Response of Fruit Growth and Ripening to Crop Level in Dry-Farmed Cabernet Sauvignon on Four Rootstocks

Vitale Nuzzo[1]* and Mark A. Matthews[2]

Abstract: An estimate of the amount of clusters that a vine can reasonably bring to maturity is essential for optimizing crop level. This work was conducted to determine whether the timing of maturity in a high-yielding, dry-farmed *Vitis vinifera* L. Cabernet Sauvignon vineyard could be manipulated through rootstocks and crop level. Cabernet Sauvignon, grafted on 5C Teleki (*V. berlandieri* Planch. *x V. riparia* Michx), 1103 Paulsen, 140 Ruggeri, and 110 Richter (*V. berlandieri* Planch. *x V. rupestris* Scheele), was used in a trial carried out in 1997 and 1998 in an 8-year-old vineyard near Oakville, California. Four levels of crop were imposed by winter pruning all vines to four-bud spurs and cluster thinning at veraison: treatment 1 (100%), or double crop, no thinned vines with ~26 shoots and 40 clusters per vine; treatment 2 (75%), in which 25% of clusters were thinned; treatment 3 (50%), the standard crop level in the study area or control, in which 50% of clusters were thinned and one cluster per shoot was retained; and treatment 4 (25%), in which 75% of clusters were thinned and one cluster every two shoots was retained. The time required to reach 23.5, 24.0, and 25.0 Brix was linearly dependent on crop level with a rate of about one day per each ton of grapes. Rootstocks and crop levels had no or little impact on fruitfulness, cluster and berry size, and final Brix. The reduction in sugar accumulation seems to be a sensitive measure for crop level and does not appear to be influenced by rootstock or environmental conditions.

Key words: berry growth, berry composition, yield, 1103 Paulsen, 140 Ruggeri, 110 Richter, 5C Teleki

There is much discussion on the proper balance of vegetative and reproductive growth in viticulture. To optimize reproductive growth and ultimately yield, it is essential to have an estimate of cropping potential, that is, the amount of fruit that can ripen. In grapevine, as in other perennial plants, vegetative and reproductive growth occurs simultaneously. Competition between the two processes begins when resources are not sufficient to support growth at potential rates. Such competition is generally agreed to be the basis for the partitioning of resources to reproductive and vegetative organs (Wardlaw 1990). The indeterminate growth habit allows vegetative growth to compete for resources well beyond flowering, in contrast to determinate crops such as corn or sunflower. Several cultural factors contribute to the partitioning between vegetative and reproductive growth, including direct manipulation of sinks, water and nutrient status, and grafting via rootstock-scion combinations.

In a vineyard, common methods to regulate partitioning into vegetative and reproductive growth are winter pruning to manipulate the number of buds per vine, cluster thinning, or a combination (Winkler et al. 1974). Since most buds in cultivated grape are mixed buds, pruning necessarily affects both vegetative and reproductive growth. Reproductive growth (measured as yield) is more responsive than vegetative growth (usually measured as pruning weight) to pruning (buds/vine) (Lider et al. 1973, Freeman et al. 1979, Williams 1996). Consequently, vines can be "overcropped" (bear more reproductive sinks than the vegetative growth can mature) by pruning to high numbers of buds per vine (Winkler 1954). Overcropping can be avoided after pruning by removal of some reproductive sinks by cluster thinning that directly reduces reproductive growth. Some compensatory shoot and fruit growth can occur, but only when thinning is done early in the season (Winkler 1931). When clusters are thinned at veraison or later, there is a slight or no effect on leaf area per shoot or per cluster, higher concentrations of carbohydrate reserves accumulate (Duchene et al. 2003), yield is reduced, and grapes ripen earlier (Bertamini et al. 1991). The impact of overcropping and cluster thinning on sensory attributes of wines was recently studied (Chapman et al. 2004).

Cropping potential and growth partitioning can also be affected by manipulating vine water status, but the role of water status is complex. First, irrigation to increase vine water status is widely used to increase crop production. Yet, irrigation, similar to pruning, affects both vegetative and reproductive growth. Contrary to pruning, the available evidence indicates that vegetative growth is more sensitive to vine water status. One study showed that when any fraction of applied water was reduced, in irri-

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gated viticulture, vegetative growth decreased; but applied water could be reduced as much as 50% before yield decreased (Williams 1996). Another study showed that when furrow irrigation produced slightly lower midday leaf water potentials than drip irrigation, shoot length was reduced by 17%, but fruit weight was reduced only by 6% (Araujo et al. 1995). It was recently shown that fruit growth was not inhibited until midday leaf water potential decreased to -1.25 MPa (Roby et al. 2004), but shoot growth is completely inhibited at about -1.2 MPa (Matthews et al. 1987, Schultz and Matthews 1988).

Second, water deficits are reported to accelerate fruit ripening (van Leeuwen et al. 2003), but it is clear that water deficits inhibit the photosynthesis and translocation processes required for ripening (Chaves and Oliveira 2004). Moderate water deficits may result in sugar accumulation in fruit by decreasing partitioning to alternate vegetative sinks (Roby et al. 2004), but severe water deficits limit the crop that can be ripened by reducing photosynthate production via inhibiting the rate of photosynthesis, inhibiting the development of photosynthetic leaf area, and accelerating leaf senescence while having less impact on reproductive sinks.

The role of rootstocks in partitioning and reproductive growth is less clear, particularly with respect to dry conditions. Although differences are often reported, for example, more vegetative growth compared to yield on Rupestris St. George (*Vitis rupestris*) (Ough et al. 1968), and conversely a consistently greater partitioning to fruit on Riparia Gloire (Ollat et al. 2003), the many comparisons of relative vegetative and reproductive growth of scions have produced few consistently significant differences among rootstocks. This lack of consistency may indicate that the potential for rootstocks to impact scion growth can be obscured by the various environments (irrigation and fertilization) in which the trials have been conducted. Thus, despite references to drought tolerance (Galet 1988, Pongracz 1983), there are few data directly addressing drought tolerance in the literature to indicate significant differences among rootstocks. However, Ezzahouani and Williams (1995) showed clear effects of rootstocks on vegetative and reproductive growth of table-grape scions when grown under dry-farmed conditions.

The primary objective of this study was to determine how much crop could be ripened when irrigation water was not available or used. This trial determined the crop potential and fruit ripening of Cabernet Sauvignon grafted onto four rootstocks and grown under dry-farmed conditions in an irrigated viticulture region (Napa Valley, CA). The rootstock cultivars with distinct growth habits—5C Teleki (*V. berlandieri* Planch. x *V. riparia* Michx) and 1103 Paulsen (1103 P), 140 Ruggeri (140 Ru), and 110 Richter (110 R) (*V. berlandieri* Planch. x *V. rupestris* Scheele)—are established as commercially viable, phylloxera-resistant rootstocks with some reputation for differences in drought tolerance (110 R and 140 Ru tolerant, 5C sensitive) (Galet 1988, Pongracz 1983). However, there is little data directly addressing drought tolerance in the literature to indicate significant differences among rootstocks.

Materials and Methods

Plant material and experimental design. *Vitis vinifera* L. cv. Cabernet Sauvignon scions grafted onto *V. berlandieri* Planch. x *V. riparia* Michx (5C Teleki) and *V. berlandieri* Planch. x *V. rupestris* Scheele (1103 P, 140 Ru, and 110 R) rootstocks were planted at 1.0 x 2.44 m (vine x row) spacing and a 4,000 vines/ha vine density at the Oakville Experimental vineyard (Napa Valley), operated by the Department of Viticulture and Enology, University of California, Davis (lat: 38.43°; long: 122.41°). Vines were trained to unilateral cordons with a trunk height of 0.9 m, spur-pruned with six 2-bud spurs per meter of cordon, and trellised for vertical shoot-positioning. Summer pruning as shoot thinning, shoot topping (removal of shoot apex), or hedging was not performed. The vineyard was not irrigated. Pest control and soil management practices were performed according to local recommendations. The climate is low region III with an average of 1720 growing degree days (base 10°C) (Winkler et al. 1974). The soil is a gravelly, Bale clay loam (Lambert and Kashiwagi 1978), characterized as being part of alluvial fans with depths of 183 cm or greater. Soil water-holding capacity is considered moderate to high, at 0.08 cm of water per cm of soil. It is common for this soil type to have a water table during the winter and spring at ~120 cm depth.

Yield treatments were imposed in 1997 and 1998 by pruning to 4-bud spurs (24 to 28 buds/vine) and cluster thinning. The 4-bud spurs resulted in 100% more buds than the 2-bud spurs in standard practice. Initial crop level was determined by counting the clusters and shoots of each vine at flowering. Four treatments were then imposed: 100%, 2x standard crop (all clusters retained); 75%, 1.5x standard crop (75% of clusters retained); 50%, standard crop (50% of clusters retained, leaving one cluster per shoot); 25%, half standard crop (25% of clusters retained, leaving one cluster every two shoots). Cluster thinning was imposed at the onset of veraison and started with the apical cluster. Onset of veraison was determined from a visual assessment of 5 to 10% of the berries having black color. Clusters were thinned on 8 July 1997 and 3 Aug 1998. Harvest started as each treatment exceeded 23.5 Brix.

At harvest, the number of clusters, the number of shoots, and yield were determined for each vine. In 1998, four representative primary shoots per treatment (16 shoots per rootstock) were collected; leaf area per shoot was measured with a video-based area meter calibrated with opaque triangles of known area (Delta-T Device, Cambridge, UK). Mean shoot leaf area was multiplied by primary shoot number per vine to calculate leaf area per vine.

In 1997, the weight of pruning material was determined during pruning the following winter when vines were dormant. In 1998, after harvest, 16 randomly selected primary shoots were collected and weighed in each rootstock. Mean shoot weight was multiplied by primary shoot number per vine to calculate kg pruning weight per vine. Crop load was expressed on vine basis as yield to pruning weight ratio and as leaf area to yield ratio.

Treatments were arranged as a split-plot design with four replications. Rootstocks were the whole plots, and crop load was the split plot. Whole plots were 4 rows x 12 vines; split plots were three vines within each row. Rootstock plots were randomly distributed down the rows, and cluster-thinning treatments were randomly distributed within rootstock plots. Only the center two rows were used for data collection; each of the three vines in a split plot was subsampled for a total of 192 vines (4 rootstocks x 4 yield treatments x 4 replications x 3 subsamples).

Meteorological variables were measured by a standard weather station of the California Irrigation Management Information System (CIMIS) placed close to the experimental field. Growing degree days (GDD) were calculated by subtracting 10°C (the minimum temperature threshold) from average temperature reported by the CIMIS daily report. Daily values were added from 1 Apr to 31 Oct.

Fruit samples and juice analysis. Samples of 50 to 100 berries were collected at 10-day intervals beginning approximately two weeks after fruit set and concluding at harvest. Berries were randomly picked from the clusters of the vines of each split plot. The berries sampled were immediately enclosed in a plastic bag, stored in a portable refrigerator, and transported to the laboratory where fresh weight (the rachis stem was removed) was recorded. After veraison, sampled berries were counted, weighed, macerated in a mortar, and then squeezed through two layers of cheesecloth. Aliquots of the expressed juice were immediately analyzed for total soluble solids (Brix) with a hand refractometer. In 1998, titratable acidity (TA) by titration to a pH end point of 8.4 with 0.1 N NaOH using phenolphthalein as indicator (expressed as g tartaric acid equiv. per L of juice). The pH of the juice was measured with a pH meter, using a glass electrode (HI1048; Hanna Instruments, Woonsocket, RI). At harvest, a further sample of 100 berries randomly selected from vines of each split plot was collected. Disks of dermal tissue (0.20 cm^2) were removed with a cork borer. Anthocyanins were extracted with acidified methanol and the concentration estimated from the A_{535} according to (Amerine and Ough 1988).

Leaf water potential. Vine water status was determined as midday leaf water potential (LWP) measured with the pressure chamber technique as described by Matthews et al. (1987). Briefly, healthy, fully expanded, and well-exposed leaves positioned between the 10th and the 15th nodes of the primary shoots were enclosed in a polyethylene bag, excised, and immediately placed into a humidified pressure chamber for measurement. Measurements of LWP were performed each month from 10 July to 5 Oct.

Data analysis. Data were analyzed by the analysis of variance using SigmaStat 3.0.1 software (SSPS, Inc. Chicago, IL). When warranted, the Student-Newman-Keuls test was used to compare the means or a linear and second-degree polynomial regression analysis was performed.

Results

This trial included the hottest (1997) and the coolest (1998) years of the preceding decade, 1989 to 1998 (Figure 1). The difference between the two years was soon evident in the growing season. Accumulation of growing degree days (GDDs) began almost one month earlier in 1997 than in 1998. In 1997 fruit set was completed on 8 June when 589 GDD were accumulated, while in 1998 fruit set completed on 29 June when only 427 GDD were accumulated. Veraison was on 8 July in 1997 (888 GDD) and on 2 Aug in 1998 (763 GDD). The year 1998 was also unusually rainy (1430 mm) as compared to the average of the 1989 to 1998 period (930 mm). Nevertheless, in the 1998 growing season there were five months (from the end of May to the end of October) without any rainfall.

Despite no irrigation, midday leaf water potentials (LWP) did not reach very low values in either season. In 1997, midday LWP ranged from -1.10 MPa at the beginning of veraison to -1.37 MPa at harvest. There were no differences among rootstocks. In 1998, midday LWP decreased from -0.92 MPa during stage I of berry development to -1.36 MPa at harvest (Table 1). Generally, in the first part of the growing season (from fruit set to veraison), vines on 5C showed a significantly lower midday LWP than the other rootstocks and particularly 110 R and 140 Ru. At veraison (36 days after fruit set), midday LWP was similar among rootstocks and ranged from -1.25 to -1.29 MPa. In the second part of the growing season, from veraison to harvest, vines grafted on 5C had a higher midday LWP than did vines on other rootstocks.

At fruit set, rootstocks did not differ significantly in fruitfulness (clusters/shoot) or in crop level (clusters/vine) with 4-bud spurs (Table 2). In 1997, crop level varied from

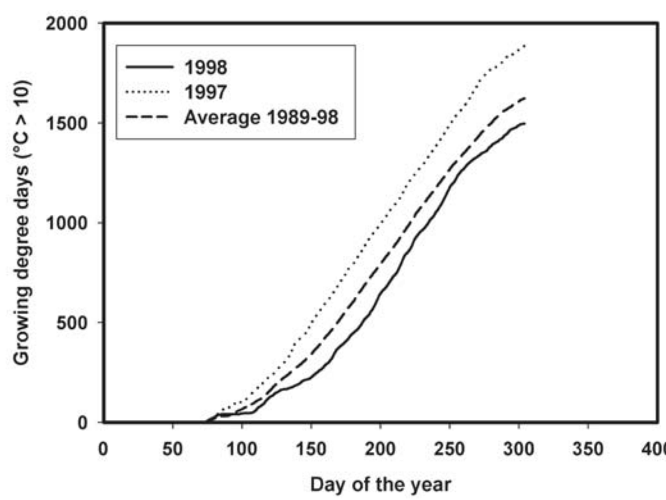

Figure 1 Accumulation of growing degree days from 15 Mar to 31 Oct during 1997 and 1998 and the average of 10 years of growing seasons (1989 to 1998). Data were collected by the automatic weather station at Oakville.

~20 to 49 clusters/vine. In 1998, the crop level was statistically well separated among the cluster-thinning treatments, varying from 16.9 ± 4.6 to 42.3 ± 6.6. The cluster-thinning treatments created crop levels that were ~150% greater on unthinned vines than on heavily thinned vines. The crop level on the vines nominally thinned to 50% of the clusters present at veraison was similar to the standard crop level for similarly trained vines.

Although there were differences in crop level at $p < 0.001$ among the rootstocks, differences were not consistent among cropping treatments. For example, in 1997 the number of clusters on 110 R was significantly lower than on 140 Ru. In the second year of the trial, crop level on 1103 P was greatest at a cropping factor of 50% and 25% and lowest at a cropping factor of 75% and 100%. In 1998, at harvest, crop level in unthinned vines was significantly lower on 1103 P (38.2 ± 6.8) than on 140 Ru (44.8 ± 5.2) and 110 R (43.8 ± 6.2); at a cropping factor of 75% there were significantly less clusters on 1103 P (28.6 ± 3.6) with respect to 140 Ru (34.7 ± 4.6). For the lower two cropping treatments, there were significantly more clusters on 1103 P than on 5C. Moreover, no statistical difference was observed in number of clusters of 1103 P vines at the cropping factors 75% and 50% (Figure 2).

Table 1 Midday leaf water potential of dry-farmed Cabernet Sauvignon vines on four rootstocks in three development stages of the 1998 growing season. Data are average ± standard deviation, n = 16.

	Midday leaf water potential (MPa)[a]		
Rootstock	Stage 1 berry growth	Veraison	Harvest
5C	-1.04 ± 0.04 a[b]	-1.29 ± 0.07	-1.29 ± 0.11 c
110 R	-0.86 ± 0.08 c	-1.25 ± 0.05	-1.36 ± 0.08 b
140 Ru	-0.86 ± 0.04 c	-1.29 ± 0.07	-1.38 ± 0.08 b
1103 P	-0.93 ± 0.04 b	-1.29 ± 0.07	-1.43 ± 0.08 a

[a]Measurements performed on 14 July (16 days after fruit set), 11 Aug (3 days after veraison), and 5 Oct, with an average vapor pressure deficit (VPD) of 1.8, 1.8, and 0.7 KPa, respectively.
[b]Different lowercase letters indicate significant differences ($p < 0.05$) between rootstocks. Nonsignificant differences were not reported.

Table 2 Fruitfulness and crop level at fruit set of dry-farmed Cabernet Sauvignon vines on four rootstocks. Vines were winter pruned to 4-bud spurs, which left 100% more buds than the standard (2-bud spurs) pruning system of the area. Data are average ± standard deviation, n = 24.

	Fruitfulness (clusters/shoot)	Initial cluster level (clusters/vine)	
Rootstock	1998	1997	1998
5C	1.6 ± 0.2[a]	43.0 ± 5.8	40.2 ± 5.4
140 Ru	1.6 ± 0.1	49.0 ± 7.0	42.2 ± 6.0
110 R	1.6 ± 0.2	49.0 ± 7.3	41.1 ± 6.1
1103 P	1.6 ± 0.2	45.3 ± 6.6	38.2 ± 5.7

[a]Nonsignificant differences were not reported.

Yields established by thinning treatments were similar in two seasons (Table 3). In 1997, yield ranged between 1.95 in the most thinned vines and 4.63 kg/vine in unthinned ones, corresponding to 7.8 and 18.5 t/ha. In 1998, cropping treatments gave yields that varied from 1.69 to 4.08 kg/vine. The difference between the two treatments was significant at $p < 0.01$. Other treatment comparisons were also significant, but at p values <0.05. In the two years of the trial, yield of the 50% treatment was 2.79 and 2.34 kg/vine for 1997 and 1998, respectively, corresponding to ~11.2 and 9.4 t/ha. In 1998, the high yield in the 100% cropping treatment was 4.08 kg/vine, corresponding to 16.3 t/ha, 76% greater than the 50% cropping treatment.

In 1998, there were significant differences ($p < 0.05$) among rootstocks, with yield per vine on 1103 P significantly lower than on 5C and 140 Ru (Table 3). Within the cropping levels, there were few significant differences ($p < 0.05$) among rootstocks. For the higher-yielding treatments in particular, the yield per vine on 1103 P was significantly lower than on other rootstocks (Figure 3).

In the two years of the trial, thinning the clusters at veraison had no influence on vegetative growth expressed both as weight of pruning material or leaf area at harvest (Table 3). The weight of pruning material was influenced by rootstock. In 1997 and 1998 140 Ru produced significantly more vegetation than 5C. In 1997 vegetative growth of 5C was statistically lower than the other rootstocks, while in 1998 the vegetative growth of 110 R was statistically different from 140 Ru (Table 3). Only 5C showed a significantly lower pruning weight in 1997 with respect to the following year.

In 1997, the yield/pruning weight ratio ranged from 5.85 kg/kg in the unthinned vines to 2.46 kg/kg in the 75%

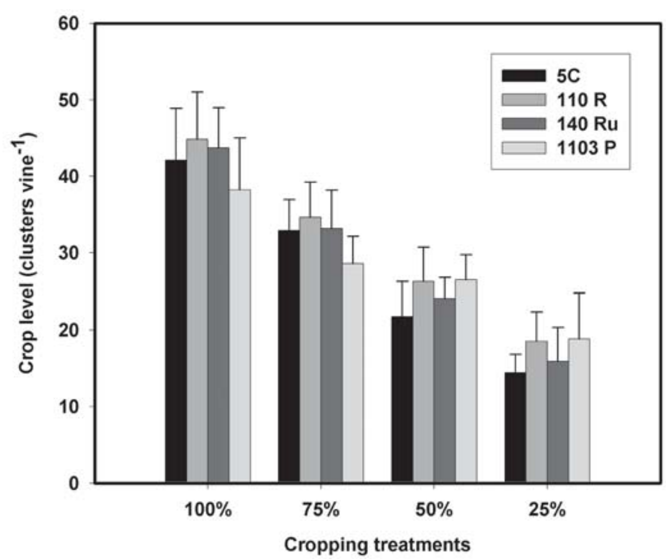

Figure 2 Crop level of Cabernet Sauvignon vines exposed to various cropping treatments in 1998. Crop level on each of four rootstocks (n = 4). Cropping treatments were imposed by winter pruning to 4-bud spurs and cluster thinning at veraison to various crop levels. The standard crop level of vines in the area has ~25 clusters/vine corresponding to 50% thinning treatment.

Table 3 Yield and vegetative growth of dry-farmed Cabernet Sauvignon grafted on four rootstocks with four crop levels. Data were collected at harvest of 1997 and 1998. Data are average ± standard deviation, n = 16.

	Yield (kg vine⁻¹)		Pruning wt (kg vine⁻¹)		Yield:Pruning wt (kg kg⁻¹)		Leaf area (m² vine⁻¹)	Leaf area:Yield (m² kg⁻¹)
	1997	**1998**	**1997**	**1998**	**1997**	**1998**	**1998**	**1998**
Crop level								
100%	4.63±0.95a[a]	4.08±0.78a	0.84±0.30	1.06±0.37	5.85±1.33a	4.37±1.85a	5.33±2.10	1.35±0.65a
75%	3.78±0.26ab	3.00±0.58b	0.78±0.18	1.09±0.38	5.15±1.69a	3.13±1.30b	4.18±2.26	1.41±0.80a
50%	2.79±0.64bc	2.34±0.41c	0.83±0.27	1.33±0.53	3.63±1.32b	2.20±1.48bc	5.68±2.74	2.49±1.23b
25%	1.95±0.43c	1.69±0.44d	0.85±0.30	1.39±0.45	2.46±0.73c	1.36±0.62c	4.96±2.29	3.04±1.46b
Rootstock								
5C	2.78±1.08	3.15±1.2a	0.46±0.05c	1.06±0.33bc	5.93±1.88a	3.44±2.08a	5.03±1.82	1.87±1.20
110 R	3.66±1.44	2.71±1.08ab	0.84±0.08b	0.97±0.31c	4.40±1.88b	3.25±1.89ab	4.12±2.65	2.54±1.20
140 Ru	3.47±1.33	2.90±0.97a	0.94±0.10ab	1.46±0.51a	3.70±1.37bc	2.44±1.54abc	6.24±2.16	1.71±1.43
1103 P	3.24±1.19	2.34±0.7 b	1.05±0.06a	1.38±0.45ab	3.07±1.06c	1.93±1.11c	4.80±2.46	2.17±1.25

[a]Different lowercase letters indicate significant differences ($p < 0.05$) between rows (crop level or rootstock). Nonsignificant differences were not reported.

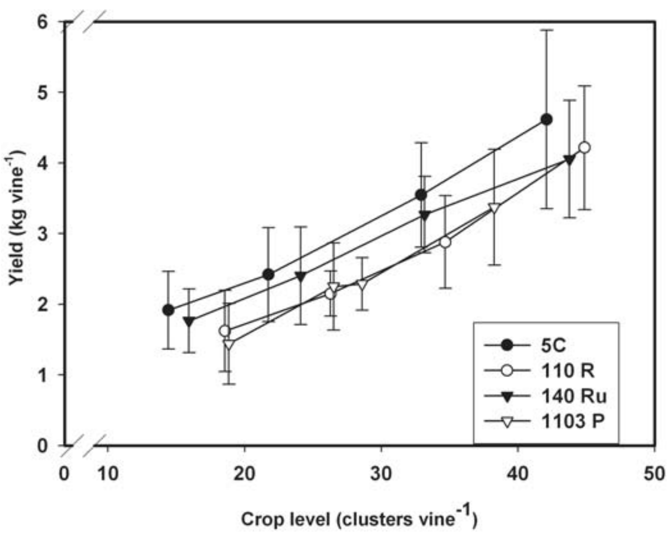

Figure 3 Crop yield of Cabernet Sauvignon vines exposed to various cropping treatments in 1998. Yield for vines on each four rootstocks (n = 4). Cropping treatments were imposed by winter pruning to 4-bud spurs and cluster thinning at veraison to various crop levels.

thinned vines. In 1998, the thinning treatments gave a yield to pruning weight ratio varying from 4.37 to 1.36 kg/kg (Table 3). The difference between the two treatments was significant at $p < 0.001$. Other comparisons between treatments were not always significant. For example, in 1997 similar values of the yield/pruning weight ratio were calculated at cropping factors of the 100% and 75%, while the comparisons were significantly different between these two treatments and 3.63 and 2.46 kg/kg, calculated respectively for the cropping factor of 50% and 25%. The yield/pruning weight ratio values of the 50% and 25% treatments were significantly different. In 1998, the effect of thinning on the yield to pruning weight ratio was well separated from the unthinned treatment. Within the thinned treatments, the values were significantly different with the 75% and 25% treatments (Table 3).

Yield to pruning ratio was also influenced by rootstock: 5C has generally shown the highest values and 1103 P the lowest. In 1997, the value of yield to pruning weight ratio calculated in vines grafted on 5C was statistically different from the other rootstocks, but in 1998, 5C, 110 R, and 140 Ru showed similar crop load values (Table 3). In 1998, rootstocks had no influence on the leaf area/yield ratio that was 1.71 and 2.54 m^2/kg, respectively, for 140 Ru and 110 R. Leaf area per kilogram of fresh fruits was lower in 100% and 75% treatments than in the remaining two treatments (Table 3). In the two years of the trial, there were no interactions between years for rootstock and for crop level factors in yield, pruning weight, and crop load.

Cluster weight was largely unaffected by the treatments. In 1997, the cluster weight ranged from 94.2 to 103.6 g/cluster, with no significant differences. Similarly, in 1998 the average cluster weight varied from 92.0 to 101.2 grams in the 75% and 25% cropping treatments, respectively (Figure 4); again with no significant difference. However, there were significant differences among rootstocks, with cluster weight significantly higher on 5C ($p < 0.01$) (Figure 4). The 25% cropping level on 5C also produced clusters that weighed 21% more than clusters from the 100% cropping level ($p < 0.05$). Rootstocks 140 Ru and 110 R showed the same trend, but the gain in cluster weight from 100% to 25% cropping levels was only 6% and 7%, respectively.

In the two years of the trials, there were no differences among rootstocks in maximum berry size and in berry size at harvest (Table 4). On all rootstocks, berry size reached a peak 7 to 15 days before harvest. Thereafter berries shrank from 8.0 to 11.6%, in 1997, and from 3.0 to 6.0%, in 1998, between reaching maximum size and harvest. The differences between the two years were due to a significantly lower berry weight at harvest measured in 1997 compared with 1998.

When considering seasonal patterns of berry growth, there were statistical differences in berry size among rootstocks and crop levels. For example, in 1998 vines grafted on 1103 P reached the maximum weight of 1.05 g/berry 87 days after fruit set, while vines grafted on the other rootstocks reached peak berry weight one week later. At this stage, 1103 P berries were significantly smaller with respect to the other rootstocks (Figure 5A). Moreover, during the growing season, 1103 P generally shows smaller berry size than other rootstocks; on the contrary, 5C and 140 Ru generally show the highest value, but the differences were not always statistically significant. The effect of cropping level was generally insignificant. In particular, only 51 days after fruit set, berries of the 100% cropping treatment were significantly smaller than berries of 50% thinned vines. This difference was still present 71 days after fruit set (Figure 5B). The greatest differences between the highest and the lowest cropping levels were on 5C. Values were statistically different during most of the growing season (Figure 5C).

In 1998, sugar accumulation was more rapid in the lowest cropping treatment and slower in the highest cropping treatment. Moreover, from veraison to harvest the sugar content was statistically different among the highest cropping level and the other treatments (Figure 6A). There were significant differences in sugar content among rootstocks from veraison to about 20 days before harvest, with sugar accumulation significantly lower on 5C (Figure 6D). In all cropping treatments, the rate of sugar accumulation was initially very high (~0.7 Brix per day); it rapidly decreased for the first 30 days after veraison and then sustained a fairly constant value of about 0.2 Brix/day until harvest (Figure 6B,E). The accumulation of sugar was dramatically different among cropping treatments (Figure 6C). The differences between treatments were established primarily in the first 30 days after veraison. The final yield of sugar was ~120% greater in the 100% cropping treatment than in the 25% treatment. Sugar yielded from vines grafted on 1103 P was significantly lower than the other rootstocks; at the end of the growing season, vines on 1103 P yielded ~38% less sugar than 5C (Figure 6F).

The time required to reach a target Brix was a linear function of yield carried on the vines (Figure 7). The slope of the relationship was ~1.2 days/(t ha) in 1997 and 1.1 days/(t ha), and was similar regardless of the year and whether the target was 23.5, 24.0, or 25.0 Brix. Among rootstocks, at the highest cropping levels (100 and 75%), vines on 5C needed an additional 3 to ~8 days to reach a target value of Brix, while at the lowest cropping levels (50 and 25%) 5C needed an additional ~3 days (Table 5).

In general, the 50% and 75% thinned vines had higher TA and pH and a lighter color (sometimes significantly) than vines with higher cropping factors. Particularly, there were significant differences in TA, juice pH, and berry skin color between crop level and rootstock. Generally, TA on 5C was lower than the other rootstocks, even if this difference was significant only at lower crop levels. The pH values were significantly higher in vines grafted on 1103 P at crop levels 50%, 75%, and 100%. The comparison for crop levels within rootstocks indicated that the pH of the highest cropping level was lower in all rootstocks, but the differences were significant only within 5C, 110 R, and 140 Ru. The skin color was statistically different only on 110 R and at the highest cropping levels (Table 6).

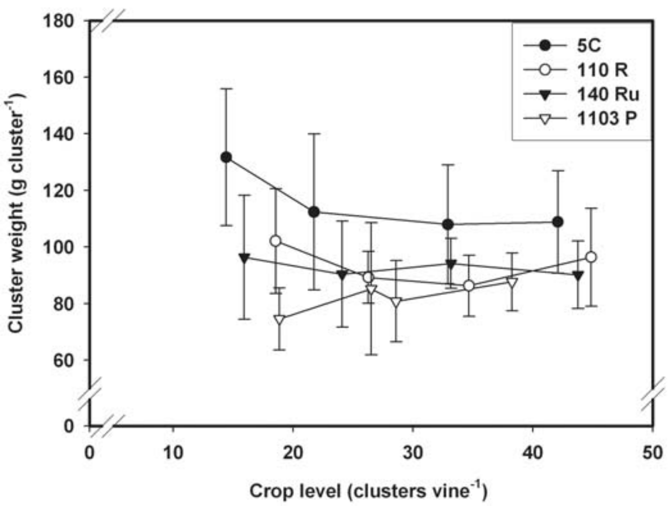

Figure 4 Cluster weight at harvest of Cabernet Sauvignon vines exposed to various cropping treatments in 1998. Cluster weight for vines on each of four rootstocks (n = 4). Cropping treatments were imposed by winter pruning to 4-bud spurs and cluster thinning at veraison to various crop levels.

Table 4 Berry size and shrinkage of dry-farmed Cabernet Sauvignon vines on four rootstocks. Data were collected when berries attained maximum fresh weight and at harvest. Shrinkage indicates loss of fresh weight between the two sample dates. Data are average ± standard deviation, n = 16.

	Berry (g) 1997			Berry (g) 1998		
Rootstock	Maximum	Harvest	Shrinkage (% of max)	Maximum	Harvest	Shrinkage (% of max)
5C	1.07 ± 0.06[a]	0.98 ± 0.08	8.0	1.11 ± 0.12	1.08 ± 0.10	3.0
110 R	1.08 ± 0.06	0.96 ± 0.08	11.6	1.12 ± 0.06	1.06 ± 0.07	6.0
140 Ru	1.14 ± 0.06	1.01 ± 0.05	11.6	1.11 ± 0.08	1.05 ± 0.07	5.5
1103 P	1.07 ± 0.07	0.96 ± 0.05	10.3	1.05 ± 0.07	1.02 ± 0.05	3.0

[a]Nonsignificant differences were not reported.

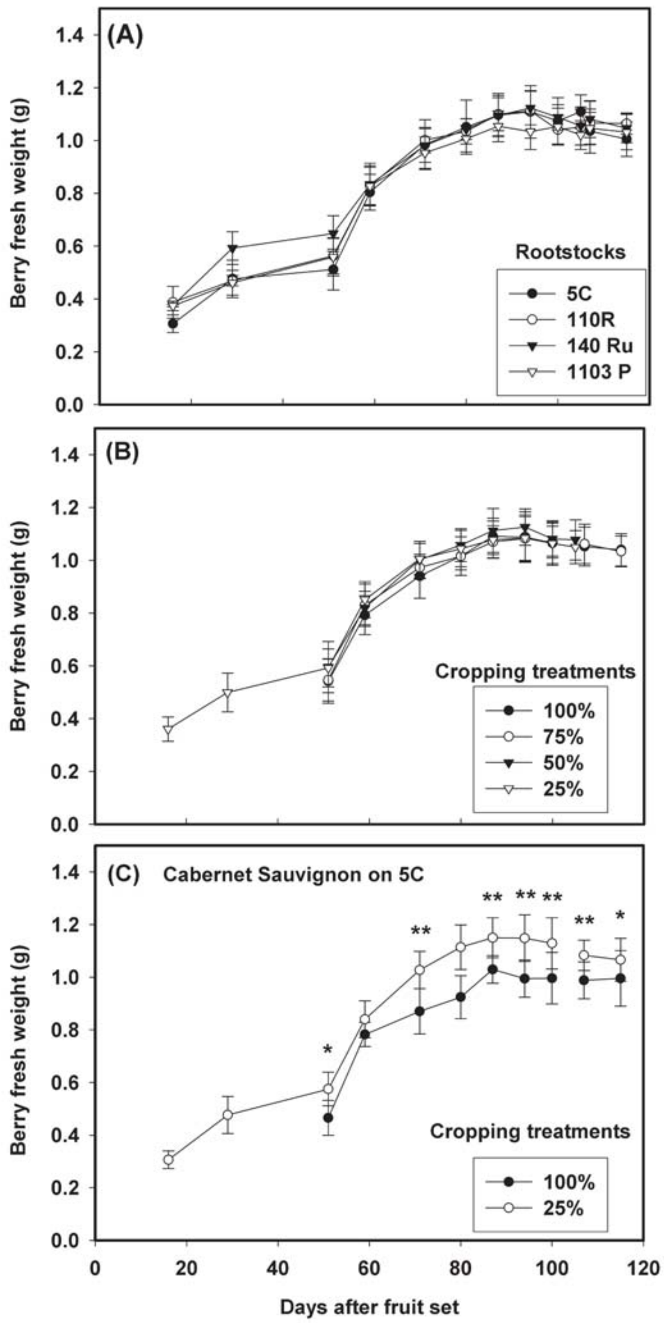

Figure 5 Berry fresh weight at different days after fruit set of Cabernet Sauvignon vines exposed to various cropping treatments in 1998. (**A**) mean berry weight across four rootstocks (n = 4); (**B**) berry weight across four cropping factors (n = 4); (**C**) berry weight for vines on 5C rootstock with two cropping treatments (n = 4). Cropping treatments were imposed by winter pruning to 4-bud spurs and cluster thinning at veraison to various crop levels. Standard crop level of vines in the area has ~25 clusters/vine corresponding to 50% thinning treatment.

Discussion

This study showed that it is possible to obtain high yields and to bring fruit to 25 Brix on dry-farmed soil in Napa Valley. Doubling the number of buds retained at pruning compared to standard practice increased yield by over 50% in each of two consecutive seasons, reaching 20.92 t/ha in 1997 in two treatments. The yield differences were closely associated with differences in clusters per vine, and there was little response of berry size to the range of crop levels imposed. The crop level treatments also had no effect on vegetative growth, but significantly affected the rate of increase in sugar concentration (Brix) in berries after veraison. The time required to reach a Brix maturity index was a linear function of the crop level. However, the slope of that relation, indicating days of maturity delay/ton of crop, was approximately 1.1 to 1.2 days/(t ha). The various rootstocks used had no significant impact on these observations.

Most Napa Valley vineyards are irrigated, presumably to avoid severe water deficits or increase yield. In our experimental conditions, high yields were obtained without severe water deficits or irrigation, although there was no significant rainfall between flowering and harvest and no irrigation water applied. There were no visible signs of severe water deficits, such as basal leaf abscission or accelerated leaf senescence, even in 1103 P where a midday LWP of -1.43 MPa was measured at harvest. Although the stored soil water was probably considerably less than the evaporative demand indicated by the cumulative ETo of 1000 and 720 mm for April through September of the 1997 and 1998 growing seasons, respectively, closer attention should be paid to the use of irrigation in these soils.

The high ETo of 1997 was driven by high temperatures. For the cultivar Cabernet Sauvignon, suitable climate regions are reportedly where accumulated GDD is normally from 1164 to 1421 (Jackson and Cherry 1988). That is considerably cooler than the Napa Valley in general (Winkler et al. 1974). From 1989 to 1998, the GDD accumulated at the Oakville site used in this study was always higher than the upper limit found in Jackson and Cherry's research, and ranged from 1447 in 1998 to 1888 in 1997. Although indicating wine quality was a factor in the climate designations, Jackson and Cherry's analysis included no data on ripening. The grouping of varieties into climate segments occurred before the index was developed, not as a result of analysis with the proposed index. In this study, fruit growth and development was similar despite having the hottest and coolest years in a decade, although harvest dates were accordingly displaced. Thus, our results show that environmental conditions—temperature and soil water content—are not limiting to the ripening of Cabernet Sauvignon at Oakville.

The standard crop level, regulated by winter pruning, is about 14 to 15 buds/m of cordon (Wolpert et al. 1996), and representative yields for Cabernet Sauvignon that is traditionally trained, pruned, and irrigated ranges from 9 to 12 t/ha in Napa County (Chapman et al. 2004, Wolpert et al. 1996, Kasimatis et al. 1985, Winkler 1969). In our experiment, we winter pruned to ~26 buds/m of cordon or per vine, or approximately double the standard. The mean yield of these vines (unthinned) was 4.4 kg/vine or 17.6 t/ha, while yield of vines thinned at the control level (50%) was ~10.3 t/ha (Table 3). Jackson and colleagues conducted pruning experiments in which the number of buds

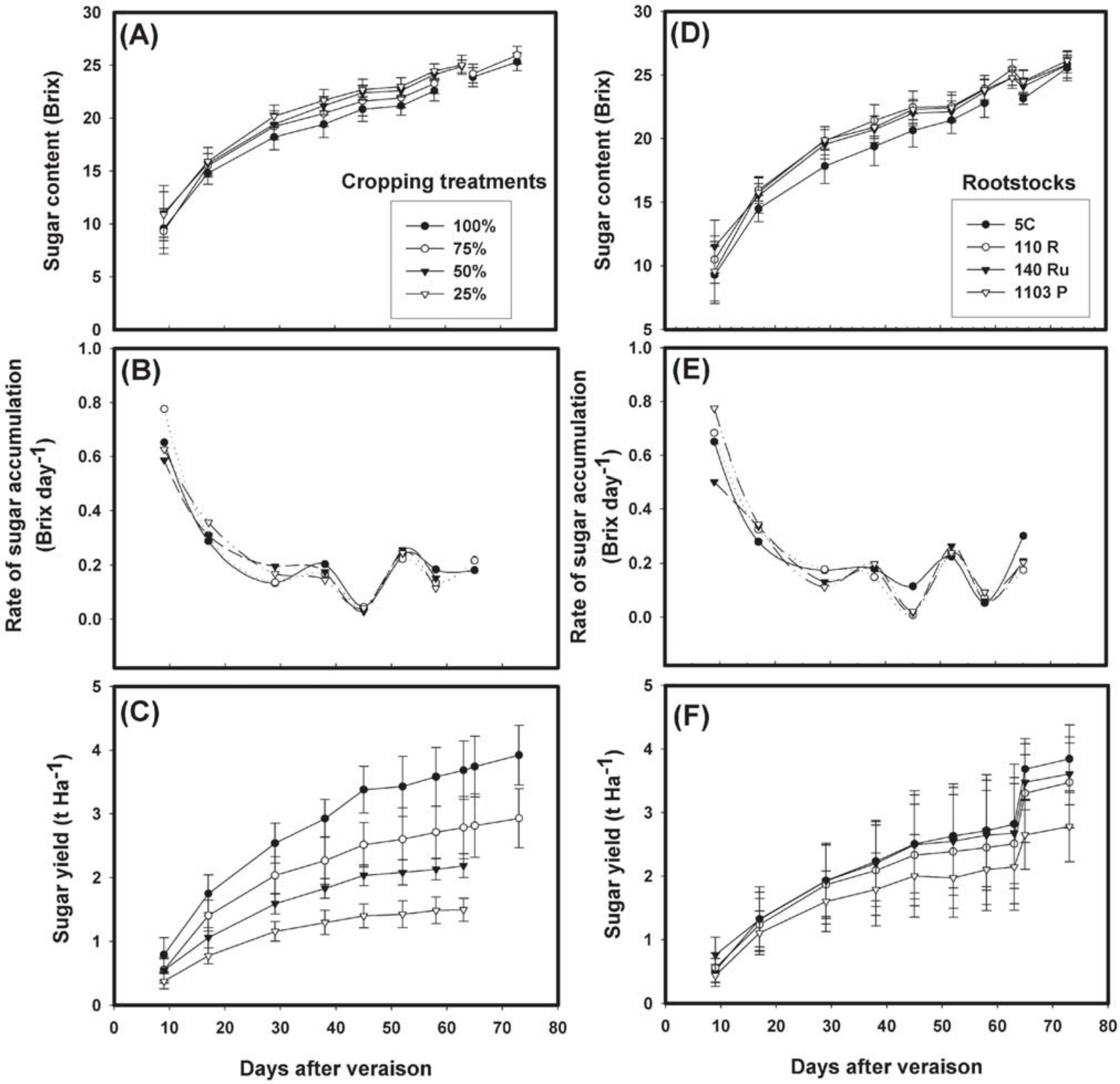

Figure 6 Sugar accumulation in fruit of Cabernet Sauvignon vines exposed to various cropping treatments (**A**, **B**, **C**) and rootstocks (**D**, **E**, **F**) during the 1998 season. (**A**, **D**) soluble solids determined by refractometry on aliquots from 50-berry samples; (**B**, **E**) rate of change of soluble solids determined as slopes of curves in **A** and **D,** respectively; (**C**, **F**) yield of hexose sugar in t ha^{-1} calculated from product of data in Fig. 5B and Fig. 6A, D. Data are means of four replications. Cropping treatments were imposed by winter pruning to 4-bud spurs and cluster thinning at veraison to various crop levels. The standard crop level of vines in the area has ~25 clusters/vine corresponding to 50% thinning treatment.

was increased to more than double our high number (over four times the standard practice), and reported no further increase in yield, that is, yield per vine in Cabernet Sauvignon was stable at four to five kg/vine even with further increases above 26 buds/m of row (Jackson et al. 1984). In a recent study where we imposed similar high bud numbers on Cabernet Sauvignon in a nearby vineyard, yields of over 20 t/ha were obtained one year, but yields did not exceed 17 t/ha the following season. Thus, the high yields that were obtained here may approach the highest that are sustainable without a divided canopy. There were slightly fewer clusters per vine in 1998 with respect to the previous year, but the effect was similar across treatments, suggesting that the decrease was not an effect of overcropping, as was observed on Alicante Bouschet (Winkler 1931).

In our experiment, the value of crop load was calculated, on vine basis, by the yield to pruning weight ratio (kg/kg) and, in 1998, by the leaf area to yield ratio (m^2/kg). Thinning whole clusters at the beginning of veraison caused a reduction in yield and in the yield/pruning weight ratio, and an increase in the leaf area/yield ratio that was proportional to the number of clusters thinned. For example, the 50% treatment retained about 58% of the clusters of the 100% treatment and produced a yield that was 56% of the yield at 100%, with no change on both as

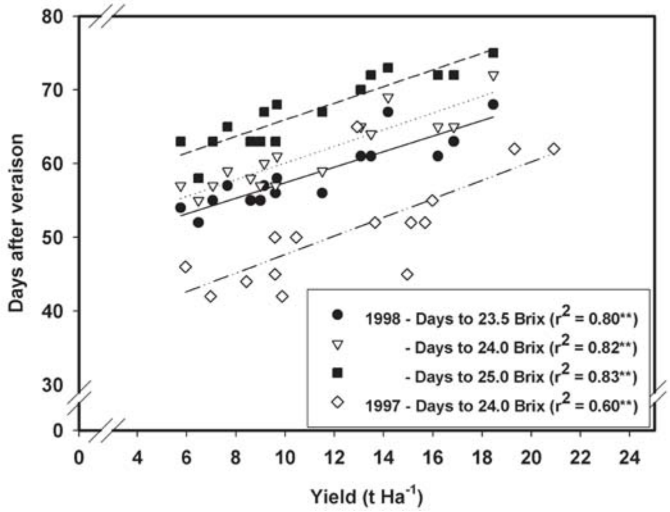

Figure 7 Harvest date (relative to veraison) for Cabernet Sauvignon vines exposed to cropping treatments that resulted in various crop yields in the two years of the trial. Cropping treatments were imposed by winter pruning to 4-bud spurs and cluster thinning at veraison. Each point is the average of four single values. Data are shown for harvest at three maturity criteria: 23.5, 24.0, 25.0 Brix. Curves represent linear regressions for each maturity criteria.

well as on leaf area per vine and weight of pruning material. The proportionally reduced yield, as first reported by Winkler (1931), indicates that most of the effects of overcropping on source-sink relationships occur early in summer when shoot growth, fruit bud differentiation, and stage I of berry growth occur.

In this study, crop load calculated as yield per pruning weight ratio for the 50% treatment gave an average value of 2.92 kg/kg over the two years of the trial. This value is lower than the ideal of 4 to 7 (Smart and Robinson 1991), but it was in the range of the values found for Cabernet Sauvignon with comparable yield per hectare (Wolpert et al. 1995, 1996). Unthinned vines have shown a yield to pruning weight ratio ~75% greater than the standard crop level of Napa Valley area (50% treatments), but it was in the range of 4 to 7 and was similar to the value found in a five-year trial for unthinned and irrigated Cabernet Sauvignon vines (Bravdo et al. 1985). Our values of the yield/pruning weight ratio, compared with "ideal" values suggested by the literature, could be referred to standard cropped vines (100% and 75% treatments) and to undercropped vines (50% and 25% treatments). The situation is

Table 5 Yield and number of days to 24.0 Brix of dry-farmed Cabernet Sauvignon vines on four rootstocks with four crop levels. Data are average ± standard deviation n = 12.

	5C		110 R		140 Ru		1103 P	
Crop level	Yield (t ha^{-1})	Days to 24 Brix	Yield (t ha^{-1})	Days to 24 Brix	Yield (t ha^{-1})	Days to 24 Brix	Yield (t ha^{-1})	Days to 24 Brix
1997								
100%	12.93±3.49 b,B[a]	65	20.92±2.47 a,A	62	20.92±1.74 a,A	62	19.32±3.20 a,A	62
75%	15.98±6.83 A	55	15.69±1.16 B	52	15.11±6.97 B	52	13.66±2.03 B	52
50%	9.59±2.18 C	50	14.96±8.72 C	45	9.59±2.03 C	45	10.46±0.87 B	50
25%	5.96±3.49 C	46	6.97±6.68 D	42	9.89±1.16 C	42	8.43±2.06 C	44
1998								
100%	18.46±5.05 a,A	72	16.85±3.50 a,A	65	16.21±3.32 a,A	65	13.48±3.28 b,A	64
75%	14.18±2.95 a,B	69	11.51±2.62 a,B	59	13.07±2.16 a,B	65	9.15±1.48 b,B	60
50%	9.67±2.67 C	61	8.60±1.28 C	58	9.61±2.77 C	57	9.00±2.46 B	57
25%	7.66±2.20 C	59	6.48±2.30 C	55	7.06±1.80 D	57	5.75±2.29 C	57

[a]Different lowercase letter indicate significant differences ($p < 0.05$) between columns (or rootstocks); different uppercase letters indicate significant differences ($p < 0.05$) between rows (or crop levels). Nonsignificant differences were not reported.

Table 6 Titratable acidity (TA), pH, and berry skin color of dry-farmed Cabernet Sauvignon grafted on four rootstocks with four crop levels. Data were collected on 12 Oct 1998 when vines subjected to 1.0 and 0.5 crop levels were harvested. Each value is an average of four single measurements.

	5C			110 R			140 Ru			1103 P		
Crop level	TA (g L^{-1})	pH	Color	TA (g L^{-1})	pH	Color	TA (g L^{-1})	pH	Color	TA (g L^{-1})	pH	Color
100%	2.56	3.48 ab,B[a]	0.73 ab	2.91	3.34 b,C	1.06 a,A	2.78	3.37 b,B	0.61 b	2.76 BC	3.64 a	0.57 b
75%	2.43	3.45 ab,B	0.80	2.67	3.44 ab,BC	0.87 AB	2.82	3.39 b,B	0.69	2.67 C	3.62 a	0.70
50%	2.58 b	3.54 b,AB	0.64	2.90 ab	3.59 ab,AB	0.60 B	3.00 ab	3.62 ab,A	0.69	3.12 a,AB	3.74 a	0.53
25%	2.42 b	3.67 A	0.69	3.03 a	3.66 A	0.66 B	3.12 a	3.70 A	0.63	3.34 a,A	3.78	0.48

[a]Different lowercase letter indicate significant differences ($p < 0.05$) between columns (or rootstock); different uppercase letters indicate significant differences ($p < 0.05$) between rows (or crop levels). Nonsignificant differences were not reported.

different when our values are compared with the values found for Cabernet Sauvignon in a similar site (Wolpert et al. 1995, 1996). In this case, our treatments showed an undercropped situation for 25% treatments, and overcropped vines for 75% and 100% treatments.

The usefulness of the leaf area/yield ratio as a measure of crop load has recently been reviewed, and the authors proposed that ~0.8 to 1.2 m^2/kg was required to fully ripen winegrapes on single-canopy type trellis systems (Kliewer and Dokoozlian 2005). Those values are lower than data presented here and suggest that even the unthinned vines could be undercropped. However, as crop load (leaf area/yield ratio) increases, the number of days from veraison to a target value of sugar concentration in the berry decreases from ~65 in the unthinned vines to 50 in the most thinned ones. A delay of about 15 days in fruit maturity should be an indication that there was a too high fruit load per leaf area in the unthinned vines compared with the most thinned vines. Moreover, we harvested the 75% and 100% treatments 20 to 30 days later (22 Oct 1998) than the standard harvest period of the area and almost at the end of the growing season. At that time leaves start senesce and drop, and accumulation of GDD reaches its peak. Unfortunately, our experiment provided no results on other physiological parameters linked to source-sink relationship (such as storage reserves and vine decline) that could be used to assess "cropping status" of vines.

In our conditions that varied sink size at veraison, berry size and composition were only slightly influenced. No compensation growth of the cluster was measured in any scion-rootstock combinations except for the most thinned vines grafted on 5C. The compensation growth measured in 25% crop level on 5C may have been due to incomplete veraison at the time of thinning in 1998. However, our cluster weight was comparable with that found in other research on Cabernet Sauvignon (Wolpert et al. 1995, 1996, Kasimatis et al. 1985, Bravdo et al. 1985, Winkler 1969).

High yield of sugar per hectare was principally obtained by producing a high number of berries per hectare. At harvest there were no statistically significant differences in sugar concentration among cropping factors and among rootstocks, while yield per hectare was significantly different among cropping factors. Sugar accumulation is delayed by heavier crop loads. In our range of yield values, 15 days was the average delay between the first and the last vines to achieve ripeness. In fact, the slope of the regression line was almost equal to one day of delay for each ton of yield to reach the target Brix level. The slope of the regression line did not change with increasing the target in Brix level to 25.0 Brix.

In all treatments, the rate of increase in Brix decreased rapidly during the first 30 days after veraison. Maximum berry size is attained during this same 30 days (Dokoozlian and Kliewer 1996, Poni et al. 1994). Thus, the rate of sugar import/berry may have been constant, indicated by a 2.3 Brix increase with each 0.1 gram increase of berry fresh weight during this period. After berry growth ceased and Brix reached 16 to 18 degrees, the rate of sugar accumulation per berry decreased. This rapid phase of sugar transport is when differences in sugar accumulation between cropping factors were established; the differences were then maintained until harvest. At the end of the growing season there was some shrinkage; at this stage, a further increase of sugar accumulation occurred at a rate of ~0.55 Brix for each 0.01 gram of decrease in berry fresh weight. This apparent accumulation may be the result of water loss and not sugar uptake.

In general, a minimum of 23.0 Brix, TA of ~5 to 7 g/L, and pH below 3.6 are required by the Napa Valley wineries for Cabernet Sauvignon grapes. Data from this experiment indicate that values occur weeks before the maximum of 25.0 Brix. Our values for TA and pH may describe fruit that will not evoke maximum sensory impact in the wine. In a trial where different crop yield levels were obtained from cluster thinning at veraison and from different bud numbers at winter pruning (Chapman et al. 2004), the authors found that veggie attributes decreased in intensity and fruity attributes increased in intensity as bud number and yield increased. In contrast, there were few sensory differences detected in wines made from the various cluster-thinning treatments, although the yield range was greater in that experiment than in the pruning experiment. They concluded that Cabernet Sauvignon aromas and flavors respond to yield manipulation, but do so significantly only when yield is altered early in fruit development.

The rootstocks produced few consistent differences in the growth and sugar accumulation parameters evaluated in this study. As also reported elsewhere, the most vigorous (1103 P and 140 Ru) tended to produce clusters with less color and higher pH and TA (Lider 1957), but the differences were not always statistically significant with respect to the less vigorous 5C and 110 R.

Conclusions

Results showed that timing of ripening in a high-yield, dry-farmed Cabernet Sauvignon vineyard can be manipulated through crop level, while the rootstocks tested had no effect on ripening. The delay in sugar accumulation seems to be a sensitive measure for crop level and does not appear to be influenced by rootstock or by environmental conditions. In both years, thinning clusters at veraison considerably reduced yield of grapes, sugar per vine, and sugar per unit of surface. The reduction in yield was only compensated by early ripening of the grapes and not by higher quality of the berries based upon standard assays of fruit composition. Since quality was not changed, production costs increased, and thus cluster removal of Cabernet Sauvignon at veraison should be carefully evaluated in the environmental conditions of Napa Valley, even in nonirrigated vineyards. We suggest that the thinning of clusters at or after veraison be considered only as a tool to control the time of picking, and we consider it to be economically profitable only when vines are substantially overcropped or noticeably stressed or when environmental conditions do not allow a growing season as long as needed to ripen the grapes.

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