi-Vasconcelos et al. 1994). Crop load may also alter the size of the permanent structure (Edson et al. 1993); thus, high crop loads may reduce the amount of vine reserves accumulated until harvest, and the delayed fruit maturation may shorten the postharvest period (Koblet et al. 1996). These effects reduce the capacity to accumulate carbohydrates for the following season, particularly if low autumn temperatures lead to early leaf senescence. Other studies, however, found no effect of crop load (Bravdo et al. 1985) or harvest date (Wample and Bary 1992) on cane reserve carbohydrate concentration.

Photosynthesis declines after harvest (Scholefield et al. 1978) along with leaf nitrogen content (Williams and Smith 1991), but it continues to be important for carbohydrate storage (Loescher et al. 1990). Scholefield et al. (1978) showed that leaf removal at harvest can lead to yield reduction of more than 50% in the following year. Even partial defoliation at veraison can delay budbreak in the following spring and reduce bud fruitfulness (Mansfield and Howell 1981). Fruit set also depends strongly on the supply of carbohydrates to the inflorescences which, in turn, is determined by the interaction of vine reserve status, current photosynthesis, and demand by competing sinks (Zapata et al. 2004).

These considerations suggest that conditions during the postharvest period can affect at least three stages of reproductive development: initiation, differentiation, and fruit set. The length and effectiveness of the postharvest phase can be altered not only by climatic factors but also by vineyard management practices. Despite the apparent significance of this period for vine performance, however, little is known about the changes induced by mechanical harvesting and other cultural practices and their influence on growth and fruiting. This study examined the impact of various treatments simulating altered length of the postharvest period and damage inflicted by machine harvesting on vine vigor, balance, and yield formation and their consequences for berry maturation in the subsequent seasons.

Materials and Methods

Vineyards and treatments. Trial sites were established in four *Vitis vinifera* L. cv. Semillon (on their own roots) vineyards that differed in cropping level and postharvest growing conditions. Two of the sites were chosen in high-yielding, furrow-irrigated vineyards in the Riverina region (34°S, 146°E), and two in lower-yielding, drip-irrigated vineyards in the neighboring Hilltops region (34°S, 148°E) of New South Wales, Australia. The Riverina has been classified as a very hot grapegrowing region with a mean January temperature of 24.2°C (Dry and Smart 1988) and mean annual rainfall of 406 mm. Annual rainfall in the Hilltops region is 653 mm, and the mean January temperature is 22.9°C, placing it in the hot-climate category (Dry and Smart 1988). All vineyards were trained to a single-wire cordon, while planting density varied among vineyards (Table 1). The Hilltops vineyards (H1, H2) were at a higher elevation than the more recently planted Riverina vineyards (R1, R2). The phenological dates of the four sites indicate that the season is slightly longer in Riverina and harvest date was also earlier in the first season, resulting in a longer postharvest period. This is even more apparent in the postharvest heat accumulation (growing degree days [GDD] base 10°C) of that season; the Riverina vineyards accumulated considerably more heat after harvest (Table 1). The GDD were calculated from budburst to the end of the growing season (leaf fall). Rain and irrigation amounts were much lower in the Hilltops vineyards, especially during the postharvest period. Only vineyard H1 received some irrigation water in the 2001/2002 season after harvest, while vineyard H2 received no additional water during postharvest. In the last season of the study, H2 was not irrigated, and there was no commercial harvest.

Table 1 Elevation and vine planting details of four Semillon vineyards used to manipulate postharvest canopy efficiency. Phenological stages, heat accumulation, and rainfall plus irrigation for two seasons (2001/2002 and 2002/2003).

	Riverina vineyards		Hilltops vineyards	
	R1	**R2**	**H1**	**H2**
Elevation (m)	125	125	500	560
Planting (year)	1998	1996	1990	1987
Planting density (vines/ha)	1800	1600	1470	1600
Vine spacing (m)	1.5	1.6	2.0	1.9
Row spacing (m)	3.7	3.9	3.4	3.9
2001/2002 Season				
Phenology				
Budbreak	20 Sep	20 Sep	20 Sep	20 Sep
Flowering	7 Nov	7 Nov	28 Nov	28 Nov
Harvest date	26 Feb	10 Mar	18 Mar	27 Mar
Leaf fall	16 May	16 May	12 May	12 May
Seasonal				
GDD (°C)	2184	2184	1985	1985
Rain/irrigation (mm)	770	570	346	343
Postharvest				
GDD (°C)	674	526	334	252
Rain/irrigation (mm)	206	166	42	39
2002/2003 Season				
Phenology				
Budbreak	20 Sep	20 Sep	17 Sep	17 Sep
Flowering	4 Nov	4 Nov	11 Nov	11 Nov
Harvest date	27 Feb	10 Feb	20 Feb	14 Feb
Leaf fall	21 May	21 May	1 May	1 May
Seasonal				
GDD (°C)	2482	2482	2043	1943
Rainfall + irrigation (mm)	786	586	199	190
Postharvest				
GDD (°C)	593	839	633	625
Rainfall + irrigation (mm)	235	291	42	42

The soil was sandier in H2, which could have reduced the availability of water, thereby increasing the impact of the drought conditions in the 2002/2003 season. Under commercial operation all vineyards were machine-harvested. Vineyards R2 and H1 were hand-pruned, and vineyards R1 and H2 were machine-pruned, but vineyard R1 received a follow-up hand-pruning.

At each site, six treatments were imposed over two consecutive seasons to change either the length of or accumulation level during the postharvest period. Relative to control vines, four of these treatments were designed to reduce the amount of carbohydrate reserves accumulated after harvest, and one treatment was designed to increase reserve accumulation. The treatments were as follows: untreated control (hand-harvested at commercial maturity); crop removal (harvested several weeks before harvest in other treatments); leaf removal (all leaves removed at harvest); leaf damage (a simulated 50% loss of leaf area by machine-harvesting); juice spray (a simulated effect of juice splashing on leaves by machine-harvesting); and leaf damage plus juice spray (combined simulated leaf loss and juice splashing). Under the crop-removal treatment, the grapes were removed during the phase of rapid berry sugar accumulation, when fruit sink strength is at its maximum (Candolfi-Vasconcelos et al. 1994). The crop-removal treatment was applied about 5 weeks (2000/2001) and 7 weeks (2001/2002) before the commercial harvest on average for each region. Total soluble solids (TSS) at the time of crop removal was recorded only in 2001/2002 and was 7.4 Brix in the Riverina vineyards and 12.2 Brix in the Hilltops vineyards. In the second season the leaf-removal treatment required repeated defoliation after harvest because of regrowth of shoots. Leaf damage was inflicted at harvest in 2001 by a commercial harvester followed by a lawn trimmer to ensure similar damage in all vineyards. At harvest 2002, the leaf damage was done manually by hitting the canopy with two 1-m-long wooden sticks to simulate the effect of the mechanical beaters on the machine harvester. Approximately 50% of the leaves were removed based on visual assessment, with this level of damage confirmed by subsequent aerial imaging as described by Hall et al. (2004). For the juice-spray treatments, grape juice was filtered through a cloth and applied with a 10-L garden sprayer. Between 5 and 10 L was sprayed on the leaves of each five-vine replicate, covering the whole canopy until runoff.

All treatments were replicated four times on five consecutive vines in a fully randomized block design and implemented over two growing seasons (2000/2001, 2001/2002). The data and sample collection started at harvest in 2001 and concluded shortly after pruning in 2003, but only data from the last two full growing seasons (2001/2002, 2002/2003) are reported here, since the treatments would have only altered vine productivity and grape composition in those seasons.

Vine and berry measurements. Yields were determined by hand-harvesting the three middle vines in each treatment plot just before the commercial harvest (except H2 in 2003). In the 2001/2002 season the Riverina vineyards were harvested several weeks earlier than the Hilltops vineyards, while in the following season (2002/2003) all vineyards were harvested in February (Table 1). The clusters were counted at harvest in the 2001/2002 season and about four weeks after budbreak in the 2002/2003 season. A 100-berry sample was taken at harvest from both sides of the canopy to determine berry weight and TSS with a digital bench refractometer (PR-101, Atago, Tokyo, Japan). Juice pH and titratable acidity (TA) were determined using an automatic titrator (TitraLab 80, Radiometer Copenhagen, Lyon, France). Berries per cluster, cluster weight, and sugar per berry (TSS x total berry weight) were calculated from these data. The canes were counted at pruning, and the average cane weight was calculated using the weight of prunings from each vine. All vines included in each trial (treatment vines) were pruned to equal bud numbers, but otherwise the vines were hand-pruned to match the surrounding commercial vineyard. Vineyard R1 was pruned to ~60 buds per vine; R2 and H1 to ~50 buds per vine; while H2 was pruned to ~110 buds per vine. Trunk circumference was measured in winter with a measuring tape at two positions (30 cm from the vine base and 30 cm below the wire) from each sampling vine in a replicate.

Data analysis. Statistical analysis was conducted using GenStat release 6.1 (VSN, Herts, UK). An analysis of variance was applied separately for each site to detect differences among the treatments. Differences between means were detected using a least significant difference (LSD) test ($p = 0.05$).

Results and Discussion

The impact of postharvest treatments from two seasons on vine performance in the following year is most likely more pronounced because of carry-over effects and the reproductive cycle of vines over these two growing seasons. The yield in the last season of the study (2002/2003) could have been altered by the first season's treatment (2001/2002), with an additional impact on bud fruitfulness rather than only cluster size. In addition, the second season allowed an assessment of effects not only on reproductive growth of two altered postharvest periods but also on canopy development.

Yield and pruning weight. Vine productivity was affected by crop removal, and leaf removal at all sites except H2, but the magnitude of the effects varied between regions, perhaps because of the differences in productivity levels (Table 2). In the higher yielding Riverina vineyards the impact on yield and pruning weight was great, while in the Hilltops vineyards the changes were small or not detectable. The yields in vineyard R1 were affected in both years; the yield reduction because of leaf removal was ~20% in 2002 and ~50% in 2003. In contrast, yields were increased by 20% when the crop was removed early, while leaf damage had no effect on yield. Yields in vineyard R2 were reduced by leaf removal or increased by crop removal by ~30% at harvest 2003, and the other treatments had minor effects as in vineyard R1. There was a similar response pattern in the same year in vineyard H1, where these were decreased or increased ~40% by leaf and crop removal, respectively. There was no response to treatments in vineyard H2, probably because of the drought conditions since the vineyard received no irrigation during the 2002/2003 season or in the previous postharvest period. In addition, the sandier soil in vineyard H2 would have retained less soil water from winter rains that would be available to vines during the growing season. Surprisingly, spraying juice on the leaves did not reduce vine productivity, but rather increased yield in 2003 in one of the Riverina vineyards because of larger clusters. Despite being sprayed to runoff with grape juice, the spray did not induce the leaf burning sometimes seen after machine-harvesting in Semillon.

The reduction in yield in the seasons following complete defoliation at harvest and the increasing effect over multiple seasons have been reported previously (Scholefield et al. 1978), suggesting an impact on all key stages of reproductive development. As in our study, the authors found only a minor impact of partial defoliation on yields. The cumulative effect of defoliation during berry development applied in previous seasons on yield was also demonstrated by Candolfi-Vasconcelos and Koblet (1990), who found concomitant reduction in starch reserves. According

Table 2 Vine productivity and balance of Semillon grapevines following manipulation of the postharvest canopy efficiency.

	Yield (kg/vine)		**Pruning wt (kg/vine)**		**Vine balance**[a]		**Berry sugar (kg/vine)**	
Treatment	**2002**	**2003**	**2002**	**2003**	**2002**	**2003**	**2002**	**2003**
R1 vineyard								
Control	29.4 a[b]	27.6 bc	2.2 ab	2.0 ab	13.6	14.2	5.4 a	5.3 b
Leaf removal	22.9 b	13.9 d	1.5 c	0.9 d	15.4	15.1	4.5 b	3.0 c
Crop removal[c]	–	35.2 a	2.5 a	2.4 a	–	14.8	–	6.1 a
Leaf damage	27.3 a	25.4 c	1.7 bc	1.5 bc	16.0	17.6	5.1 a	5.3 b
Juice spray	29.2 a	30.6 b	2.1 ab	1.8 bc	14.0	17.6	5.4 a	6.0 a
Leaf damage + juice	26.4 a	25.1 c	1.8 bc	1.7 bc	14.6	15.3	4.9 ab	4.9 b
	**[d]	***	***	***	ns	ns	*	***
R2 vineyard								
Control	22.6	14.5 b	1.6 b	1.3 b	13.9	11.1	5.1	3.2 b
Leaf removal	17.7	9.4 c	1.5 b	0.9 c	11.9	10.8	4.2	2.4 c
Crop removal[c]	–	23.1 a	2.3 a	2.2 a	–	10.8	–	4.4 a
Leaf damage	19.7	13.5 b	1.5 b	1.3 b	12.8	10.6	4.5	3.0 bc
Juice spray	24.0	16.5 b	1.8 b	1.4 b	13.8	12.3	5.4	3.6 b
Leaf damage + juice	19.9	13.6 b	1.5 b	1.2 bc	13.5	11.9	4.6	3.2 b
	ns	***	**	***	ns	ns	ns	***
H1 vineyard								
Control	11.3	2.5 bc	1.5	0.4 bc	7.7	6.2	2.5	0.6 b
Leaf removal	9.0	1.6 d	1.1	0.3 c	7.8	4.6	2.2	0.4 c
Crop removal[c]	–	3.4 a	1.6	0.6 a	–	5.4	–	0.7 a
Leaf damage	9.8	1.9 cd	1.2	0.4 bc	8.6	5.0	2.3	0.4 bc
Juice spray	10.6	1.9 cd	1.2	0.3 c	8.5	5.8	2.4	0.5 bc
Leaf damage + juice	11.8	2.8 ab	1.3	0.5 b	9.5	5.9	2.7	0.7 ab
	ns	**	ns	***	ns	ns	ns	**
H2 vineyard								
Control	2.2	0.1	0.7 a	0.1	2.9 a	2.3	0.6	0.0
Leaf removal	2.5	0.3	0.4 b	0.1	6.1 c	5.2	0.7	0.1
Crop removal[c]	–	0.1	0.7 a	0.1	–	2.7	–	0.0
Leaf damage	2.0	0.4	0.6 ab	0.1	3.3 bc	5.1	0.5	0.1
Juice spray	2.8	0.4	0.6 ab	0.1	4.7 ab	5.8	0.7	0.1
Leaf damage + juice	2.5	0.3	0.6 ab	0.1	4.4 bc	5.4	0.6	0.1
	ns	ns	*	ns	*	ns	ns	ns

[a] Yield-to-pruning-weight ratio.

[b] Means separated within columns using Fisher's LSD test. Different letters within a column indicate a significant difference ($p = 0.05$).

[c] All fruit removed at midripening, therefore yield could not be determined for 2002 harvest.

[d] *, **, ***, and ns indicate significance at $p < 0.05$, < 0.01, < 0.001, and not significant, respectively.

to Loescher et al. (1990), late-season defoliation always results in diminished carbohydrate reserves and can also result in nitrogen deficiency in the following season. Complete defoliation not only would have prohibited nutrient resorption from the leaves and reallocation to storage (that is, it interfered with the normal senescence process in autumn), but also would have greatly reduced late-season nutrient uptake from the soil because of the elimination of transpiration. These vines would therefore also have a reduced nutrient status (especially for nitrogen), as indicated by lower nutrient levels in the spurs at leaf fall 2002 (Holzapfel and Smith 2005). Both vegetative growth and fruiting of grapevines may be more dependent on nitrogen reserves than on carbohydrate reserves (Cheng and Xia 2004). Increasing reduction in yield over multiple seasons could be due to a progressive decline in vine reserve levels, which may impact all stages of reproductive development. The minor impact of the damage of the simulated mechanical harvester could have been due to a compensatory increase in photosynthetic activity of the remaining functional leaves, as shown for partial defoliation (Hunter and Visser 1988), or to improved light interception by the remaining leaves. Alternatively, the remaining 50% of the leaves may have been sufficient to maximize yield potential for the following season.

In addition to the higher crop levels, the Riverina vineyards had much higher pruning weights than the Hilltops vineyards and were more affected by the treatments in both years (Table 2). The Riverina vineyards responded differently in the first year (2002); pruning weights were lowered by leaf removal in vineyard R1 and elevated by crop removal in vineyard R2. In the following season pruning weights were reduced by leaf removal and elevated by crop removal similarly in both vineyards. Crop removal also increased pruning weights in vineyard H1 but had no effect in vineyard H2, where drought stress led to low pruning weights. Response to the other treatments did not differ from that to the control in any vineyard. Crop reduction often leads to larger vines in the following year (Edson et al. 1993). The yield-to-pruning-weight ratio was highest in vineyard R1, followed by vineyards R2, H1, and H2. Only vineyard H1 fell into the optimal range of 5 to 10 (Smart and Robinson 1991), whereas vineyards R1 and R2 would be classified as overcropped and vineyard H2 as undercropped. The postharvest treatments did not modify the yield-to-pruning-weight ratio in any vineyard in either of the two years. This proportional change in yield and pruning weight reacted most strongly to manipulations of the postharvest period in the overcropped vineyards, and least in the undercropped vineyard. The difference in magnitude of the reaction in the two regions might be due to differences in vine reserve dynamics. The high crop loads may have reduced vine reserve accumulation until harvest (Candolfi-Vasconcelos et al. 1994), while in the low-yielding vineyards impact on reserves may have been minimal.

The impact of cropping levels on the vines was also revealed by the sugar yields per vine. In the first year, only vineyard R1 had a reduction in sugar yield per vine when leaves had been removed at harvest in the preceding season. In the second year, both Riverina vineyards and Hilltops vineyard H1 responded with increased sugar yield when the crop had been removed early in the previous two years and with decreased sugar yield when the leaves had been removed at harvest. The relative differences of these changes in sugar yield were not as great as the yield differences caused by the treatments, likely because fruit from the higher cropped vines was less mature at harvest than that from the lower cropped vines. A delay in fruit maturation is often associated with high crop loads (Koblet et al. 1996).

Trunk size and cane number and size. Despite the differences in productivity levels and vine age, trunk girth was similar in all vineyards in the first season (Table 3). In the second season, trunk girth of the more productive vines in the Riverina was larger compared to the first season, while in the Hilltops vineyards, the trunks were slightly smaller than in the previous year. The apparent decrease in trunk circumference in the Hilltops vineyards might have been due to poor growing conditions caused by drought. The cane numbers per vine were similar among the Riverina vineyards and vineyard H1 in the second season, but vines in H2 had almost 50% more canes (Table 3). The impact of the treatments on cane numbers was inconsistent among vineyards and years, but indicates some impact on budburst, since the vines were pruned to similar bud numbers the previous season. For instance, in the first season (2001/2002) some treatments reduced cane numbers in vineyard R2, while in the following season they had no effect. In vineyard H2, crop removal led to the highest number of canes in both seasons, which may have been due to improved vine reserve status (Miller et al. 1997). With the exception of vineyard H2, differences in cane weight in winter (vigor) were more pronounced in the second season (2002/2003). In vineyard R1, cane weight was more than 60% lower in response to the leaf removal than to the crop removal after two years of implementation. Cane weight was more responsive than cane length (data not shown) to postharvest manipulations; in most cases the canes were lighter following leaf removal or leaf damage and heavier following crop removal or juice spray. In addition, the decrease in cane weight following leaf removal at harvest was stronger in the second season, suggesting that vine reserves were further depleted over consecutive seasons. These results also show that the differences in pruning weights were primarily due to cane size (diameter and length) rather than to cane number.

Yield components. Clusters per vine and cluster weight were highest in R1, followed by R2, and were lowest in the Hilltops vineyards (Table 4). Berries per cluster were similar in all vineyards, except in H2 where clusters had approximately one-third as many berries. In the first year, treatments affected yield components only in R1, where juice spray led to more berries per cluster. The yield reduction in response to leaf removal observed in R1 was attributed to fewer and smaller clusters. There was a trend in the Riverina, particularly in R1, but not in the less-fruitful Hilltops vineyards for leaf removal and leaf damage to decrease bud fruitfulness (clusters per shoot) (Table 3). Crop removal produced about double the berries per bunch than the leaf removal in H1. In the Riverina vineyards, the treatments modified all yield components except berry weight. Leaf removal generally decreased and crop removal increased cluster and berry numbers and cluster weight. In addition, cluster weight in R1 was also increased by the juice-spray treatment. These results suggest that differences in carbon assimilation during the postharvest period caused variation in flower numbers and fruit set. Moreover, the differences in the number of clusters per shoot in the two Riverina vineyards indicate that the treatments also affected cluster initiation and/or differentiation (and hence bud fruitfulness) in these high-yielding vineyards. Vineyard productivity level changed with berry weight, which was highest in R1 and lowest in H2. However, the postharvest treatments failed to alter berry weights.

The potential crop produced by individual vines is comprised of several yield components determined at least

Table 3 Vegetative growth measured after leaf fall and clusters per shoot of Semillon grapevines following manipulation of the postharvest canopy efficiency.

	Trunk circumference (cm)		Cane number		Cane wt (g)		Clusters/ shoot	
Treatment	**2002**	**2003**	**2002**	**2003**	**2002**	**2003**	**2002**	**2003**
R1 vineyard								
Control	15.4	17.3	52	51 a[a]	43.3 ab	39.2 ab	2.3	2.0 a
Leaf removal	15.0	16.6	51	49 a	29.4 c	19.3 d	1.9	1.4 b
Crop removal[b]	15.6	18.0	51	49 a	49.7 a	49.7 a	–	2.2 a
Leaf damage	15.3	17.0	56	53 a	31.1 c	27.9 cd	1.9	1.7 ab
Juice spray	15.2	17.1	46	43 b	45.4 ab	41.1 ab	2.1	2.2 a
Leaf damage + juice	15.1	17.0	52	50 a	35.1 bc	33.4 bc	2.2	2.0 a
	ns[c]	ns	ns	**	**	***	ns	**
R2 vineyard								
Control	14.4	16.7	49 ab	45	34.0 c	29.5 bc	2.0 bc	1.8 bc
Leaf removal	14.1	15.7	42 cd	39	35.2 c	22.5 c	2.1 ab	1.9 bc
Crop removal[b]	15.1	17.5	43 cd	41	54.1 a	52.3 a	–	2.3 a
Leaf damage	14.2	16.3	50 a	43	30.9 c	29.6 bc	1.8 c	1.7 c
Juice spray	14.8	17.1	39 ab	40	45.0 b	35.3 b	2.4 a	2.1 ab
Leaf damage + juice	14.0	16.2	45 bc	41	32.8 c	28.2 bc	1.9 bc	1.8 bc
	ns	ns	***	ns	***	***	*	*
H1 vineyard								
Control	15.8	15.1	46	54	32.0 ab	7.3 cd	1.5	0.9
Leaf removal	15.5	15.0	46	65	24.8 c	5.2 c	1.4	0.7
Crop removal[b]	15.9	15.6	45	61	35.3 a	10.4 a	–	0.9
Leaf damage	15.1	14.9	48	56	24.5 c	7.0 cd	1.5	0.9
Juice spray	15.8	14.5	47	61	26.9 bc	5.5 c	1.5	0.8
Leaf damage + juice	15.8	15.2	47	55	26.8 bc	8.9 ab	1.6	1.0
	ns	ns	ns	ns	*	***	ns	ns
H2 vineyard								
Control	14.9	14.2	57 ab	81 bcd	13.0 a	0.7	1.3	0.4
Leaf removal	14.7	14.3	55 b	83 bc	7.7 b	0.8	1.4	0.6
Crop removal[b]	15.2	14.2	63 a	89 a	11.8 a	0.6	–	0.4
Leaf damage	15.0	13.9	53 b	72 d	10.8 a	1.2	1.1	0.5
Juice spray	15.0	14.2	58 ab	87 ab	10.5 ab	0.8	1.4	0.5
Leaf damage + juice	14.8	14.7	52 b	80 bcd	10.9 a	0.9	1.2	0.6
	ns	ns	*	*	*	ns	ns	ns

[a] Means separated within columns using Fisher's LSD test. Different letters within a column indicate a significant difference ($p = 0.05$).

[b] All fruit removed at midripening, therefore yield could not be determined at harvest 2002.

[c] *, **, ***, and ns indicate significance at $p < 0.05$, < 0.01, < 0.001, and not significant, respectively.

15 months before harvest (May 2004). The differences in yield components could be caused by altered reserve levels as indicated in spurs at leaf fall (Holzapfel and Smith 2005). Vines appear to be particularly susceptible to the influence of reserves during inflorescence initiation, differentiation, and bloom. Other studies have shown that both fruitfulness (cluster initiation; Keller and Koblet 1995) and fruit set (Zapata et al. 2004) are dependent on carbohydrate supply from current photosynthesis or reserve pools. Nevertheless, crop load and defoliation are generally thought to have little effect on cluster initiation and differentiation in the current season (Goffinet 2004). Reproductive development is most dependent on reserves during the budbreak period, when inflorescences must compete with unfolding leaves for access to reserves (Goffinet 2004). Therefore, cluster and flower numbers would be expected to be most vulnerable to poor reserve status during this period. However, Goffinet (2004) found no effect on flower initiation and development in Concord vines subjected to carbohydrate reserve depletion by defoliation and high crop load in the previous season, but fruit set was not reported. These observations indicate that changes in yield were attributable to berry numbers in the first season and also to bud fruitfulness in the second season.

Fruit composition. Berry maturity at harvest (Table 5) reflected the yield level, yield-to-pruning-weight ratio, and sugar yield reported above. At first sight, the cropping level in vineyard R1 might have been excessive and hindered fruit ripening, since vines with high crop loads of-

Table 4 Yield components of Semillon grapevines following manipulation of the postharvest canopy efficiency.

	Clusters/ vine		Cluster wt (g)		Berries/ cluster		Berry wt (g)	
Treatment	**2002**	**2003**	**2002**	**2003**	**2002**	**2003**	**2002**	**2003**
R1 vineyard								
Control	118	103 ab[a]	251	268 b	109 b	119 bc	2.3	2.3
Leaf removal	99	67 c	232	209 c	102 b	108 c	2.3	2.0
Crop removal[b]	–	107 a	–	328 a	–	147 a	–	2.2
Leaf damage	107	91 b	258	282 b	114 ab	129 ab	2.3	2.2
Juice spray	96	94 ab	311	328 a	131 a	140 ab	2.4	2.4
Leaf damage + juice	110	99 ab	244	264 b	107 b	125 bc	2.3	2.1
	ns[c]	***	ns	***	*	*	ns	ns
R2 vineyard								
Control	97	81 b	233	181 b	132	128 b	1.8	1.4
Leaf removal	88	73 b	202	128 c	112	105 c	1.8	1.2
Crop removal[b]	–	94 a	–	248 a	–	163 a	–	1.5
Leaf damage	86	72 b	228	190 b	130	127 b	1.7	1.5
Juice spray	95	82 b	253	205 b	136	134 b	1.9	1.5
Leaf damage + juice	84	74 b	237	188 b	125	132 b	1.9	1.4
	ns	**	ns	***	ns	***	ns	ns
H1 vineyard								
Control	71	51	159	48	119	76 ab	1.3	0.6
Leaf removal	66	48	134	33	98	55 b	1.4	0.6
Crop removal[b]	–	54	–	65	–	98 a	–	0.6
Leaf damage	73	53	135	36	105	70 b	1.3	0.5
Juice spray	71	52	148	37	119	67 b	1.2	0.6
Leaf damage + juice	74	56	159	50	121	77 ab	1.3	0.7
	ns	ns	ns	ns	ns	*	ns	ns
H2 vineyard								
Control	73 abc	32	30	3	30	24	1.0	0.1
Leaf removal	77 ab	46	32	6	32	31	1.0	0.2
Crop removal[b]	–	36	–	3	–	25	–	0.1
Leaf damage	59 c	36	33	6	32	37	1.0	0.2
Juice spray	80 a	44	35	10	35	42	1.0	0.2
Leaf damage + juice	65 bc	44	38	7	36	31	1.0	0.2
	*	ns	ns	ns	ns	ns	ns	ns

[a] Means separated within columns using Fisher's LSD test. Different letters within a column indicate a significant difference ($p = 0.05$).

[b] All fruit removed at midripening, therefore yield could not be determined at harvest 2002.

[c] *, **, ***, and ns indicate significance at $p < 0.05$, < 0.01, < 0.001, and not significant, respectively.

ten show delayed maturation (Koblet et al. 1996). However, although the crop load (yield-to-pruning-weight ratio) in vineyard R2 was only slightly lower than that in vineyard R1, fruit from those vines in both years ripened to commercial standards. Moreover, the concentration of sugar accumulated per berry was the highest in vineyard R1, suggesting that the low Brix levels were due to the large berry size achieved in this vineyard, perhaps the result of overirrigation. Indeed, this vineyard received the most irrigation (Table 1), with the aim to produce high yields (Table 2). While the treatments had little effect in the Hilltops vineyards, soluble solids in the Riverina vineyards was decreased by crop removal and increased by leaf removal after two seasons. Juice acid composition was also altered (Table 5). Leaf removal resulted in lower TA and higher pH and crop removal had the opposite effect. Therefore, fruit maturity at harvest mirrored the crop level but not the crop load, suggesting that high yield rather than crop load was associated with delayed ripening (Jackson and Lombard 1993). This suggests an indirect effect of the postharvest period on berry composition in the following year, brought about by impacts on amount of fruit per vine.

The above conclusion is supported by the negative correlations between yield and soluble solids in each vineyard (data not shown), suggesting that higher crop levels decreased the rate of fruit ripening. However, a third factor may have also played a role. Intriguingly, there was no difference in vine balance (as indicated by the yield-to-pruning-weight ratio), which is generally

Table 5 Fruit composition of Semillon grapevines following manipulation of the postharvest canopy efficiency.

	TSS (Brix)		Sugar/ berry (mg)		pH		TA (g/L)	
Treatment	**2002**	**2003**	**2002**	**2003**	**2002**	**2003**	**2002**	**2003**
R1 vineyard								
Control	18.2	19.2 b[a]	419 b	434	3.46	4.06 c	5.77	4.15 ab
Leaf removal	19.5	21.7 a	444 a	424	3.53	4.18 a	5.18	3.80 c
Crop removal[b]	–	17.1 c	–	383	–	3.98 d	–	4.24 a
Leaf damage	18.5	20.8 ab	421 b	454	3.51	4.11 b	5.34	3.77 c
Juice spray	18.4	19.8 b	438 a	465	3.50	4.04 c	5.23	4.00 bc
Leaf damage + juice	18.7	19.7 b	426 ab	414	3.53	4.08 bc	5.08	3.97 bc
	ns[c]	***	ns	ns	ns	***	ns	**
R2 vineyard								
Control	22.6	22.4 bc	397	319	3.60 c	4.01 a	4.83 ab	3.75 bc
Leaf removal	23.7	25.5 a	426	311	3.67 a	4.07 a	4.49 c	3.58 c
Crop removal[b]	–	19.2 d	–	293	–	3.91 b	–	4.53 a
Leaf damage	23.1	22.7 bc	403	336	3.63 bc	4.03 a	4.63 bc	3.83 ab
Juice spray	22.4	22.0 b	414	329	3.62 c	3.98 ab	4.91 a	4.02 b
Leaf damage + juice	23.1	23.6 c	438	335	3.67 ab	4.02 a	4.51 bc	3.67 bc
	ns	***	ns	ns	**	*	*	**
H1 vineyard								
Control	22.4	22.6 bc	300	144	3.81	4.09	3.49	3.46
Leaf removal	24.1	22.0 bc	328	131	3.82	4.17	3.33	3.35
Crop removal[b]	–	21.6 c	–	140	–	4.10	–	3.73
Leaf damage	23.3	23.3 ab	297	122	3.77	4.19	3.48	3.62
Juice spray	22.5	23.8 a	281	131	3.77	4.16	3.56	3.62
Leaf damage + juice	22.7	23.5 a	300	153	3.75	4.07	3.46	3.57
	ns	*	ns	ns	ns	ns	ns	ns
H2 vineyard								
Control	25.5	29.0	248	43	3.73	3.81	4.32	5.42
Leaf removal	26.2	28.2	268	52	3.70	3.85	4.31	5.39
Crop removal[b]	–	28.3	–	38	–	3.79	–	5.40
Leaf damage	25.8	28.5	267	47	3.72	3.73	4.25	5.86
Juice spray	25.7	28.1	256	70	3.71	3.85	4.32	4.63
Leaf damage + juice	25.9	28.4	272	64	3.70	3.81	4.30	4.85
	ns	ns	ns	ns	ns	ns	ns	ns

[a] Means separated within columns using Fisher's LSD test. Different letters within a column indicate a significant difference (p = 0.05).

[b] All fruit removed at midripening, therefore yield could not be determined for 2002 harvest.

[c] *, **, ***, and ns indicate significance at $p < 0.05$, < 0.01, < 0.001, and not significant, respectively.

thought to be more important than crop level for fruit quality (Kliewer and Dokoozlian 2005). Indeed, high yields were also associated with vigorous vegetative growth. These vines may have invested more resources in vegetative and reproductive growth rather than in storage reserves of the perennial parts of the vine. Conversely, smaller vines may have less sink demand for vegetative growth, which would allow more carbohydrates to be diverted to the fruit during the ripening phase. These vines could have a more effective leaf area for assimilate production because of better leaf exposure. Since all treatment plots of vines within the same vineyard were harvested on the same day, we do not know whether delaying the harvest date could have compensated for the slower ripening rates. However, in 2002 R1 was harvested much earlier than the other vineyards because of disease pressure and commercial demand for the grapes; consequently, R1 had a much longer postharvest period for the treatments to be effective.

The differing response to the treatments among vineyards, particularly between regions, could be due to a number of factors. First, production levels are much higher in the Riverina, suggesting that nutrient uptake and reserve accumulation during postharvest may be more important in sustaining the high yields. High crop level may cause low vine reserve status at harvest either because reserves are required to assist ripening the crop or because the vine cannot produce sufficient assimilates to replenish the storage reserves during the grape ripening period, or both. It has been suggested that high crop levels reduce the amount of vine reserves accumulated until harvest (Koblet et al. 1996) and that mobilization of reserves can occur if the supply of photoassimilate to the fruit is insufficient because of stress situations (Candolfi-Vasconcelos et al. 1994). Vines in the Riverina vineyards were not only more productive but also considerably younger (R1 was only in its third year at the start of the study) than those in the Hilltops vineyards, which probably affected their ability to manage with defoliation and cropping stress.

Second, averaged over the two treatment seasons (2000/2001 and 2001/2002) the Riverina vineyards received more water from irrigation and rainfall after harvest (+186 mm) than the Hilltops vineyards and more heat accumulation (+369 GDD) during the postharvest period. Therefore, vines growing in the Riverina are more able to produce assimilates and take up nutrients late in the season than vines growing in the Hilltops. Third, the drought during the 2002/2003 season, which primarily affected (nonirrigated) H2, probably masked some of the treatment effects.

Conclusions

Vine productivity was considerably changed by manipulating the postharvest period in the previous year. An extended period (early crop removal) stimulated vigor and yield formation in the subsequent season, while shortening the assimilation period after harvest (leaf removal at harvest) had the opposite effect, while vine balance remained unchanged. Treatment effects became stronger over consecutive seasons, indicating a cumulative effect of the manipulations during the postharvest period. A partial (50%) loss of effective leaf area (leaf damage at harvest) and/or splashing grape juice on the leaves generally did not alter vine growth and productivity. Fruit ripening was accelerated by leaf removal or delayed by crop removal in the previous season in the warmer and more productive of the two regions tested. The impacts on shoot and cluster development, canopy size, and yield could be due to altered vine reserve levels of carbohydrates and nutrients, which are crucial for early vegetative and reproductive growth. Our results suggest that a gradual decline in vine productivity caused by damage inflicted by machine harvesting is not likely unless the damage is sufficiently severe to cause more than 50% defoliation. The postharvest period may be more important for vine productivity and grape maturity in high-yielding vineyards in warmer regions. In other words, the longer the potential postharvest period, the more important is its effectiveness for sustaining high vine productivity. That is somewhat counterintuitive, but it may be the main reason vineyards in warmer regions can support higher crop levels than those in cooler regions. Our results indicate that management of the postharvest period in highly productive vineyards is important to sustain yield levels, but it could also be used to optimize vine vigor and productivity by manipulating the length and effectiveness of this period, for instance by modifying irrigation and nutrition management after harvest.

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