Cluster Thinning Effects on Three Deficit-Irrigated *Vitis vinifera* Cultivars

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Abstract: Crop load adjustment is widely accepted as an important vineyard management tool for premium-quality wine production. However, little information is available on its effectiveness under warm, dry climatic conditions. Crop loads were altered on three own-rooted winegrape cultivars grown in a mature, deficit-irrigated vineyard in the arid Yakima Valley (Washington) over a five-year period (1997 to 2001). Thinning consisted of preferentially removing clusters on shoots not arising from nodes deliberately retained at pruning, either one month after bloom or at veraison, to achieve target yields for Cabernet Sauvignon (6.7 t/ha), Riesling (9.0 t/ha), and Chenin blanc (11.2 t/ha). Removing, on average, 39% of the clusters from Cabernet Sauvignon, 30% from Riesling, and 38% from Chenin blanc reduced yields by 36%, 17%, and 20%, respectively. Average crop loads varied from 6.7 to 14.8 kg fruit/kg pruning weight for nonthinned vines and from 4.4 to 9.2 for thinned vines, and average yields varied from 7 to 25 t/ha for nonthinned vines and from 5 to 16 t/ha for thinned vines, depending on cultivar and season. Cluster thinning and its timing had little or no influence on shoot growth, leaf area, pruning weight, berry number, berry weight, and fruit composition (soluble solids, titratable acidity, pH, color) in both the current and subsequent seasons. Differences in vegetative growth, yield formation, and fruit composition within cultivars were mostly due to season (including weather and soil moisture) rather than to yield or crop load.

Key words: crop load, yield components, grape berry, fruit composition, color

The growing season in the Yakima Valley of Washington is characterized by an absence of rainfall and warm, dry days and cool nights. However, it is often curtailed by late spring and early fall frosts and on average lasts less than 160 days, although in practice this may be prolonged significantly by the widespread use of wind machines. Given these climatic constraints, there is concern among growers and winemakers that even slight overcropping of vineyards designed for premium-quality winegrape production may result in inadequate fruit ripening and poor quality. Indeed, many wineries require their growers to limit vineyard yields based on the assumption that higher yields result in lower quality fruit and wine. In Europe this assumption is often written into the law, and only relatively low yields are permitted for controlled appellation wines. However, although it is clear that very high yields delay ripening and reduce fruit and wine quality (reviewed by Jackson and Lombard 1993), evidence for a strict yield-quality relationship is very limited, inconsistent, and mostly based on data collected in cool climates that struggle to ripen the crop in some seasons (Reynolds 1989) or from vineyards with very high yields (Sinton et al. 1978, Bravdo et al. 1984). Moreover, there may be differences among cultivars in terms of their response to or tolerance of heavy crops. For instance, low yields may not be as important for white grapes, since high alcohol levels and deep coloration are less desirable in white wines. Although adjustment of crop load (fruit weight per unit pruning weight or leaf area) is widely accepted as an important canopy management tool for high-quality wine production, little information is available on its effectiveness under warm, dry climatic conditions. In their review, Jackson and Lombard (1993) concluded that “each region should investigate for each cultivar and training system the optimum yield that will still produce quality wine yet still return an economic crop.”

The leaf-area:fruit weight ratio (expressed as m^2/kg or cm^2/g) has been used as a measure of crop load and vine balance, and approximately 0.8 to 1.2 m^2/kg is generally required to fully ripen winegrapes on single-canopy type trellis systems (reviewed by Kliewer and Dokoozlian 2001). In addition, a fruit:pruning-weight ratio of 5 to 10 has been used as an indicator of balanced vines capable of producing high-quality fruit (Bravdo et al. 1985, Reynolds 1989, Smart et al. 1990). The aim of cluster thinning is to adjust crop load so grape maturation may be advanced

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and potential wine quality improved. This may be especially important in vines that are overcropped and thus out of balance. Naor et al. (2002) reported a negative correlation between crop load (varied by shoot and cluster thinning) and wine sensory score despite no consistent differences in fruit composition of field-grown Sauvignon blanc studied in Israel over three years. In a field study with Nebbiolo in the Italian Piedmont region, also conducted over three years, removing half the clusters at the pea-size stage (one month after bloom) reduced yield by 43% and increased berry soluble solids by 7% and anthocyanin concentration by 18% (Guidoni et al. 2002). In contrast, another three-year field study with Cabernet Sauvignon in Napa Valley, California, where either one-third or two-thirds of clusters were removed two weeks after bloom, found that although yield was reduced by about 20% and 33%, respectively, juice composition and wine quality were very little affected by cluster thinning (Ough and Nagaoka 1984).

In addition to the amount of fruit removed by cluster thinning, the timing of the operation may be important. Removing crop early in the season (at bloom or soon thereafter) may not lead to the desired result because the reduced sink size might in turn lead to lower leaf photosynthesis rates (Hofäcker 1978, Edson et al. 1995a, Naor et al. 1997), so that the remaining berries may not have extra sugar available for import. If, however, photosynthesis remains unchanged, surplus photoassimilates could also be used to fuel more shoot (and root) growth. This growth would counteract the benefits of lower crop load because of its negative effect on vigor and canopy microclimate (Smart et al. 1990, Jackson and Lombard 1993). Therefore, it might be beneficial to delay thinning until shoot growth has slowed and assimilates may be diverted to the fruit.

The purpose of the present experiment was to study the effect of timing of crop adjustment by cluster thinning on the rate of grape ripening and final fruit composition in different cultivars (one red, two white) of mature, field-grown grapevines. The study was conducted over five seasons in order to test the hypothesis that cluster thinning, especially early thinning, would accelerate ripening, advance fruit maturity, and lead to improved fruit composition.

Materials and Methods

Vineyard site and experimental conditions. The experiment was conducted in a mature, drip-irrigated vineyard north of Prosser, Yakima Valley, Washington (lat. 46°17' 49'N; long. 119°44'07'W; elevation 270 m), from 1997 to 2001. The vineyard was planted in 1983 on a uniformly deep (>4 m) Warden fine sandy loam with a 3% southwest slope, and rows in north-south direction. Soil field capacity was ~25% (v/v) and the permanent wilting point 8% (v/v) (Evans et al. 1993). The vineyard consisted of four replicated blocks (main plots) of own-rooted *Vitis vinifera* L. cvs. Cabernet Sauvignon, Riesling, and Chenin blanc spaced at 1.8 m (within rows) by 3.1 m (between rows). Average seasonal water use on this site has been estimated at about 430 mm for mature Cabernet Sauvignon and Chenin blanc, and 390 mm for Riesling (Evans et al. 1993). Vines were trained to a bilateral cordon at 125 cm and loosely vertical shoot-positioned (“lazy VSP”) using two foliage wires spaced 46 cm apart at 150 cm. Riesling was pruned to 48 nodes per vine, whereas Cabernet Sauvignon and Chenin blanc were pruned to 42 nodes per vine (36 nodes in 1997). The relatively light pruning level (23 to 26 nodes/m of canopy) was applied to provide a potentially high crop load. The vineyard was usually irrigated to maintain at least 13% (v/v) soil moisture after budbreak but was allowed to dry down through bloom until fruit set to control shoot growth, followed by regulated deficit irrigation (RDI) to maintain soil moisture in the top 90 cm at approximately 11% (v/v). Irrigation scheduling and amount were based on weekly neutron-probe measurements. Soil moisture was replenished after harvest to minimize root injury from winter freeze. All fertilizer applications and pest and disease management practices were applied commercially and as uniformly across the vineyard as possible.

Three cluster-thinning treatments were imposed as completely randomized subplots within each cultivar main plot. There were four replicates per treatment with 20 vines each, four of which were designated “data” vines. Treatments were early thinning (E, approximately one month after bloom), late thinning (L, at veraison, which normally occurred approximately one month after early thinning; see Table 1), and nonthinned control (C). The E treatment was based on earlier research indicating a reduction of shoot growth rates about 30 days after bloom in eastern Washington (R.L. Wample, unpublished data) and Central California (Winkler and Williams 1936). This also coincides approximately with the cessation of cell division in grape berries (Nakagawa and Nanjo 1965, Harris et al. 1968). Target yields (Cabernet Sauvignon 6.7 t/ha, Riesling 9.0 t/ha, Chenin blanc 11.2 t/ha, based on industry standards at the start of the study) were used to determine the amount of crop to be removed at each thinning time. Crop thinning consisted of preferentially removing clusters on noncount shoots (shoots originating from basal buds and latent buds) and small uppermost clusters on weak (length <30 cm) count shoots (shoots originating from nodes retained at pruning). Adjustment was based on yield estimations based on cluster number per vine (from prebloom counts on data vines), berry number per cluster (from clusters collected on adjacent vines), and historical mean harvest berry weight from the experimental vineyard (Cabernet Sauvignon 0.89 g, Riesling 1.01 g, Chenin blanc 1.42 g).

Data collection. Meteorological conditions were monitored throughout the experimental period using raw data derived from the Washington State University Public Agricultural Weather System (WSU-PAWS) northern Prosser weather station, which is located ~1 km from the experi-

Table 1 Key phenological stages and time of cluster thinning of own-rooted grapevines in the Yakima Valley, Washington.

Cultivar/season	Budbreak	Bloom	Fruit set	Early thinning	Veraison/late thinning	Harvest
Cabernet Sauvignon						
1997	28 April	10 June	19 June	28 July	24 August	1 October
1998	27 April	15 June	18 June	21 July	16 August	30 September
1999	27 April	21 June	24 June	19 July	28 August	10 October
2000	18 April	9 June	19 June	17 July	16 August	6 October
2001	28 April	11 June	18 June	12 July	15 August	11 October
Riesling						
1997	25 April	6 June	19 June	28 July	24 August	18 September
1998	23 April	15 June	18 June	21 July	16 August	16 September
1999	23 April	15 June	18 June	19 July	28 August	28 September
2000	18 April	9 June	19 June	17 July	15 August	19 September
2001	25 April	1 June	18 June	12 July	16 August	21 September
Chenin blanc						
1998	17 April	15 June	18 June	21 July	16 August	13 September
1999	20 April	21 June	24 June	19 July	28 August	28 September
2000	12 April	9 June	19 June	17 July	16 August	26 September
2001	25 April	11 June	18 June	12 July	16 August	18 September

mental vineyard. Soil moisture was monitored using neutron probes (503 DR Hydroprobe; CPN Corp., Pachero, CA). One PVC probe access tube per treatment replicate was installed to a soil depth of 120 cm, located within rows and equidistant between drip emitters. Pruning weights were recorded in winter, and the number of shoots per vine was counted in the week before bloom. Shoots were separated into count shoots, originating from nodes retained at pruning, and noncount shoots, originating from basal buds and latent buds. From 1999 to 2001, shoot length, number of leaves per shoot, and leaf area per shoot were determined at bloom and at 650 growing degree days (GDD, base temperature 10°C). Leaf area of each leaf on one representative count shoot per vine was determined by measuring leaf width and calculating the corresponding area, using a quadratic regression equation derived from leaf-area measurements with a LI-COR 3100 area meter (LI-COR Biosciences, Lincoln, NE). Shoot leaf area was multiplied by the number of shoots per vine to provide a rough estimate of total vine leaf area. Although there is necessarily considerable variation in shoot leaf area (owing to large differences in shoot length), the large sample size (16 vines per treatment per cultivar) ensured reasonable accuracy of the estimation of vine leaf area. Shoot lignification (“maturation”) was assessed in 2000 and 2001 by counting the number of internodes per shoot with brown periderm at veraison and at harvest. Yield components other than vine, node, and shoot numbers were determined as follows: yield per vine was recorded at harvest; number of clusters per vine was counted just before bloom and at harvest (clusters removed by thinning were also counted); number of berries per cluster and mean berry weight were recorded at harvest. Harvest time was based on a 21.5 Brix threshold for the white cultivars and 23 Brix for Cabernet Sauvignon and was determined by weekly measurements of fruit composition beginning at veraison. Samples were collected from apical berries of basal clusters to provide uniformity in sampling procedure and to reduce variation from week to week, while recognizing that this strategy may not have been fully representative of the whole vine. Between 250 and 300 berries per treatment replicate were collected each time. A 100-berry subsample was weighed, crushed, and processed on the same day. Juice was extracted from Riesling and Chenin blanc berries and analyzed for soluble solids, titratable acidity (TA), and pH as described by Spayd et al. (1994). Cabernet Sauvignon berries were extracted and analyzed for the same components and total color as described by Spayd et al. (2002). Vegetative and yield component data were collected on a per vine basis, whereas fruit composition data were collected as composite samples on a per replicate basis.

Data analysis. The Statistica software package (version 6.1; StatSoft, Tulsa, OK) was used for data analysis. All results were tested for homogeneity of variance using Levene’s test and subjected to three-way (cultivar x thinning x season) analysis of variance (ANOVA). The effects of season and season x cultivar interactions were almost always highly significant ($p < 0.001$). Therefore, data were also analyzed as two-way (cultivar x thinning) ANOVA for each season, using the general linear model procedure for split-plot design with cultivar as the main plot and thinning as the subplot. Because there were few cultivar x thinning interactions, cultivar and thinning treatment means are presented separately for each season. Significant interactions are indicated and described in the text.

The consecutive berry weight and fruit composition data were analyzed with a repeated-measures design. Calculating means of pH values is mathematically meaningless (since pH = $-\log_{10}[H^+]$; thus pH values were converted to $[H^+]$ for statistical analysis, and the reported means were recalculated from means of $[H^+]$. Duncan's new multiple range test was used for post hoc comparisons of significant treatment means. Selected variables were subjected to correlation analysis following appropriate transformations where necessary. Curves were fitted using the negative exponential-weighted least squares method.

Results

Weather and soil moisture. Meteorological conditions for the experimental site are summarized in Table 2 and Figure 1. Four of the five growing seasons were above average in terms of heat accumulation (growing degree days, GDD, base 10°C). However, an exceptionally warm season (1998) was followed by an unusually cool season (1999), and an early fall frost truncated the season in 2000 (-0.9°C on 23 September). Mean maximum temperatures during the bloom to fruit-set period varied from 24.6°C (2001) to 27.4°C (1999), but did not differ among seasons despite substantially ($p < 0.001$) less heat accumulation up to bloom in 1999 compared to the other seasons (Figure 1). In contrast, the mean minimum bloom-time temperature was lower ($p < 0.05$) in 2001 (8.0°C) than in the other four seasons (average 10.4°C). Rainfall and solar radiation (global irradiance) during the bloom to fruit-set period were similar in all five seasons (data not shown).

Because of the extremely limited rainfall and high evaporation (Table 2), and as intended by the application of RDI, the soil generally dried down during bloom to reach 11 to 11.5% (v/v) moisture in the top 90 cm by fruit set, then increased again after around the middle of July (data not shown). Average soil moisture during the fruit-set to veraison period was highest in 1998 (13.6%), followed by 1999 (12.4%), 2000 (11.5%), 1997 (11.2%), and, finally, 2001 (11.0%). These differences were highly significant ($p < 0.001$), except 1997 and 2001, which did not differ between them. Averaged over the berry development period (fruit set to harvest), soil moisture in the top 90 cm was very similar in 1997 (12.3%), 1999 (12.3%), and 2000 (12.2%), but the soil was considerably ($p < 0.001$) wetter in 1998 (12.9%) and drier in 2001 (11.2%) compared with the other three seasons. Except in 1997, when it was significantly ($p < 0.001$) higher (12.7%), mean soil moisture in the 90 to 150 cm range remained consistently at about 11% during the same period. There was no consistent difference among cultivars in terms of soil moisture and water depletion (data not shown).

Vegetative and reproductive growth. Cabernet Sauvignon always had higher pruning weights than the two white cultivars (Table 3), and there was a trend for the pruning weight to decrease as the number of shoots per vine increased. Shoot density (shoots/m canopy) was very high in all cultivars and all five seasons, mostly due to excessive growth of noncount shoots (Table 3). Despite the consistent and relatively light pruning level (23 to 26 nodes/m of canopy) the number of shoots per vine (43 to 161) and per meter of canopy (23 to 87) was high and varied widely across the three cultivars. However, there was no consistent effect of shoot number on early-season shoot vigor (Table 3) and late-season shoot maturation (Table 4), although Chenin blanc tended to have more shoots and to be less vigorous than the other cultivars. There was no consistent cultivar effect on leaf size, but Riesling had the smallest leaf area, because it had the fewest shoots of the three cultivars (Tables 3 and 4). There was a tendency for early-season vigor to decrease as the crop load of the previous-season (fruit:pruning-weight ratio) increased in Cabernet Sauvignon ($r = -0.35$, $p < 0.001$, $n = 143$) and Chenin blanc ($r = -0.33$, $p < 0.001$, n

Table 2 Meteorological data from the Washington State University Public Agricultural Weather System (WSU-PAWS) weather station north of Prosser, WA.

Season	GDD (°C)[a]	Precipitation (mm)		Evaporation (mm)[c]	
		Annual	Seasonal[b]	Annual	Seasonal
1997	1427	223	105	1404	1205
1998	1598	207	72	1400	1190
1999	1246	94	33	1479	1224
2000	1384	208	73	1469	1286
2001	1455	167	69	1516	1325
1954-2004	1344	199	91	1491	1274

[a] Cumulative growing degree days (base 10°C) from 1 April to 31 October.

[b] Period from 1 April to 31 October.

[c] US class A pan evaporation (long-term mean for the period 1989-2004).

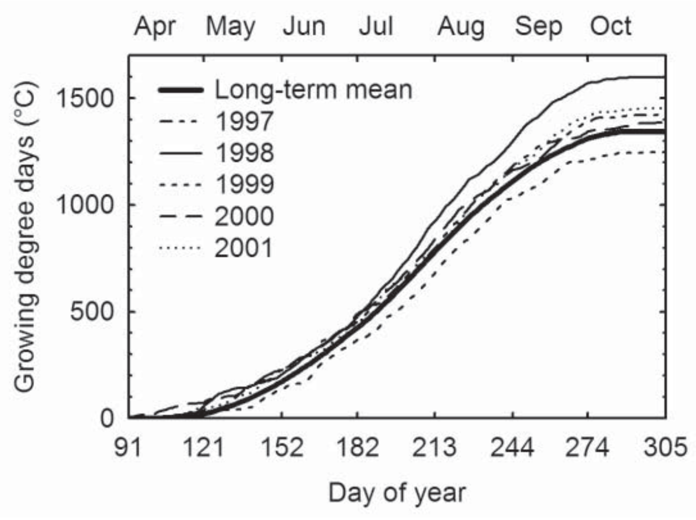

Figure 1 Growing degree day accumulation (base 10°C) in Prosser, WA, from 1 April to 31 October between 1997 and 2001; the long-term mean is for the period 1954 to 2004.

= 138). However, there was no such trend in Riesling, and vigor did not decline further when the crop load increased beyond 8 in Cabernet Sauvignon or 15 in Chenin blanc. Almost all of the crop load values >8 (Cabernet Sauvignon) or >15 (Riesling, Chenin blanc) were in the C treatment. Nevertheless, cluster thinning generally failed to influence vegetative growth, regardless of cultivar. The exception was the slightly reduced vigor of the C vines in 1999 (Table 3), which followed a season with unusually high yields but also was the season with the largest proportion of noncount shoots. Moreover, the cultivar by thinning interaction in 1999 (Table 3) was due to the fact that the C vines of Chenin blanc, in contrast to the other two cultivars, had slightly fewer noncount shoots per vine. In 2001, nonthinned Chenin blanc again had a smaller proportion of noncount shoots, which was also true for Riesling, whereas in Cabernet Sauvignon it was the E treatment that had the fewest noncount shoots. In addition, there was a trend across all three cultivars toward fewer clusters per shoot (prior to crop adjustment) as the number of shoots in the previous season increased ($r = -0.40$, $p < 0.001$, $n = 510$), suggesting that denser canopies slightly reduced bud fruitfulness.

All three cultivars carried by far the heaviest crop in 1998 (Table 5); the C vines of Cabernet Sauvignon topped 25 t/ha, and Riesling and Chenin blanc were ~19 t/ha. All yield components contributed to the exceptional yield in that year (Table 6). The vines had an unusually high number of clusters per shoot, and Cabernet Sauvignon and Chenin blanc clusters also had high berry numbers. Nevertheless, berry weights also were above average. The larger berry size was apparent ($p < 0.001$) soon after fruit set (data not shown). Environmental conditions (temperature, irradiance, soil moisture) were favorable for fruit set in 1998, and the high soil moisture between fruit set and veraison probably contributed to the difference in berry size. However, this is unlikely to be the only explanation, considering that there were many more berries per vine (clusters/vine x berries/cluster) in that season. While average daily maximum temperatures during the berry cell division phase (roughly the period from fruit set to early thinning) were similar in 1998 and other seasons, mean daily minimum temperatures were higher ($p < 0.001$) in 1998 (13.0°C) than in the other years (10.6°C). However, the cool season of 1999 (mean minimum 9.6°C) did not result in unusually small berries. Berry weights of the two

Table 3 Effect of cultivar, cluster thinning, and growing season on vine capacity, canopy density, and vigor of own-rooted grapevines in the Yakima Valley, WA. Note: values per meter of canopy or row can be calculated by division by 1.8.

	Pruning weight (kg/vine)					Shoots/vine				
Treatment	**1997**	**1998**	**1999**	**2000**	**2001**	**1997**	**1998**	**1999**	**2000**	**2001**
Cultivar										
Cabernet Sauvignon	1.45 a[a]	1.41 a	0.68 a	0.95 a	1.34 a	59 b	70	89 b	82 b	80 a
Riesling	0.79 b	0.96 b	0.46 b	0.55 b	0.78 c	65 a	70	80 c	73 c	72 b
Chenin blanc	nc[b]	0.88 b	0.44 b	0.63 b	0.91 b	nc	67	100 a	95 a	82 a
Thinning										
Early	1.11	1.10	0.50	0.71	0.99	63	67	89	83	81
Late	1.16	1.10	0.56	0.72	1.00	61	71	89	82	77
Control	1.10	1.05	0.52	0.73	1.05	62	69	91	85	75
Interaction	ns[c]	ns	ns	ns	ns	ns	ns	**	ns	ns

	% Noncount shoots					Shoot vigor (mm/day)[d]				
	1997	**1998**	**1999**	**2000**	**2001**	**1997**	**1998**	**1999**	**2000**	**2001**
Cultivar										
Cabernet Sauvignon	45 a	48 a	63 a	60 a	48 a	nc	nc	12 a	12	17
Riesling	25 b	38 b	52 b	42 b	34 c	nc	nc	13 a	11	18
Chenin blanc	nc	48 a	65 a	57 a	44 b	nc	nc	9 b	9	15
Thinning										
Early	41	45	60	52	41 b	nc	nc	11 a	11	17
Late	40	46	60	54	47 a	nc	nc	12 a	11	17
Control	39	44	61	54	39 b	nc	nc	10 b	11	17
Interaction	ns	ns	*	ns	***			ns	ns	ns

[a] Means within columns followed by different letters differ significantly at $p < 0.05$ by Duncan's new multiple range test.

[b] nc: data not collected.

[c] Cultivar x thinning interaction; *, **, ***, ns: significant at $p < 0.05$, 0.01, 0.001, or not significant, respectively.

[d] Mean shoot growth rate between budbreak and bloom.

Table 4 Effect of cultivar, cluster thinning, and growing season on vegetative growth of own-rooted grapevines in the Yakima Valley, WA. Note: data were not collected in 1997 and 1998.

	Shoot length at bloom (cm)			Leaf area at bloom (m^2/vine)		
Treatment	**1999**	**2000**	**2001**	**1999**	**2000**	**2001**
Cultivar						
Cabernet Sauvignon	64 a[a]	63	75	8.58	7.81 a	8.14
Riesling	67 a	55	67	8.19	6.53 b	6.31
Chenin blanc	55 b	55	72	8.73	8.11 a	8.63
Thinning						
Early	64 a	57	71	8.57	7.41	7.84
Late	66 a	59	71	8.96	7.47	7.63
Control	56 b	57	72	7.96	7.57	7.60
Interaction	ns[b]	ns	ns	ns	ns	ns
	Mean leaf size (cm^2/leaf)			**Shoot maturity at harvest[c]**		
	1999	**2000**	**2001**	**1999**	**2000**	**2001**
Cultivar						
Cabernet Sauvignon	73 a	72	71 a	nc[d]	14	11
Riesling	72 a	67	63 b	nc	12	11
Chenin blanc	66 b	66	74 a	nc	12	11
Thinning						
Early	71 ab	68	69	nc	13	10
Late	73 a	71	69	nc	13	11
Control	67 b	67	71	nc	12	11
Interaction	**	ns	ns		ns	ns

[a] Means within columns followed by different letters differ significantly at $p < 0.05$ by Duncan's new multiple range test.

[b] Cultivar x thinning interaction; *, **, ***, ns: significant at $p < 0.05$, 0.01, 0.001, or not significant, respectively.

[c] Number of internodes/shoot with brown periderm.

[d] nc: data not collected.

white cultivars generally continued to increase through harvest. In contrast, Cabernet Sauvignon berries reached a distinct maximum in mid-September, after which berry weights either remained constant or decreased (data not shown). There was a trend in all three cultivars for harvest berry weights to decrease over the course of the study (Table 6).

Pruning weight, as a measure of vine size and vine capacity, correlated positively with crop level (fruit weight per vine or per meter of canopy) or yield (fruit weight per ha) in all three cultivars both across (Cabernet Sauvignon: $r = 0.43$, $p < 0.001$, $n = 239$; Riesling: $r = 0.61$, $p < 0.001$, $n = 230$; Chenin blanc: $r = 0.26$, $p < 0.001$, $n = 185$) and within seasons. In other words, larger vines had the capacity to support a heavier crop. Nevertheless, yield did not correlate with the number of shoots per vine but instead correlated closely with the number of clusters per shoot after thinning (Cabernet Sauvignon: $r = 0.81$, $p < 0.001$, $n = 240$; Riesling: $r = 0.76$, $p < 0.001$, $n = 240$; Chenin blanc: $r = 0.75$, $p < 0.001$, $n = 192$). Clusters per shoot ranged from 0.5 to 2.4 in Cabernet Sauvignon, 0.8 to 3.0 in Riesling, and 0.5 to 1.6 in Chenin blanc. As shown by its high number of clusters per shoot before thinning, Riesling was clearly the cultivar with the most fruitful buds, followed by Cabernet Sauvignon and Chenin blanc (Table 6). After thinning, the number of clusters per vine varied from 20 to over 200 for both Riesling and Cabernet Sauvignon, but never exceeded 120 in Chenin blanc. However, Chenin blanc generally had the largest clusters because of high berry numbers and heavy berries (Table 6). The crop level increased proportionally with cluster number, regardless of cultivar or season ($0.57 < r < 0.86$, $p < 0.001$). The correlation between crop level and berry number per cluster was significant only for Cabernet Sauvignon ($r = 0.69$, $p < 0.001$, $n = 60$), while the crop level increased with increasing berry weight in all cultivars (Cabernet Sauvignon: $r = 0.27$, $p < 0.05$, $n = 60$; Riesling: $r = 0.34$, $p < 0.01$, $n = 60$; Chenin blanc: $r = 0.73$, $p < 0.001$, $n = 48$). Multiple linear regression analysis showed that 92% ($R^2 = 0.92$, $p < 0.001$) of the variation in yield for all cultivars was accounted for by variations in (in order of importance) clusters per shoot, berries per cluster, berry weight, and shoots per vine.

Over the five years the C vines of Cabernet Sauvignon averaged 104 clusters, while Riesling averaged 134 and Chenin blanc 78 clusters per vine. Thinning on average reduced cluster numbers by one-third in both Cabernet Sauvignon and Chenin blanc and by one-quarter in Riesling (Table 5). That Riesling would respond less to thinning was to be expected given that it had a smaller proportion of noncount shoots (Table 3), which were the ones chosen for crop adjustment. The effectiveness of the time of thinning (in terms of reducing cluster number) also varied with cultivar. Exactly the same number of clusters was retained regardless of timing in Cabernet Sauvignon (69 clusters/vine) and Chenin blanc (52 clusters/vine). In contrast, in Riesling the L treatment tended to leave more clusters (105 clusters/vine) than the E treatment (93 clusters/vine). As intended, cluster thinning decreased both crop level and crop load in all three cultivars, and the magnitude of the decrease was similar for the E and L treatments (Table 5). However, it proved very difficult to realize the target yields. All cultivars exceeded their targets in the first two years, even after crop adjustment. In the remaining seasons, thinning generally decreased Cabernet Sauvignon and Chenin blanc yields below target, but in Riesling this

Table 5 Effect of cultivar, cluster thinning, and growing season on yield and crop load of own-rooted grapevines in the Yakima Valley, WA. Note: yield (t/ha) can be calculated by dividing crop level by 0.558.

	Crop level (kg/vine)					Clusters/vine				
Treatment	1997	1998	1999	2000	2001	1997	1998	1999	2000	2001
Cultivar										
Cabernet Sauvignon	5.09 b[a]	9.81	3.68 c	3.84	3.54 b	58 b	117 b	82 b	75 b	72 b
Riesling	7.36 a	9.44	4.95 b	5.97	6.21 a	108 a	148 a	98 a	108 a	92 a
Chenin blanc	nc[b]	9.04	6.43 a	5.08	5.45 a	nc	70 c	65 c	56 c	50 c
Thinning										
Early	5.64 b	7.82 b	4.15 b	4.55 b	5.25 a	76 b	91 c	60 c	67 b	70 b
Late	6.05 b	8.69 b	4.53 b	4.79 ab	4.11 b	74 b	105 b	73 b	75 b	57 c
Control	6.98 a	11.78 a	6.39 a	5.54 a	5.84 a	100 a	138 a	112 a	98 a	86 a
Interaction	***[c]	***	ns	ns	ns	ns	ns	ns	**	ns

	Crop load (fruit/pruning weight)					Leaf area/fruit weight (m^2/kg)				
	1997	1998	1999	2000	2001	1997	1998	1999	2000	2001
Cultivar										
Cabernet Sauvignon	3.79 b	7.30 b	5.76 c	4.02 c	2.64 c	nc	nc	3.77 a	3.22 a	2.82 a
Riesling	9.77 a	10.03 a	11.43 b	10.47 a	8.20 a	nc	nc	2.51 b	1.67 c	1.66 c
Chenin blanc	nc	10.92 a	15.93 a	7.89 b	5.77 b	nc	nc	2.04 b	2.33 b	2.26 b
Thinning										
Early	6.74	7.81 b	9.23 b	6.60 c	5.57 b	nc	nc	3.45 a	3.00 a	2.25 ab
Late	6.45	8.27 b	9.14 b	7.08 b	4.38 c	nc	nc	3.17 a	2.35 b	2.65 a
Control	7.48	12.17 a	14.76 a	8.69 a	6.66 a	nc	nc	1.70 b	1.88 b	1.85 b
Interaction	ns	**	***	ns	*			ns	ns	ns

[a] Means within columns followed by different letters differ significantly at $p < 0.05$ by Duncan's new multiple range test.

[b] nc: data not collected.

[c] Cultivar x thinning interaction; *, **, ***, ns: significant at $p < 0.05$, 0.01, 0.001, or not significant, respectively.

was true only in 1999. Averaged over the five years, thinning reduced the crop level by 36% in Cabernet Sauvignon (crop load -34%), 17% in Riesling (crop load -20%), and 20% in Chenin blanc (crop load -35%). The smaller number of noncount shoots of Riesling led to some significant (though of small magnitude) cultivar x thinning interactions for both crop level and crop load (Table 5). For example, cluster thinning of Riesling vines failed to reduce the crop level in 1997, and only early thinning decreased the crop level (and crop load) in 1998. In 1999 and 2001 it was Cabernet Sauvignon whose crop load (but not crop level) decreased somewhat less in response to thinning than did that of the other cultivars.

Cluster thinning, of course, generally reduced the number of clusters per shoot, regardless of the time of thinning. Owing to its smaller proportion of noncount shoots (Table 3), Riesling, again, was the exception and caused the cultivar by thinning interactions on post-thinning cluster numbers per shoot in 1997 and 2000. However, because it was done after fruit set, thinning had no consistent influence on the number of berries per cluster (Table 6). That the C vines tended to have fewer berries per cluster is explained simply by the selective (nonrandom) removal of predominantly small clusters during thinning. Nevertheless, on two occasions it was the C treatment that resulted in more berries/cluster: in 1998 in Cabernet Sauvignon and in 2001 in Riesling (see cultivar by thinning interactions in Table 6). Late thinning did not affect final berry weight, and early thinning increased berry weight only in the cool season of 1999, which delayed ($p < 0.001$) berry development compared with the other seasons. The cultivar x thinning interaction in 2001 was caused by the relatively small berries of the C vines of Riesling, which was probably a compensation for the high berry number in that treatment.

Ripening and fruit composition. Although harvest timing was based on the grapes achieving a target concentration of soluble solids, fruit composition varied considerably among seasons (Table 7), which suggests that sampling only apical berries for maturity assessment was not entirely representative of whole clusters. In all seasons, soluble solids at harvest either exceeded the target or were not significantly different from it. The 2001 Cabernet Sauvignon harvest samples were lost because of equipment malfunction; hence data from the last preharvest sample set are reported in Table 7. These samples were taken nine days before harvest, which explains the apparent failure of the fruit to reach the target Brix level in that year. The three thinning treatments were always harvested on the same day within the same cultivar (Table

Table 6 Effect of cultivar, cluster thinning, and growing season on yield components of own-rooted grapevines in the Yakima Valley, WA. Note: cluster weight can be calculated by multiplying berries/cluster with berry weight.

	Clusters/shoot (prethinning)					Clusters/shoot (post-thinning)				
Treatment	**1997**	**1998**	**1999**	**2000**	**2001**	**1997**	**1998**	**1999**	**2000**	**2001**
Cultivar										
Cabernet Sauvignon	1.4 b[a]	2.1 b	1.3 b	1.3 b	1.2 b	1.0 b	1.7 b	0.9 b	0.9 b	0.9 b
Riesling	1.9 a	2.6 a	1.7 a	1.9 a	1.8 a	1.7 a	2.1 a	1.2 a	1.5 a	1.3 a
Chenin blanc	nc[b]	1.4 c	0.9 c	0.8 c	0.9 c	nc	1.1 c	0.7 c	0.6 c	0.6 c
Thinning										
Early	1.6	2.1	1.4 a	1.4 a	1.4 a	1.2 b	1.4 b	0.7 c	0.9 b	0.9 b
Late	1.6	2.0	1.1 b	1.4 a	1.4 a	1.2 b	1.5 b	0.8 b	1.0 b	0.8 b
Control	1.7	2.0	1.2 ab	1.2 b	1.2 b	1.6 a	2.0 a	1.2 a	1.2 a	1.2 a
Interaction	ns[c]	ns	ns	ns	ns	**	ns	ns	*	ns

	Berries/cluster					Berry weight (g)				
	1997	**1998**	**1999**	**2000**	**2001**	**1997**	**1998**	**1999**	**2000**	**2001**
Cultivar										
Cabernet Sauvignon	92 a	92 a	56 b	63	59 c	0.98 b	0.90 c	0.84 c	0.81 c	0.84 b
Riesling	55 b	58 c	51 b	58	74 b	1.25 a	1.12 b	1.03 b	0.96 b	0.93 b
Chenin blanc	nc	82 b	79 a	66	87 a	nc	1.63 a	1.32 a	1.33 a	1.26 a
Thinning										
Early	72 b	80 a	63	65 ab	73	1.12	1.22	1.14 a	1.04	1.03
Late	82 a	73 b	64	66 a	74	1.13	1.22	1.03 b	1.03	1.03
Control	68 b	79 a	59	57 b	72	1.10	1.21	1.02 b	1.03	0.97
Interaction	ns	***	ns	ns	*	ns	ns	ns	ns	*

[a] Means within columns followed by different letters differ significantly at $p < 0.05$ by Duncan's new multiple range test.

[b] nc: data not collected.

[c] Cultivar x thinning interaction; *, **, ***, ns: significant at $p < 0.05$, 0.01, 0.001, or not significant, respectively.

2). Nevertheless, the impact of crop adjustment on fruit composition at harvest was minor (Table 7); early (but not late) thinning slightly increased soluble solids in two out of five seasons. Other measures of fruit quality were entirely unaffected by crop removal (Table 7). Results were different early during the ripening period. The early postveraison fruit samples showed that over the five years E fruit was on average 0.5 Brix higher than C fruit ($p < 0.01$), while L fruit was intermediate regardless of cultivar (data not shown). The difference in sugar concentration progressively declined over the course of the ripening period, and neither TA nor color was different among thinning treatments at any stage during ripening. The early postveraison difference in fruit sugar concentration was not due to berry weight. On the contrary, while berry weights were similar for all thinning treatments initially, the E berries grew larger than the C berries (L berries were intermediate) as ripening progressed, even though by harvest this difference was significant only in 1999 (Table 6). As expected, TA declined as soluble solids increased, and the rate of (malic) acid degradation was fastest in Cabernet Sauvignon and slowest in Riesling (Figure 2A). Acid degradation proceeded slightly faster during the hot 1998 season than during the cool 1999 season (Figures 1 and 2B), but was unaltered by cluster thinning (Figure 2C). Anthocyanin accumulation by Cabernet Sauvignon berries was much more strongly influenced by seasonal conditions (Figure 3A) than either soluble solids or TA, but was independent of cluster thinning (Figure 3B). There was a tendency in each season, with the exception of 1999, for a temporary cessation of berry pigmentation (both on a concentration and per berry basis) in the first half of September, despite continued increases in soluble solids and declines in TA (data not shown). Color accumulation resumed after the berry-weight maximum in mid-September, except in 1998 (Figure 3A). Interestingly, the only noticeable effect of the 2000 fall freeze (23 September) was a significant ($p < 0.05$) subsequent decrease in berry color (data not shown but evident in the large variation of color at high soluble solids in Figure 3A).

Despite the wide range of crop levels (fruit mass per vine: 2 to 17 kg for Cabernet Sauvignon; 3 to 13 kg for both Riesling and Chenin blanc) and crop loads (fruit: pruning-weight ratio: 2 to 13 for Cabernet Sauvignon; 5 to 18 for Riesling; 4 to 23 for Chenin blanc), there was no clear relationship between either of these measures and soluble solids or TA. Separate calculations for low (pruning weight <0.5 kg), medium, and high-capacity (pruning weight >1.0 kg) vines, or for vines with crop loads either <10 or >10 (or any other division) did not improve correla-

Table 7 Effect of cultivar, cluster thinning, and growing season on fruit composition of own-rooted grapevines in the Yakima Valley, WA.

	Soluble solids (Brix)					**Titratable acidity (g/L)**				
Treatment	**1997**	**1998**	**1999**	**2000**	**2001**	**1997**	**1998**	**1999**	**2000**	**2001**
Cultivar										
Cabernet Sauvignon	24.2 a[a]	23.7 a	23.0 a	22.6	22.2	6.53 b	5.68 c	6.07 c	5.88 c	5.05 c
Riesling	21.4 b	21.3 c	22.4 b	22.0	21.9	10.18 a	8.69 a	8.33 a	8.76 a	7.89 a
Chenin blanc	nc[b]	22.1 b	22.2 b	22.7	22.6	nc	6.57 b	7.83 b	7.68 b	6.25 b
Thinning										
Early	23.0	22.6 a	22.9 a	22.4	22.2	8.30	7.03	7.38	7.49	6.41
Late	22.7	22.3 b	22.3 b	22.5	22.3	8.20	6.92	7.47	7.39	6.40
Control	22.7	22.2 b	22.4 ab	22.3	22.2	8.56	7.00	7.38	7.44	6.39
Interaction	ns[c]	ns	ns	ns	ns	ns	ns	ns	ns	ns

	pH					**Color (A_{520}/mL)**				
	1997	**1998**	**1999**	**2000**	**2001**	**1997**	**1998**	**1999**	**2000**	**2001**
Cultivar										
Cabernet Sauvignon	3.54 a	3.72 a	3.65 a	3.67 a	3.81 a	20.3	11.3	15.6	17.3	19.0
Riesling	3.08 b	3.06 c	3.11 b	2.95 c	3.49 c	nc	nc	nc	nc	nc
Chenin blanc	nc	3.20 b	3.14 b	3.22 b	3.67 b	nc	nc	nc	nc	nc
Thinning										
Early	3.26 a	3.26	3.26	3.18	3.63	20.1	11.8	16.2	16.7	17.8
Late	3.24 b	3.26	3.23	3.19	3.66	20.8	10.9	14.9	17.8	21.3
Control	3.25 ab	3.24	3.24	3.20	3.62	20.1	11.2	15.6	17.3	18.0
Interaction	ns	ns	ns	ns	ns	nc	nc	nc	nc	nc

[a] Means within columns followed by different letters differ significantly at $p < 0.05$ by Duncan's new multiple range test.
[b] nc: data not collected.
[c] Cultivar x thinning interaction; *, **, ***, ns: significant at $p < 0.05$, 0.01, 0.001, or not significant, respectively.

tions. The exception was 1998, when the C vines carried a very heavy crop in all three cultivars (Table 5) because of unusually high bud fruitfulness (Table 6). That was the only year with negative correlations between crop level and soluble solids (Riesling: r = -0.65, $p < 0.05$, n = 12; Chenin blanc: r = -0.95, $p < 0.001$, n = 12), as well as between crop load (fruit:pruning-weight ratio) and soluble solids (Riesling: r = -0.68, $p < 0.05$, n = 12; Chenin blanc: r = -0.73, $p < 0.01$, n = 12). However, no such relationships were found for Cabernet Sauvignon that had an even higher crop level (but not crop load). Moreover, all three cultivars were able to ripen the very heavy crop of the C treatment to the target Brix threshold (Table 7).

Fruit composition of Chenin blanc reacted more readily to both crop level and crop load than did that of the other two cultivars. A heavier crop on Chenin blanc was associated with higher TA ($0.53 < r < 0.87$, $p < 0.05$) and lower pH ($-0.93 < r < -0.62$, $p < 0.05$) in three out of four years, and there was also a significant ($p < 0.05$) trend for larger berries to have higher TA and lower pH. Moreover, TA also increased and pH decreased when Chenin blanc had more than about 50 shoots per meter of canopy. In 2001, but not in other years, a number of Riesling vines had a leaf-area:fruit-weight ratio <1.2 m^2/kg, and this was the only year with a positive correlation between this ratio and soluble solids (r = 0.74, $p < 0.01$, n = 12). Nevertheless, the fruit was harvested above the target Brix level of 21.5 (Table 7).

Although there was an overall (across all seasons and treatments) negative correlation between the fruit:pruning-weight ratio and color of Cabernet Sauvignon berries (r = -0.59, $p < 0.001$, n = 60), this was entirely accounted for by seasonal differences in both variables. Correlation, in this case, clearly did not imply causation: the crop load was unusually light in 2001 (Table 5), a year with very good color (Table 7). In contrast, the crop level and crop load were by far heaviest in 1998, the warmest year of the study (Table 1), that also resulted in the poorest fruit color. Nevertheless, removing 29% of the clusters (which decreased the crop level by 46% and the crop load by 49%) failed to improve color (as well as soluble solids, TA, and pH) even in 1998 (Table 7). No relationships between berry color (or any other berry component) and shoot vigor, shoot density, leaf area, pruning weight, crop level, crop load, or any of the yield components could be found *within* seasons.

Discussion

This study evaluated the potential benefits of crop adjustment in three own-rooted, deficit-irrigated *Vitis vinifera* cultivars in the field, using cluster thinning about one month after bloom or at veraison. Removing, on average, 39% of the clusters from Cabernet Sauvignon vines, 30% from Riesling, and 38% from Chenin blanc had no influence on vegetative growth but reduced yields by 36% in Cabernet Sauvignon, 17% in Riesling, and 20% in Chenin blanc. The smaller than anticipated yield reduction could mostly be attributed to the systematic (nonrandom) removal of noncount clusters. These clusters contributed between 30 and 45% of the total cluster number, but were 25 to 30% lighter than count clusters. Riesling was not only the most fruitful cultivar in this study, as indicated by its high number of clusters per shoot, but also was less responsive to cluster thinning than the other two cultivars. This was mainly a consequence of the fact that it had comparatively fewer noncount shoots, which were the ones targeted for crop adjustment. Despite a considerable yield penalty and regardless of timing, crop removal did not have any consistent advantageous effects in terms of vine balance, vigor, cane maturation, or fruit composition. Only in 1998, when thinning reduced the heavy crop loads of Riesling and Chenin blanc vines to less than 10 kg fruit per kg pruning weight, did soluble solids increase slightly. This would seem to confirm earlier research that had established a crop load range of 5 to 10 to be ideal for high-quality winegrape production (Bravdo et al. 1985, Reynolds 1989, Smart et al. 1990). However, thinning did not improve fruit composition in 1999, even though crop loads (but not crop levels or yields) of the two white culti-

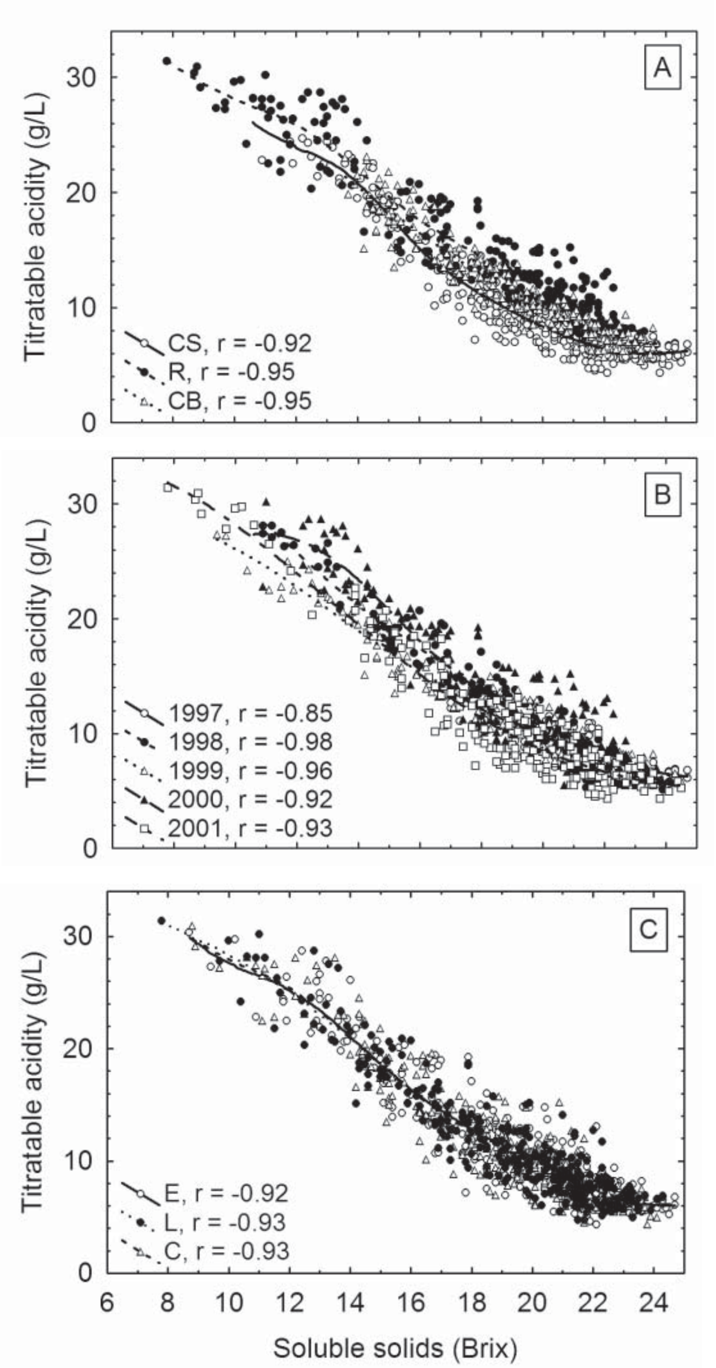

Figure 2 Relationship between soluble solids and titratable acidity during fruit ripening of three own-rooted *V. vinifera* cultivars. Data were pooled across five seasons and three cluster thinning treatments (**A**; CS: Cabernet Sauvignon, R: Riesling, CB: Chenin blanc, all $p < 0.001$, $n \geq 240$), across three cultivars and three cluster thinning treatments (**B**; all $p < 0.001$, $n \geq 108$), or across five seasons and three cultivars (**C**; E: early thinning, L: late thinning, C: unthinned control, all $p < 0.001$, $n \geq 303$).

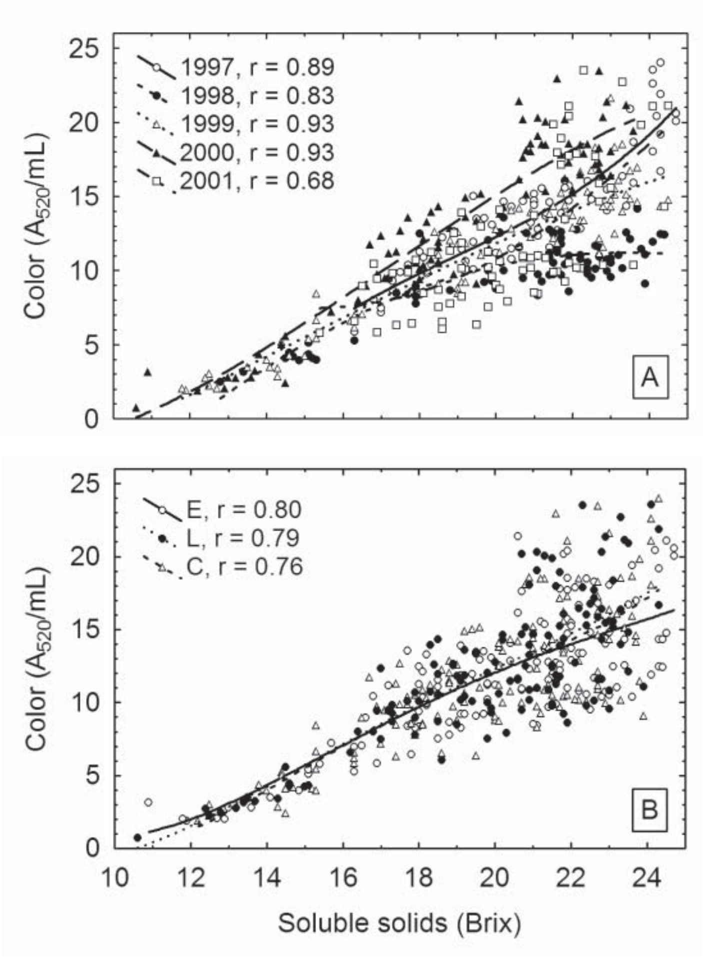

Figure 3 Relationship between soluble solids and berry color during fruit ripening of own-rooted Cabernet Sauvignon grapevines. Data were pooled across three cluster thinning treatments (**A**; all $p < 0.001$, $n \geq 72$) or across five seasons (**B**; E: early thinning, L: late thinning, C: unthinned control, all $p < 0.001$, $n \geq 132$).

vars were even higher in that year than in 1998. Moreover, even in these two contrasting seasons (1598 GDD in 1998; 1246 GDD in 1999), all three cultivars were able to ripen their crop to full maturity (target Brix level), although in the 1998 Riesling only the E fruit reached the target by harvest in mid-September. However, given that soluble solids were still accumulating at a rate of 0.24 Brix/day, the L and C fruit would have reached the target with only two more days of "hang time." Given that all vines were under an RDI regime, seasonal weather conditions were clearly the overriding factor determining fruit composition, and weather effects were always far greater than the effects of cluster thinning. These results confirm our conclusions from a concurrent study with Concord grapes (*Vitis labruscana* Bailey), where crop loads were altered by varying pruning levels (Keller et al. 2004). However, in contrast to the Concord experiment, yields in this study were not noticeably high in 1997 (despite high berry weights leading to heavy clusters). This was probably due to carry-over effects from a severe winter freeze (-25.3°C) on 2 February 1996. Cold injury to *V. vinifera* vines was substantial enough to force retraining of trunks and cordons, which did not permit data collection from Chenin blanc during the 1997 season. However, favorable weather conditions during the cluster initiation period in 1997 (Keller et al. 2004) led to unusually high bud fruitfulness (high number of clusters/shoot) for 1998 in all three cultivars, which was exactly as reported for the Concord study.

Fruit composition of Chenin blanc was more responsive to crop load compared with the other two cultivars. Chenin blanc also was the only cultivar that showed a threshold in bud fruitfulness (1.4 clusters/shoot) beyond which fruit quality declined. Cultivar differences in the response to crop adjustment were described by Weissenbach and Koblet (1993) for the very cool climate of Switzerland. In their experiments, thinning improved fruit composition much more markedly in Müller-Thurgau and Räuschling than in Pinot noir. Cluster thinning was reported to enhance "ripe fruit" characters and reduce "green fruit" flavor of Riesling wines, despite small effects on fruit composition (Reynolds et al. 1994b). However, the crop load in their study (Reynolds et al. 1994a) was considerably heavier than in the present experiment. No consistent effects of removing up to two-thirds of the clusters on Cabernet Sauvignon wine quality and aroma were found by Ough and Nagaoka (1984) and Bravdo et al. (1985) with yields similar to or even higher than the ones achieved in this study.

The canopies in this trial would ordinarily be classed as very dense because of the high number of shoots per meter of canopy (caused mainly by a high proportion of noncount shoots). An "ideal" shoot density of about 15/m was proposed for optimizing yield and fruit quality of vertically trained vines (Smart et al. 1990). However, Riesling, at least, also performed well at densities of up to 29 shoots/m (Kiefer and Crusius 1984, Reynolds et al. 1994a,b), and 35 shoots/m are common in non-European viticulture (Smart 1985). That is still less dense than the canopies in the current experiment and suggests that the pruning level was insufficient (too few nodes were retained at pruning) to meet the capacity of this site. Our vines may have been spaced too closely or could have benefited from a divided trellis system (Reynolds et al. 1994c, 2004). However, the present data are insufficient to speculate on potential reasons for the disproportionate number of noncount shoots in 1999 (and partly in 2000 as well); it was clearly not caused by low crop loads, high soil moisture, or postharvest heat accumulation in the previous season that would have led to higher than usual storage reserves in the vines. On the contrary, crop loads were highest in 1998 and 1999, and the fall frost in 1999 led to early leaf fall. If heavier crop loads had reduced cold acclimation and winter storage reserves in the permanent parts of the vines, then there should have been a concomitant decrease in shoot maturation. In addition, potential carryover effects might have appeared as differences in budbreak (growth of noncount shoots) and early-season vigor (shoot growth rate from budbreak to bloom). That happened in 1999, when C vines were slightly less vigorous following their very high crop level (although not unusually high crop load) in 1998. Apart from this exception, there were no differences in shoot maturation, percentage of noncount shoots, and vigor among treatments in any cultivar, suggesting that storage reserves were not normally limiting early growth. Therefore, it seems likely that cold acclimation and storage reserves were not influenced by crop load in this experiment. This conclusion is supported by earlier studies with Cabernet Sauvignon that failed to detect an impact of cluster thinning (Bravdo et al. 1985) or harvest date (Wample and Bary 1992) on cane reserve carbohydrate concentration and cold hardiness.

Shoot density had only minor effects on vigor, bud fruitfulness (clusters/shoot), crop level, and fruit composition: there was a trend in Chenin blanc, but not in the other cultivars, for higher acidity and lower pH with increasing shoot density. Changes in acidity and pH are frequently related to variations in cluster exposure to sunlight, but no measurements of light attenuation in the canopy were made in this study. However, although thinning failed to influence pH and acidity, the pH also decreased and acidity increased with increasing crop level and crop load in some years in all three cultivars. Since there was no correlation between crop level and shoot number per vine, it seems likely that differences in fruit composition were related to crop level rather than canopy density. Even in Cabernet Sauvignon there was no relationship between shoot density and bud fruitfulness or berry color, suggesting that shade in the cluster zone did not compromise vine productivity and fruit quality. Only minor differences in fruit composition between shaded and exposed Cabernet Sauvignon clusters were noted by Crippen and Morrison (1986a,b) in the Napa Valley of California. Sprawl-trained vines with shoot growth controlled by RDI in eastern Washington may be less susceptible to decreases in light exposure due to increasing canopy density than are vineyards in regions with less sunshine and more rainfall. Indeed, excessive fruit temperature (especially above 35°C) in this region has been noted to delay ripening and reduce quality (in terms of anthocyanins and other phenolic components) of exposed Merlot clusters despite the beneficial effect of increased light (Spayd et al. 2002). This was confirmed in the present study when, in the hot 1998 season (combined with relatively high soil moisture), anthocyanin accumulation in Cabernet Sauvignon berries ceased two weeks after veraison and color remained unchanged throughout the remainder of the ripening period, even though soluble solids continued to increase (both in concentration and content per berry) through harvest four weeks later.

According to the leaf-area:fruit weight ratio, even the C vines of all cultivars always had sufficient or even excessive leaf area to ripen their crop. The linear increase in yield over the entire range of clusters per vine for all three cultivars and in each season also suggests that source limitation was not important in yield formation and ripening (Naor et al. 2002). However, according to the fruit: pruning-weight ratio, Riesling tended to be on the brink of overcropping, Chenin blanc varied between ideal and overcropped, and Cabernet Sauvignon had a tendency to be undercropped. This apparent contradiction may be at least partly related to the uncertainties inherent in estimating vine leaf area. Indeed, leaf area turned out to be a poor predictor of pruning weight; the correlation was significant only for Cabernet Sauvignon in each year ($0.29 < r < 0.51$, $p < 0.05$). Thus the fruit:pruning-weight ratio may be a more robust indicator of crop load and vine balance than the leaf-area:fruit weight ratio.

The range of fruit composition in the current experiment was small in comparison with the variation in crop level or crop load. In agreement with the studies discussed by Kliewer and Dokoozlian (2001), there was no improvement in fruit composition in any cultivar when the leaf-area:fruit weight ratio increased above 1.0 to 1.2 m^2/kg. Indeed, the light crop loads found in this study would normally be considered problematic in terms of competition for assimilates from growing shoots and shading of the cluster zone. On the other hand, high leaf-area:fruit weight ratios have also been reported to result in reduced leaf nitrogen and build-up of nonstructural carbohydrates in the leaves, leading to a reduction of photosynthesis in response to the low sink demand (Hofäcker 1978, Edson et al. 1995a, Naor et al. 1997, Urban et al. 2004). Although not measured in the present study, such a reaction may be particularly important for deficit-irrigated vineyards in arid regions (such as eastern Washington) with little shoot growth after fruit set that could sustain photosynthetic rates when clusters are removed. Despite the high shoot density, shoot length generally reached the “ideal” 60 to 90 cm (Smart et al. 1990) by bloom. Thereafter, shoot vigor was controlled by RDI in all treatments, so that on average shoots grew only by another 13.5 cm through veraison. Therefore, in the absence of increased vegetative sink demand compensating for decreased reproductive sink demand (Eibach and Alleweldt 1985, Edson et al. 1995b), vines may downregulate photosynthesis to balance supply with the low demand (Hofäcker 1978). We speculate that this could explain why removing up to 36% of the fruit in this study did not consistently improve fruit composition, except (slightly) in 1998, the year with an exceptionally heavy crop (exceeding 21 t/ha in the control vines across the three cultivars). However, targeted (nonrandom) removal of “slow” clusters (clusters that develop more slowly than others) rather than thinning noncount and small clusters might be more beneficial in terms of improving overall fruit quality, and that, of course, is what should be done in practice. Moreover, we cannot exclude the possibility that there might have been an effect on shoot and fruit development if thinning had been done earlier (at bloom) or if even more fruit had been removed.

Conclusions

While significantly reducing crop loads and harvest yields, cluster thinning had little effect on vegetative growth, fruit ripening, and fruit composition of mature, field-grown Cabernet Sauvignon, Riesling, and Chenin blanc vines on a high-capacity site, regardless of whether crop adjustment was carried out one month after bloom or at veraison. Over the five years of this study, the effects of seasonal conditions (especially differences in temperature and soil moisture) were far greater than the impact of thinning. As usual, there were good years and better years, but thinning turned out to be unnecessary for deficit-irrigated winegrapes in eastern Washington’s arid Yakima Valley, except in seasons with extraordinarily high yield potential (1998 in this study). It is therefore questionable whether the minor increase in sugar concentration justifies the time required to carry out the thinning operation and the loss of potential yield. Provided fall temperatures remain high enough, similar (and greater) increases in grape sugar can often be achieved by slightly delaying harvest. Cluster thinning should, however, be considered as a “band-aid” management option when exceptional yield potential (such as the one encountered in 1998) coincides with a cool growing season (such as the one experienced in 1999).

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