Effect of Vertical Shoot-Positioned, Smart-Dyson, and Geneva Double-Curtain Training Systems on Viognier Grape and Wine Composition

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Abstract: Viognier grapes grown in northern Virginia and resultant wines were evaluated as a function of training system. Treatments included vertical shoot-positioned (VSP), Smart-Dyson (SD), and Geneva double curtain (GDC), with vines of all treatments spaced 2.4 m apart in 3.0 m wide rows. In addition to increased cluster numbers and crop yield, GDC training generally increased fruit zone sunlight interception and fruit exposure, while it decreased cane pruning weights per meter of cordon, compared with SD and VSP. Crop adjustments were made between bloom and veraison in six seasons, to result in average yields of 10.5 kg/vine (GDC), 9.9 kg/vine (SD), and 6.0 kg/vine (VSP), with the lower SD canopy bearing 30 to 40% less crop than the corresponding upper SD canopy. Crop loads (yield/cane pruning weight) were generally between 4 and 12; GDC crop load approached 20 in three seasons, while SD approached 14 in one. Leaf area per crop ratio was determined one season and exceeded 1.8 m^2/kg of fruit for all systems. Fruit was harvested at similar Brix values, with differences in berry weight, pH, titratable acidity, and malic and tartaric acids among treatments generally not significant. Volatile compounds were analyzed using headspace solid-phase microextraction GC-MS. Fruit showed consistent differences in linalool, α-terpineol, β-damascenone, and *n*-hexanol concentrations among training systems. SD had the highest concentration of most free volatiles quantified in both juice and wines, while GDC wines frequently had the highest concentration of phenol-free glycosides. Triangle difference sensory testing demonstrated differences between GDC and SD in wine aroma and flavor and between VSP and SD in flavor. GDC wines generally had higher fruity and floral aromas compared with the other systems.

Key words: Viognier, training system, volatile compounds, glycosides, wines

Substantial research has advanced our understanding of how various viticultural practices, such as crop level (McCarthy et al. 1987), crop exposure (Bergqvist et al. 2001, Zoecklein et al. 1998), leaf area to crop ratio (Kliewer and Dokoozlian 2005), and shoot density and training systems (Reynolds and Wardle 1991), affect grape and wine components, including volatile compounds and sensory response. Viognier has received relatively scant attention in this regard, yet the variety has emerged as an important white winegrape in the mid-Atlantic United States (Wolf and Warren 2000). Viognier wines have a distinctive aromatic profile, with apricot, peach, mango, melon, and tangerine descriptors. The compounds responsible for these varietal descriptors are, in part, monoterpene alcohols such as linalool and terpineol. The quantitative and qualitative balance of grape-derived volatiles is influenced by the degree of fruit ripeness, the level of solar exposure (Marais 1994, Price et al. 1995, Smart et al. 1988), and the thermal environment in which the grapes ripen (Smart 1985).

Northern Virginia's climate, like much of the mid-Atlantic, is warm and humid, with about 1900 heat units (10°C base) and 550 mm of rain measured from April to October. Coupled with fertile soils and a long growing season, vines often produce more vegetation than can be adequately presented for optimal sunlight interception with conventional (e.g., VSP) training systems. Management of excessive vigor includes repeated summer pruning, conversion to divided canopy-training systems, or application of multiple strategies to arbitrarily balance vegetative and reproductive growth. Canopy division offers a means to reduce the frequency of summer pruning and can translate to increased crop yields. The yield increase is particularly attractive, given the relatively small size of many eastern U.S. vineyards (<10 ha) and their need to increase crop production efficiency. Both winemakers and growers, however, are concerned with the real or perceived potential for overcropping vines and negatively impacting wine quality.

Aside from increased node fruitfulness and crop yields, canopy division can increase grape and wine quality by exposing a greater percentage of the canopy's leaf area to sunlight (Shaulis et al. 1966), by increasing evaporative potential, which can improve fruit rot management, and

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possibly through increased fruit and wine aromas and flavors (Reynolds et al. 1996). Sunlight exposure of fruit is profoundly affected by training system, and fruit exposure has a direct impact on the concentration of grape glycosides (Zoecklein et al. 1998, 1999). Many secondary plant products are accumulated and stored as glycosides, since glycosidic linkages between oxygen, carbon, nitrogen, and sulfur atoms of different compounds can be linked to any one sugar. Certain grape glycosides are, in part, aroma and flavor precursors, quantification of which may offer a means of determining the impact of cultural practices on potential wine quality (Williams and Francis 1996, Zoecklein et al. 2000).

This study evaluated the impact of vertical shoot-positioned (VSP), Smart-Dyson (SD), and Geneva double-curtain (GDC) training systems on Viognier fruit, and on wine composition and sensory characteristics in the humid environment of northern Virginia. An underlying hypothesis was that canopy division could be used to increase crop per vineyard area above that of the more conventionally used VSP single-curtain canopies and that crops could be increased without compromising grape and wine quality potential.

Materials and Methods

Viognier (*Vitis vinifera* L.) was grown on three different training systems in Winchester, Virginia (39°12’N). The Viognier clone was obtained from La Jota vineyards (Angwin, CA), which had obtained bud wood in the early 1980s from the New York State Agricultural Experiment Station in Geneva, NY (W. Smith, personal communication, 2006). The New York selection originated in Bordeaux, France, as clone #12 and was previously evaluated at Winchester (Wolf and Warren 2000). Vines were grafted to C-3309 rootstock and planted in 1998. Winchester’s macroclimate is typified as warm, humid, and continental. Mean monthly precipitation from April through October is 81 mm, with ~1900 (10°C base) accumulated heat units for that period and a mean relative humidity of 75% in September. An automated weather station on-site was used to collect temperature and rainfall data during the study.

Soil was a Frederick-Poplimento loam, with an effective rooting depth greater than 100 cm. Vines were not irrigated and were subject to pest management and other general cultural practices routinely used in the region. Comparisons were made of two divided canopy systems (Geneva double curtain [GDC] and Smart-Dyson [SD]) and the “standard,” nondivided vertical shoot-positioned (VSP). SD represents a vertically divided canopy with the upper canopy confined between paired foliage wires, as with VSP. Shoots of the lower SD canopy originated from the same cordon as the upper canopy shoots and were manually positioned downward and held in that vertical position with the aid of a single foliage wire. GDC is a horizontally divided canopy with shoots oriented downward from cordons spaced 1.2 m apart. Manual shoot-positioning was performed at least twice each season to maintain two discrete canopies per vine. All three training systems used bilateral, cordon-training, and spur-pruning, with the VSP and SD cordons positioned 1.1 m aboveground and the GDC cordons positioned ~1.7 m aboveground. Rows were oriented 45°/225° from north, and row spacing was 3.05 m, with vine spacing of 2.44 m for all training systems.

Vines were established in three-vine plots, with each training system having three replicates that spanned three rows. The experimental treatments were designed and established as a split-plot, randomized, complete block design with the three training systems as main plots and four varieties as subplots. Since the focus of this research was effects of training on Viognier fruit and wine composition, the viticultural response data that might impact fruit and wine composition were analyzed as a randomized complete block design using the PROC MIXED procedures of SAS version 9.1 (SAS Institute, Cary, NC), with blocks as the random component. Treatment means were evaluated for statistical differences with the least squares mean separation procedure. The SD training was evaluated in one of two methods. Although the upper and lower SD canopies are not independent treatments, response means for these two canopies were occasionally compared to other systems as independent treatments, when the interest was in specific components of yield (e.g., berry weight) or fruit chemistry. Means comparisons with some responses (e.g., crop per meter of cordon) were based on the sum or averages obtained from the two SD canopies. (The effects of training on fruitfulness, shoot periderm development, bud necrosis, and dormant bud cold hardiness will be addressed in a separate communication.)

Shoots were thinned shortly after flower cluster counts were done in the spring to ~12 shoots/m of cordon for the VSP, GDC, and the upper canopy of the SD, while the lower SD canopy was thinned to ~9 shoots/m. Crops were further regulated, as shoot thinning alone was insufficient to maintain crops within our targeted crop ranges (~7 to 10 t/ha for VSP and ~15 t/ha for GDC and SD). In addition to shoot thinning, canopy management included shoot positioning with all systems and shoot hedging with the VSP and upper SD canopies to retain ~17 primary nodes per shoot. Shoot tipping was done, if necessary, with the GDC and lower SD canopies to prevent equipment tires from pulling shoots from the vine. Minimal leaf and summer lateral removal from the more easterly side of fruit zones was done between fruit set and veraison to maintain one or two leaf layers in the fruit zone. Leaf area was measured in 2004 by removing two shoots per vine (six per plot) about 80 days postbloom and determining the area of primary and lateral leaves with a belt-type area meter (model LI-3000; LI-COR, Lincoln, NE). The average leaf area per shoot was then multiplied by the total number of shoots per vine to estimate primary, secondary, and total leaf area per vine. Canopy measures of photosynthetically active radiation (PAR, 400-700 nm) were made each year shortly before veraison, using an AccuPAR ceptometer (model PAR80, Decagon Devices, Cambridge, UK). Three canopy interior readings of PAR were taken in each treatment plot within two hours of solar noon on uniformly sunny or hazy days. Each reading consisted of three ceptometer sensing plane orientations: 90°E, 0°, and 90°W, with the ceptometer positioned just above and parallel to the cordon. Readings from the three ceptometer orientations were averaged for a single interior reading. Additional PAR readings were taken outside canopies at cordon height of each plot to determine ambient PAR. Insolation was then expressed as the percentage of available PAR measured within the vine canopy.

Grape harvest date was predicated upon attainment of varietal aroma and flavor in juice and the constraints of impending weather conditions. To the extent possible, all training systems were harvested within 1.0 Brix of each other, even if it required harvesting on different dates, as was the case in 2005. Prior to harvest, 50-berry samples were randomly collected by treatment replicate for determining berry weights and fruit chemistry. Components of crop yield were obtained at harvest and included clusters per vine, crop weight per vine, berry weight, and berries per cluster. Separate data were collected for the upper and lower canopies of the SD-trained vines. Cane pruning weights were obtained by vine in the dormant periods and were used with crop per vine to calculate crop loads.

Wine was made at Virginia Tech's research winery in Blacksburg, Virginia, using standard vinification procedures. Equal weights (average 68.5 kg) of treatment lots were processed each season. Chilled fruit (10°C) was whole-cluster pressed in a Willmes 100-L bladder press (model TP-100; Bensheim, Hessen, Germany) to 1.7 bar, and 16 µL/L pectic enzyme (Cinn-Free; Scott Labs, Petaluma, CA) added. Juice was settled for 24 hr at 7°C and racked into 19-L glass carboys in duplicate lots of 9.4 L of must per training system. Fermentation was conducted using 238 mg/L *Saccharomyces cerevisiae* (VL-1 yeast; Laffort Enologie, Bordeaux), 238 mg/L Fermaid K (Lallemand, Montréal, Québec), and 298 mg/L Go-Ferm (Lallemand). Fermentation temperatures averaged 16°C, and rates were monitored daily by measuring changes in degrees Brix. After completion of fermentation, wines were settled for 4 days at 7°C, racked into 3.8-L glass carboys, and stored at 7°C. Wines produced in 2005 were retained with 3.5 g/L reducing sugar.

Berry samples were crushed for 1 sec in a commercial laboratory blender (model 31 BL 91; Waring, New Hartford, CT) and placed in a filter bag (model 400; Steward Stomacher Lab Systems, London), and juice expressed. The juice was filtered through a 0.45-µm syringe filter (25 mm GD/X; Whatman, Florham Park, NJ) for subsequent chemical analyses. Juice Brix was measured using a handheld refractometer (model 10430; American Optical Scientific Instruments, Keene, NH), pH with an Accumet pH meter (model 20; Fisher Scientific, Pittsburgh, PA), and titratable acidity (g/L tartaric acid) and % alcohol (v/v) analyses were conducted as described elsewhere (Zoecklein et al. 1999). Fermentable nitrogen was determined as described elsewhere (Gump et al. 2002). Samples were taken three weeks postfermentation and absorbance at 280, 320, 420, and 520 nm was determined using a Genesys 5 spectrophotometer (Spectronic Instruments Inc., Rochester, NY).

Total juice, skin, and wine glycosides were determined using the analysis of glycosyl-glucose as described elsewhere (Williams et al. 1995) and further modified (Zoecklein et al. 2000, Whiton and Zoecklein 2002), using a Labsystems Multiskan microplate reader (model MCC/340; Fisher Scientific) at 340 nm. Fifty-berry samples for total skin glycosides were prepared by removing all pulp from the skins. A 1.0 g sample of skins was placed in a Waring commercial laboratory blender (model 31 BL 91) with 10 mL 50% ethanol and blended for 30 sec. An additional 10 mL of 50% ethanol was used to rinse the blender jar and combined with the macerate. Skins were extracted in ethanol for 1 hr, after which the supernatant was removed and filtered through a 0.45-µm filter, adjusted to pH 2.25, and passed through a Strata C18-T solid-phase extraction column (Phenomenex, Torrance, CA).

Free juice and wine volatiles were analyzed using solid-phase microextraction, gas chromatography-mass spectrophotometry, as described elsewhere (Whiton and Zoecklein 2000) using a model 5890 GC, model 5972 mass selective detector (Hewlett Packard, Palo Alto, CA), and a Carbowax 65-µm fiber (Supelco, Bellefonte, PA). A means comparison between training systems was performed for each test, with one-way ANOVA, least significant difference (LSD), and/or Tukey-Kramer HSD pairwise comparison, using JMP statistical software (SAS Institute, Cary, NC).

Sensory analysis was performed on pooled Viognier wine treatment replicates five to six months postfermentation using triangle difference testing (Meilgaard et al. 1999). All wines submitted for sensory analysis were prescreened for the presence of sulfur off-odor compounds. A consumer panel evaluated wine aroma and retronasal aroma (hereinafter referred to as flavor) separately, using randomized coded samples within isolated booths under standard conditions (Meilgaard et al. 1999). Evaluations were conducted using 20 mL wine at 17°C in clear ISO wineglasses. Wines were tested under white lighting in 2001 and 2002 and red lighting in 2003, when there were measurable color differences. Difference testing was performed using nine groups of six panelists each, with no more than six wines per flight. Panel membership required only that participants were regular wine consumers (consumed wine at least once per week) and that they attend three general wine orientation sessions. For each evaluation session, panelists were given 10 min to determine aroma differences and 10 min to determine flavor differences, with a 5-min break between, using different sample sets for aroma and flavor. Evaluations were conducted every half hour, and panelists could not participate in consecutive sessions. This test had an α-level of 0.05, a β-level of 0.1, p_d = 30%, and a sample size of 54 per testing.

Descriptive analysis was performed on pooled wine treatment replicates in 2003 to 2005 using 11 trained panelists (nine female and two male), according to established procedures (Meilgaard et al. 1999). Twenty-five mL of wine at 20°C was presented in standard ISO wineglasses under standard conditions to panel members who evaluated each treatment three times. All evaluations were done 6 to 7 months postfermentation on randomized coded samples within isolated booths. Evaluators were requested to rate the intensity of aroma and flavor, as well as tastes and the tactile descriptor *astringency*, using a 10-cm unstructured line score sheet anchored at each end. Panelists had one to 10 years experience in descriptive sensory analysis. A list of descriptors was developed from three preevaluation training sessions and included aromatic, fruity, sulfur, vegetative, geranium, woody, brown spice, sweet vanilla, fusel oil, sweet, sour, astringent, bitter, and alcohol. At the start of the testing, panelists received a reference sample for calibration purposes. Six samples were served each session with 24 hr between sessions.

Results and Discussion

Crop yield and crop loads. Smart-Dyson-trained vines consistently produced the greatest yields per meter of cordon (Figure 1A), with VSP and GDC substantially lower but comparable to each other. The increased productivity per meter of cordon with SD training was not unexpected and resulted from increased shoots (upper and lower canopy) originating from a common cordon. Yield per vine was similar for GDC and SD, both of which were typically much greater than VSP (Figure 1B). Greatest VSP yields occurred in 2002 and 2005, when average cluster weights (202 and 230 g, respectively, Table 1), exceeded the six-year (2000 to 2005) average of 158 g.

The yield responses reported here were somewhat manipulated. Flower clusters per shoot were counted each year before bloom and crop was adjusted in a two-part process of shoot thinning and, if needed, cluster thinning postbloom to target the desired crop levels. The level of cluster thinning was generally minimal; however, GDC vines in particular generally exhibited increased fruitfulness (shoots/node and clusters/shoot) and, consequently, required more attention to both shoot thinning and follow-up cluster thinning. Details on fruitfulness will be reported separately.

Except for the 2003 season, in which VSP vines had pruning weights of 0.30 kg/m of cordon, SD and VSP vines consistently had cane pruning weights well in excess of the 0.3 kg/m cordon used as a lower threshold recommended (Smart 1985) for acceptable crop yields and crop quality (Figure 2). GDC vines, by contrast, had much lower cane-pruning weights, often at or below 0.20 kg/m of cordon, which reflected a smaller individual cane mass due, in part, to smaller diameter but also to fewer “ripe” nodes (nodes that bore visibly well-matured periderm) in the fall (data not shown). The leaves of downward-oriented shoots exhibit altered gas exchange, compared with upright-growing shoots, which may account for differences in cane mass and cane maturation (Schubert et al. 1995). The devigorating effect of downward shoot training was also evident in the leaf area measures in 2004 (Table 2). For example, the area of a single primary leaf of GDC vines averaged only 116 cm^2, 28% smaller than the average primary leaf on VSP vines. The average primary single leaf area of the lower SD canopy was even smaller. The reduced leaf area of downward-oriented shoots is similar to responses observed with Cabernet Sauvignon (Kliewer et al. 1989).

Shoots of all three training systems bore greater secondary leaf area on lateral shoots than they did primary leaf area (Table 2). The lateral leaf area reflects the growth potential of vines in environments where soil moisture is a nonlimiting resource. Fully expanded leaves of lateral shoots are an important source of carbohydrates during the final fruit ripening period. Lateral development was greatest on the upright growing shoots (VSP and upper SD) of the systems used here and comprised ~70% of the measured leaf area of those systems.

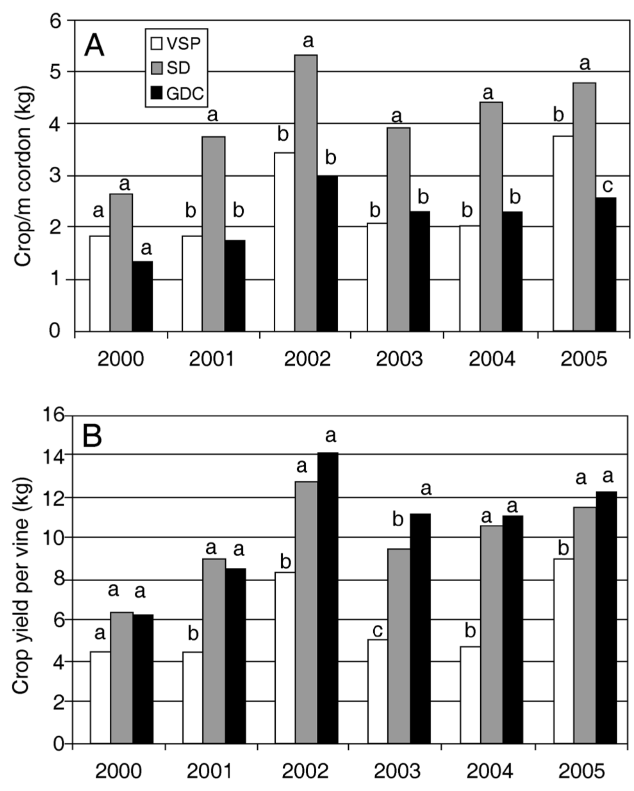

Figure 1 Viognier crop yield per meter of cordon (**A**) and crop yield per vine (**B**) as affected by Geneva double curtain (GDC), Smart-Dyson (SD) combined canopies, and vertical shoot-positioned (VSP) training, 2001–2005. Values of bars topped by common letters within a year were not significantly ($p \leq 0.05$) different. Values of bars topped by different letters are significantly different.

Table 1 Effect of training system on Viognier berry parameters at harvest, 2002–2005.

Year/ training[a]	Berry wt (g)	Berry per cluster	Cluster wt (g)	Cluster per vine	Brix	pH	TA (g/L)	Malic acid (g/L)
2002								
VSP	1.78a[b]	120.6a	201.9a	41.4c	22.6a	3.96a	5.13a	5.48a
SD-Up	1.75ab	126.1a	202.3a	37.2sn	22.8a	3.88a	4.54a	4.65b
SD-Down	1.65ab	124.9a	195.1a	27.2sn	23.9a	3.89a	5.15a	5.03ab
SD	1.70ab	125.5sn[c]	198.7sn	64.4b	23.5a	3.89a	4.81a	4.84b
GDC	1.61b	121.6a	195.0a	71.8a	22.8a	3.92a	5.00a	5.01ab
2003								
VSP	1.78a	73.8b	131.5bc	38.2c	19.9a	3.85ab	6.28a	7.00a
SD-Up	1.79a	86.4a	155.8ab	39.1sn	20.1a	3.74b	5.73b	6.17b
SD-Down	1.76a	90.7a	160.0a	20.7sn	20.3a	3.87a	5.58b	6.25ab
SD	1.78a	81.7sn	157.9sn	59.8b	20.2a	3.80ab	5.66b	6.21b
GDC	1.79a	82.8ab	153.5ab	72.7a	20.2a	3.91a	5.94ab	6.65ab
2004								
VSP	1.93a	90.4a	181.6a	25.6b	22.0a	3.96a	5.06a	5.68a
SD-Up	2.03a	94.1a	194.1a	32.0sn	21.9a	3.84a	4.88a	4.95a
SD-Down	1.93a	107.4a	202.6a	21.6sn	22.3a	3.91a	4.83a	4.92a
SD	1.98a	100.7sn	198.4sn	53.6a	22.1a	3.88a	4.85a	4.94a
GDC	1.95a	99.8a	198.6a	55.0a	22.1a	3.90a	4.85a	5.01a
2005								
VSP	1.83a	125.5b	230.4ab	39.2b	23.5a	nd[d]	nd	nd
SD-Up	1.78a	140.2ab	246.1ab	32.1sn	24.0a	3.75ab	4.35a	2.32b
SD-Down	1.59a	137.9ab	222.4b	16.0sn	24.2a	3.72b	4.60a	2.07b
SD	1.56sn	139.0sn	234.2sn	48.1a	23.6sn	3.73sn	4.50sn	2.17sn
GDC	1.63a	156.1a	255.4a	47.8a	24.0a	3.79a	4.77a	2.72a

[a]VSP: vertical shoot-positioned; SD-Up: Smart-Dyson upper canopy; SD-Down: SD lower canopy; SD: SD combined canopies; GDC: Geneva double curtain.
[b]Different letters down columns indicate significance at $\alpha = 0.05$.
[c]sn: statistical analysis not conducted; see Materials and Methods.
[d]nd: not determined.

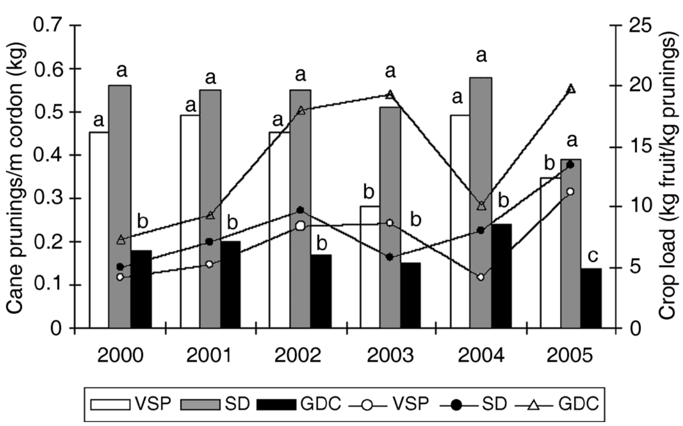

Figure 2 Cane pruning weights per meter of cordon (bars and left axis) and crop load (lines and right axis) for Viognier trained to Geneva double curtain (GDC), Smart-Dyson (SD) combined canopies, and vertical shoot-positioned (VSP) over six seasons. Values of bars topped by different letters are significantly ($p \leq 0.05$) different. Crop load values (lines) of VSP and SD were statistically similar and significantly lower than crop load values of GDC vines in all years except 2004, when only GDC and VSP vines differed from each other.

Crop loads (kg crop/kg cane pruning weight) ranged from 4 to 13 with VSP and SD and were close to 20 for GDC vines in 2002, 2003, and 2005 (Figure 2). A generally accepted crop load range is 5 to 10, but that range may vary with environment, cultivar, and training system, and a slightly greater range of 4 to 12 was proposed under some conditions (Bravdo et al. 1985). The relatively high crop loads in 2005 reflected high crop levels (Figure 1B) as well as a relatively dry growing season (Table 3) and reduced pruning weights. Overcropping has been defined as a deficiency of leaf area to a corresponding fruit weight (Buttrose 1968). Generally, the leaf area per fruit weight ratio, below which fruit sugar accumulation is measurably retarded, is between 0.7 and 1.0 m^2/kg (Kliewer and Antcliff 1970, Smart 1985). Other researchers have suggested that greater leaf area to crop ratios might be necessary to optimize aroma and flavor in hot or drought-prone conditions (McCarthy et al. 1987). In California's Napa Valley, a lower leaf area to crop ratio (~0.5 to 0.8 m^2/kg) was necessary to mature divided-canopy Cabernet Sauvignon and Chenin blanc crops than

Table 2 Shoots per meter of cordon, individual primary leaf size, primary leaf area (LA), lateral leaf area, total leaf area, and total leaf area per fruit weight (FW) of Viognier vine training in 2004.

Training[a]	Shoot/m	Individual primary leaf size (cm^2)	Primary LA (m^2)/m	Lateral LA (m^2)/m	Total LA (m^2)/m	Total LA/FW (m^2/kg)
VSP	12.9b[c]	159.97a	2.04b	4.87ab	6.91ab	3.50a
SD-Up	12.6sn	132.25sn	1.81sn	3.43sn	5.23sn	2.24sn
SD-Down	9.9sn[d]	110.06sn	1.36sn	1.63sn	2.99sn	1.78sn
SD-C[b]	22.6a	121.15b	3.16a	5.06a	8.23a	2.01b
GDC	10.3c	116.34b	2.05b	2.66b	4.72b	1.86b

[a]VSP: vertical shoot-positioned; SD-Up: Smart-Dyson upper canopy; SD-Down: SD lower canopy; SD-C: SD combined canopies; GDC: Geneva double curtain.
[b]Only the SD-C data were statistically compared to other training systems.
[c]Means within columns that are followed by the same letter are not significantly different at $p \leq 0.05$.
[d]sn: statistical analysis not conducted; see Materials and Methods.

Table 3 Harvest dates, heat summation, days exceeding 22°C and precipitation for the last 30 days before Viognier fruit harvest in 2001 to 2005 for vertical shoot-positioned (VSP), Smart-Dyson (SD), and Geneva double-curtain (GDC) training systems.

		Heat summation (10°C base)			
Year	Harvest date	Apr–Oct inclusive	Last 30 days before harvest	Days in last 30 that temp exceeded 22°C	Precipitation (mm) in last 30 days
2001	14 Sep	1803	378	30	39
2002	12 Sep	1927	379	27	31
2003	8 Oct	1706	176	13	142
2004	13 Sep	2034	391	29	125
2005	[a]	2074	371	30	46

[a]20 Sep (VSP); 14-22 Sep (SD); 16 Sep (GDC).

Table 4 Effect of training system on the percentage of available photosynthetically active radiation (PAR) in the Viognier canopy fruiting zones 80 days postbloom, 2001–2004.

	% of available PAR in fruit zones			
Training[a]	6 Aug 2001	2 Aug 2002	14 Aug 2003	9 Aug 2004
VSP	4.2a[b]	2.3b	7.2b	2.2b
SD-Up	6.1a	2.9b	10.3b	2.6b
SD-Down	9.7a	2.8b	23.2a	7.6ab
GDC	9.8a	12.9b	7.2b	2.2b

[a]VSP: vertical shoot-positioned; SD-Up: Smart-Dyson upper canopy; SD-Down: SD lower canopy; GDC: Geneva double curtain.
[b]Means within columns that are followed by the same letter are not significantly different at $p \leq 0.05$. Values are means of three readings per plot, replicated three times.

was necessary to mature single-canopy-trained crops (0.8 to 1.4 m^2/kg) (Kliewer and Dokoozlian 2005). Divided canopies have a greater percentage of their leaf area at light saturation, compared with single-canopy systems.

Canopy characteristics. All three training systems had a surplus of leaf area when expressed on a leaf area to crop ratio (Table 2), and GDC had the least leaf area per crop ratio (~1.9 m^2/kg). Leaf area was measured only in 2004; however, counts of shoots per vine and ripe or mature nodes per shoot, collected in other years as part of a cold-hardiness evaluation, together with a visual assessment of canopies suggested that the 2004 canopies were generally representative of leaf area in other years of the study. Sunlight levels measured in canopy fruiting zones around veraison varied somewhat as a function of training system, with greatest light levels generally measured with GDC or the lower canopy of SD-trained vines (Table 4). Increased light penetration of the fruit zone is an established response to GDC training (Shaulis et al. 1966) and one that corresponded to increased clusters per shoot in this study (data not shown). The greater light levels within the lower SD canopy (SD-Down) likely resulted from a decreased shoot density. The lower SD canopy typically had between one-half and two-thirds the number of shoots borne on the corresponding upper canopy (SD-Up), although the average was closer to three-fourths in 2004 (Table 2).

Canopy transects made close to veraison in 2002 and 2003 reinforced a visual assessment of acceptable canopy architecture: leaf layer numbers were between one and two, fruit exposure ranged from 43 to 85%, and canopy gaps were present, although perhaps fewer than optimal. As with PAR levels, SD-Down canopy had an increased proportion of exposed fruit clusters, compared with the corresponding SD-Up and VSP canopies. GDC training also increased cluster exposure in 2002, but not in 2003.

Within each year, fruit was harvested at the same relative degrees Brix among treatments (Table 1). Unripe Viognier has a neutral aromatic profile somewhat reminiscent of unripe Sauvignon blanc, with grassy, herbal characteristics. While fruit in this study was generally harvested at Brix values lower than reported in some regions, varietal aroma was evident. Differences in berry weight, titratable acidity, and tartaric acids among treatments generally were not significant. The exception was pH in 2003 and 2005. Although increases in berry and leaf exposure can increase malic acid respiration (Morrison and Noble 1990), no differences in malic acid were noted at harvest in this study. The exception was a higher concentration in GDC fruit compared with SD fruit in 2005.

Fruit glycosides. The greatest concentration of total glycosides in berry skins at harvest was generally found

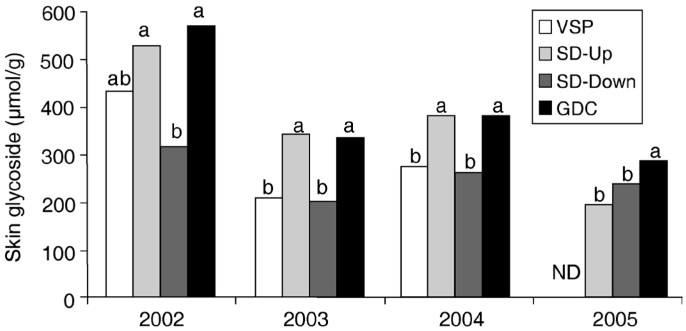

Figure 3 Effect of Geneva double curtain (GDC), Smart-Dyson (SD) Down or Up, and vertical shoot-positioned (VSP) training on Viognier skin glycosides (µmol glycosyl glucose per gram of fresh fruit weight), 2002–2005 (ND: not determined).

Table 5 Effect of training system on Viognier point quadrat analysis, 2002 and 2003.

	22 Jul 2002			4-5 Aug 2003		
Training[a]	**Leaf layers**	**% exposed fruit**	**Gaps**	**Leaf layers**	**% exposed fruit**	**Gaps**
VSP	2.06a[b]	51.3cd	1.6a	1.38a	63.6a	11.1a
SD-Up	2.08a	52.9bc	3.2a	1.24a	67.3a	11.1a
SD-Down	1.89ab	80.6ab	6.3a	1.32a	84.6a	9.5a
GDC	1.32b	85.3a	11.1a	1.86a	43.4a	4.8a

[a]VSP: vertical shoot-positioned; SD-Up: Smart-Dyson upper canopy; SD-Down: SD lower canopy; GDC: Geneva double curtain.
[b]Means within columns that are followed by the same letter are not significantly different at $p \leq 0.05$.

in SD-Up and GDC systems, the exception being 2005 (Figure 3). Glycosylation is thought to be a means of energy storage and translocation because of enhanced water solubility. Hydrolysis yields aglycones of varied composition including aliphatic compounds, monoterpenes, norisoprenoids, and shikimic acid metabolites, some of which may contribute to wine aroma/flavor and mouthfeel (Williams et al. 1995). Thus, glycoside quantification may act as an indicator of overall aroma/flavor production (Williams et al. 1995, Iland et al. 1996).

The concentration of berry skin glycosides for all treatments was highest in 2002, a season like 2005, associated with comparatively high Brix values. In contrast, the relatively cool, wet ripening month of 2003 followed a wet growing season, delayed harvest by almost one month (Table 3), and resulted in lower fruit Brix (Table 1) and glycoside concentrations (Figure 3). Although increases in fruit glycosides accompany increases in photosynthetic activity, differences among treatments within a season cannot be attributed to differences in degrees Brix, as treatments were harvested at comparable Brix levels. The confounding influences of exposed leaf area, sunlight interception, temperature, and leaf area per crop ratio on fruit glycosides may have collectively contributed to the treatment effects observed in this study.

Higher levels of fruit-zone light interception, and possibly a greater percentage of light-saturated leaves in the divided canopy systems versus VSP (Table 5), may have favored fruit glycoside production. Fruit cluster light exposure has been reported to affect terpene glycosides (Reynolds and Wardle 1993) and color (anthocyanin glycoside) production (Kliewer 1970). Fruit zone PAR was generally observed to be highest in GDC and SD-Down (Table 4), but averaged less than 12% of ambient. Maximum Pinot noir color accumulation has been reported at light intensities of less than 18% of ambient (Dokoozlian 1990), yet Cabernet Sauvignon color was almost as high at 20% sunlight interception as it was at 100% (Keller and Hrazdina 1998). In the current study, measures of PAR were a snapshot in time, in the sense of seasonal/diurnal exposure, and estimated only the relative sunlight penetration in the fruit zone near solar noon at veraison. The VSP and SD-Up canopies may have had more total irradiance in the fruit zones in the hours before and after solar noon because of their particular canopy configurations.

The temperature range for biosynthesis pathways, including glycosylation, is between 17 and 26°C (Pirie 1977). While not monitored in the current study, fruit temperature would be expected to correlate positively with solar exposure (Smart 1985). For example, in sun-exposed Riesling berries there was an increase in total glycosides above shaded fruit of 0.14 µmol per berry (Zoecklein et al. 1998), while Lee (1997) reported the phenolic quercetin-3-glucoside in exposed fruit was ~0.1 µmol per berry higher than in shaded fruit. Similarly, quercetin glycoside concentration of Pinot noir grape skins was 10-fold higher in sun-exposed than in shaded skins (Price et al. 1995) and two to three times greater in exposed versus shaded Shiraz bunches (Haselgrove et al. 2000). Quercetin glycosides may contribute to mouthfeel, but not likely to aroma/flavor. However, they could account for much of the increased glycosides observed with canopy division in the current study. It is also possible that other, yet-unidentified glycosides may have responded to fruit exposure. For example, various bound norisoprenoids were significantly higher in exposed, compared with shaded fruit, and in hot, compared with cool regions, possibly as a result of carotenoid breakdown (Marais et al. 1992).

The concentration of fruit glycosides was positively correlated with fruit yield per vine. Average GDC and SD crop yields were 45% greater than those of VSP vines. Despite significant increased crop yield, the glycoside concentration was greater in the divided canopies than in VSP, possibly because of a greater percentage of divided canopy leaves at light saturation. It has been suggested that a leaf area per fruit weight ratio (LA/FW) greater than 1.0 m^2/kg may be necessary to optimize the production of secondary metabolites (McCarthy et al. 1987). Bunch-thinning of Shiraz increased LA/FW 25%, resulting in a 16% increase in fruit glycoside concentration (Iland et al. 1996). In estimating the optimum range of LA/FW for Tokay vines, Kliewer and Weaver (1971) acknowledged that such a value is specific to cultivar, climatic region, cultural practices, and the method used to estimate total leaf area per vine. Likely, the level of foliage exposure is an important factor. In 2004, SD-Down, SD-Up, and GDC collectively averaged 1.95 m^2/kg, but VSP was twice as high. The greater light levels within the lower SD canopy, due in part to decreased shoot density and leaf area, increased the proportion of exposed fruit clusters compared with SD-Up. Thus, while leaf area to crop ratios may influence fruit glycoside concentrations, the greater influence may be due to fruit exposure, as all training systems had a surplus of leaf area to crop, at least by published standards. Most importantly, we found no evidence that the higher crops of the divided-canopy training systems negatively affected fruit glycoside concentrations.

Wine chemistry. Minor differences in alcohol, pH, titratable acidity, and organic acids were noted among treatments (Table 6). The relatively low yield, high light levels and exposed fruit clusters within the lower SD canopy may have contributed to the relatively higher wine alcohol concentrations frequently noted. Malic acid concentrations in the wine tended to be lower in SD-Down, but not consistently. Differences in wine absorbance at 280, 360, 420, and 520 nm were generally not significant (data not shown).

Wine glycosides. Total wine glycosides did not demonstrate a consistent treatment effect (Figure 4). Wine glycoside concentration would be expected to be a function of fruit composition, extraction, and hydrolysis (Williams et al. 1995). While variations in skin-to-pulp ratio could impact concentration of secondary metabolites (Kliewer and Lider 1968), including glycosides, differences in berry weights were not noted in this study. Concentration of phenol-free wine glycosides represented an average of 37% of the total, consistent with previous reports (Zoecklein et al. 1998), but was not consistently affected by treatment (data not shown).

Juice and wine volatiles. Juice and wine aroma and flavor are the result of a plethora of volatile compounds, often present in minute concentrations (Williams and Allen 1996). Analysis of selected juice volatiles for the 2002 and 2003 vintage, typical of this study, demonstrated elevated levels of linalool, α-terpineol, and β-damascenone in SD-Up (Figure 5), compared with other treatments. Many conjugated secondary metabolites, such as the monoterpene alcohols, are in a constant cycle of formation, accumulation, conjugation, and limited hydro-

Table 6 Effect of training system on pH, titratable acidity (TA), malic acid, and tartaric acid in Viognier wine, 2002–2005.

Year/ training[a]	Alcohol (%, v/v)	pH	TA (g/L)	Malic acid (g/L)	Tartaric acid (g/L)
2002					
VSP	14.40ab[b]	3.25c	6.47a	2.73a	2.10a
SD-Up	13.90b	3.38ab	6.24ab	2.37a	2.26a
SD-Down	15.00a	3.46a	5.62b	2.48a	1.57b
GDC	14.30ab	3.32bc	6.11ab	2.54a	2.04a
2003					
VSP	11.80c	3.48b	7.71a	4.51a	1.70ab
SD-Up	12.05b	3.48b	7.26a	4.39a	1.72a
SD-Down	12.45a	3.57ab	6.98a	4.30a	1.60ab
GDC	11.95bc	3.66a	6.94a	4.95a	1.40b
2004					
VSP	12.80bc	3.60a	5.95a	2.48a	nd
SD-Up	12.70c	3.69a	5.95a	2.41a	nd
SD-Down	12.90ab	3.62a	5.68a	2.27a	nd
GDC	13.10a	3.72a	5.77a	2.48a	nd
2005					
VSP	12.15ab	3.30b	6.13b	2.52a	nd
SD-Up	12.37ab	3.28c	6.22b	2.22a	nd
SD-Down	12.63a	3.25d	6.22b	2.13a	nd
GDC	12.06b	3.33a	6.83a	2.90a	nd

[a]VSP: vertical shoot-positioned; SD-Up: Smart-Dyson upper canopy; SD-Down: SD lower canopy; GDC: Geneva double curtain.
[b]Different letters down columns indicate significance at α = 0.05.

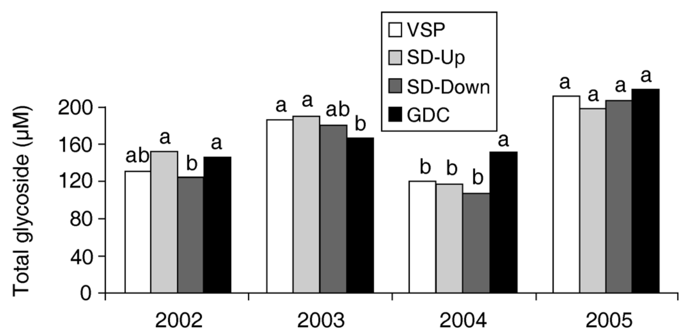

Figure 4 Effect of Geneva double curtain (GDC), Smart-Dyson (SD) Down or Up, and vertical shoot-positioned (VSP) training on Viognier wine total glycosides (µM glycosyl glucose), 2002–2005.

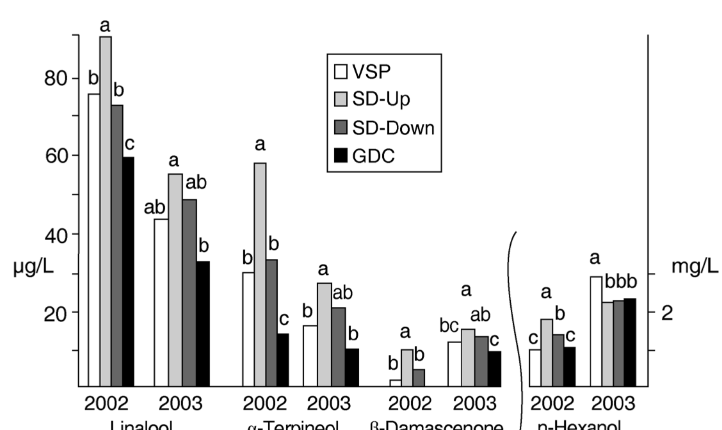

Figure 5 Effect of Geneva double curtain (GDC), Smart-Dyson (SD) Down or Up, and vertical shoot-positioned (VSP) training on Viognier juice concentrations of linalool, α-terpineol, β-damascenone, and *n*-hexanol, 2002 and 2003.

lysis. Whether or not individual free volatile flavorants accumulate in the fruit, and how fast, would be expected to depend on relative rates of accumulation and loss as a result of breakdown and/or volatilization.

Research conducted in macroclimates cooler than that of northern Virginia has demonstrated higher concentrations of aroma and flavor compounds in sun-exposed versus shaded fruit (Marais et al. 1992, Reynolds and Wardle 1989). In this study, the greatest fruit-zone light interception was generally not observed in the system with the greatest juice volatiles, SD-Up (Table 4). It has been suggested that fruit volatiles may be more influenced by light than by temperature (Morrison and Noble 1990). However, lower fruit temperature could make possible the accumulation of compounds with lower molecular weights and boiling points, down to the temperature for each compound, where slower evaporative loss is balanced by the slower synthesis. The upper SD canopy averaged a relatively high number of leaf layers and a relatively lower percentage of exposed clusters, similar to VSP. In regions with warm fruit ripening periods, maximal concentration of volatile compounds will often occur in fruit that receives moderate exposure, rather than full sun or full shade (Belancic et al. 1997). Similarly, many volatiles measured in Muscat grapes grown in southern France were more concentrated in partially shaded (85 to 90% shade) fruit than in fruit that was fully exposed to the sun (Bureau et al. 2000).

Northern Virginia is considered a warm or a hot, humid grape-production zone. Our canopy-management goals with all three training systems were aimed at simulating commercial production practices for the region. The approach of moderate or "dappled" sunlight (Haselgrove et al. 2000) fruit exposure to obtain the desired chemistry, while minimizing the potential negatives of excessive heating, was followed. While that approach provides a practical basis for evaluating varietal adaptation to commercial training practices, it also obscures the clear separation of temperature and sunlight effects on grape chemistry (Bergqvist et al. 2001, Downey et al. 2004, Spayd et al. 2002).

Wine volatile composition differed among treatments. The three important chemical classes of volatile compounds found in white wines include ethyl esters of medium-chain fatty acids, acetate esters, and higher alcohols (Simpson and Miller 1984). Quantification of members of these groups was used to determine aroma units (detection concentration threshold) and averaged for the 2002 to 2005 seasons (Table 7). The compounds that could provide the greatest wine sensory impact included linalool, octanoic acid, isoamyl acetate, ethyl hexanoate, and ethyl octanoate. Generally, wines produced from SD-Up systems had the highest concentration of linalool, isoamyl acetate, ethyl hexanoate, and ethyl octanoate. Differences in the aroma units alone do not fully allow prediction of sensory properties, partly because of the interactions of matrix components, aroma synergisms, and antagonisms.

Wine sensory. Triangle difference testing was used to screen wines produced in 2001 through 2003. Wines of the 2001 and 2003 vintages demonstrated differences in aroma and/or flavor among treatments (Table 8). In 2001, differences were noted, except in VSP and SD comparison for aroma and GDC and VSP for flavor. The 2003 wines showed differences between GDC and SD-Up for aroma and flavor, as well as differences in aroma between GDC and SD-Down. There were also differences in flavor between VSP and SD-Down.

Table 7 Effect of training system on selected mean Viognier wine volatile aroma units (concentration of volatiles/sensory threshold), 2002–2005.

Compound	Detection threshold	VSP[a]	SD-Up	SD-Down	GDC
n-Hexanol (mg/L)	4	0.26	0.30	0.28	0.27
Linalool (μg/L)	6	4.10	4.64	4.34	4.40
α-Terpineol (μg/L)w	330	0.04	0.04	0.04	0.04
2-Phenylethanol (mg/L)	50	0.24	0.26	0.28	0.24
Octanoic acid (mg/L)	3	4.54	4.92	5.28	4.76
Decanoic acid (mg/L)	6	0.79	0.85	0.82	0.71
2-Methyl propanol (mg/L)	200	0.10	0.11	0.12	0.10
Isoamyl acetate (μg/L)	1000	2.70	3.53	3.49	2.52
Ethyl hexanoate (μg/L)	300	2.51	3.32	2.93	2.40
Ethyl octanoate (μg/L)	800	1.57	1.74	1.62	1.46
Acetic acid (mg/L)	1200	0.12	0.13	0.19	0.14
Ethyl decanoate (μg/L)	510	0.76	0.74	0.83	0.64

[a]VSP: vertical shoot-positioned; SD-Up: Smart-Dyson upper canopy; SD-Down: SD lower canopy; GDC: Geneva double curtain.

Table 8 Significance of triangle difference testing of 2001 to 2003 Viognier wine between training systems for differences in aroma and flavor. (SD-Up and Down samples were pooled in 2001 and 2002.)

Comparison[a]	2001[b]	2002[b]	2003[b]
Aroma			
VSP vs SD-Up	N	N	N
VSP vs SD-Down	N	N	N
VSP vs GDC	Y*	N	N
SD-Up vs SD-Down	na	na	N
SD-Up vs GDC	Y*	N	Y*
SD-Down vs GDC	Y*	N	Y*
Flavor			
VSP vs SD-Up	Y*	N	N
VSP vs SD-Down	Y*	N	Y*
VSP vs GDC	N	N	N
SD-Up vs SD-Down	na	na	N
SD-Up vs GDC	Y*	N	Y*
SD-Down vs GDC	Y*	N	N

[a]VSP: vertical shoot-positioned; SD-Up: Smart-Dyson upper canopy; SD-Down: SD lower canopy; GDC: Geneva double curtain.
[b]N indicates no difference; Y indicates significant difference; * indicates significant at α = 0.05; na indicates not applicable.

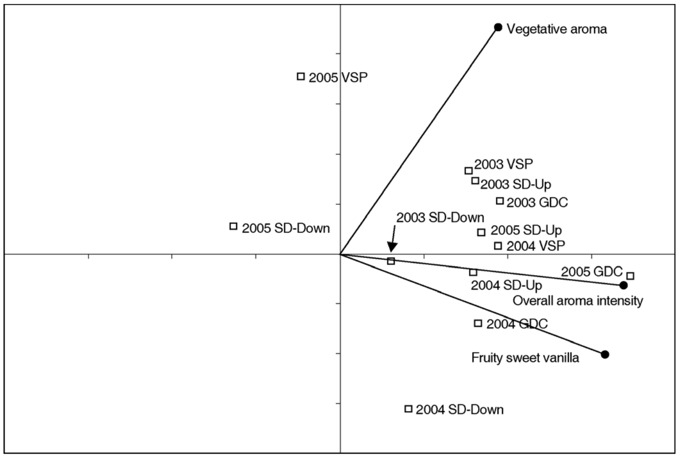

Figure 6 Principal component analysis of aroma of Viognier wines produced on Geneva double curtain (GDC), Smart-Dyson (SD) Down or Up, and vertical shoot-positioned (VSP) training, 2003–2005.

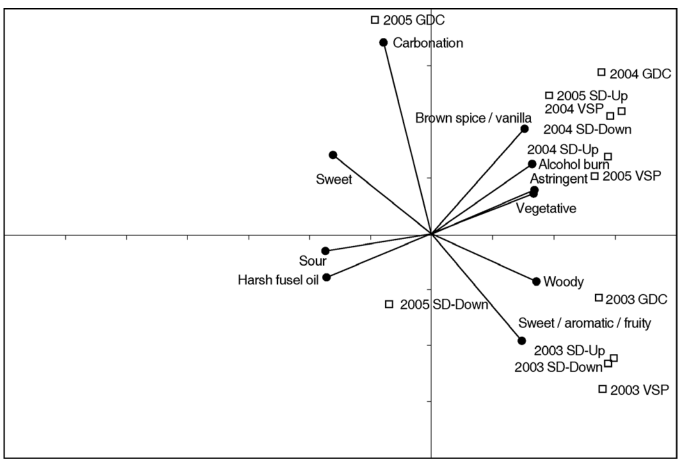

Figure 7 Principal component analysis of flavor of Viognier wines produced on Geneva double curtain (GDC), Smart-Dyson (SD) Down or Up, and vertical shoot-positioned (VSP) training, 2003–2005.

Principal component analysis for aroma and flavor were conducted on wines produced in 2003 through 2005. Aroma analysis indicated treatments accounted for an average of 59% of the variance for all three seasons (Figure 6). The first and second principal component analysis of flavor accounted for 63% of the variance among wines produced from different training systems (Figure 7). GDC wines were distinguished by overall aroma intensity, and fruity, sweet vanilla aromas. Aroma descriptors appeared to cluster around growing season. For example, wines produced in the cool, wet 2003 vintage with limited fruit Brix were generally characterized by vegetative aromas, while those produced in the drier and warmer 2004 vintage had higher fruit and overall aroma intensity. Wine flavor sensory profiles were also clustered around season. Despite the limited fruit maturity attained in 2003, wine flavors were characterized as sweet, aromatic, and fruity. The higher Brix fruit in 2004 produced wines with brown spice and vanilla flavor descriptors.

Conclusion

This study evaluated the impact of Viognier training systems on fruit and wine composition, including wine sensory response in a warm, humid environment. GDC training increased crop per vine and crop load, but decreased crop per meter of cordon relative to VSP training. SD training similarly increased crop per vine while generally not depressing the corresponding crop load, relative to VSP. Both the SD and GDC systems tended to produce higher fruit glycosides and free volatiles than the nondivided VSP. Despite higher crop loads associated with the GDC vines, triangle difference testing generally did not distinguish wines made from GDC and VSP systems. Wines produced from SD-trained vines differed in flavor, but not aroma. Generally, wine produced from GDC-trained vines differed from SD wines in aroma and flavor. Principal component analysis demonstrated GDC-produced wines were distinguished by overall aroma intensity and fruity, sweet vanilla aromas. Despite the increased yields, GDC and SD-trained vines produced wines of comparable, if not superior, sensory attributes to VSP-trained vines.

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