Shoot Density Affects ‘Riesling’ Grapevines II. Wine Composition and Sensory Response

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Abstract. ‘Riesling’ grapevines (*Vitis vinifera* L.) were subjected for 4 seasons (1987–90) to three shoot densities (16, 26, and 36 shoots/m of row) combined with three crop-thinning levels (1, 1.5, and 2 clusters per shoot) in a factorial design. Wines were made from all treatment combinations in 1989. Aroma compounds such as trans-3-hexen-1-ol, linalool, and linalool oxides 1 and 2 in many cases decreased in nonaged and aged wines by increasing shoot density and clusters per shoot, while cis-3-hexen-1-ol increased. Aging wines increased concentrations of cis-3-hexen-1-ol, citronellol, α -terpineol, and the linalool oxides, while linalool decreased. Tasters identified aged wines from the lowest shoot densities and clusters per shoot as having the most ripe-fruit flavor and the least green-fruit flavor and perceived acidity. Flavor descriptors were correlated with linalool, cis-3-hexen-1-ol, and linalool oxide 1. Shoot densities of 20 to 25 shoots/m of row are recommended for low to moderately vigorous ‘Riesling’ vines to achieve economically acceptable yields and high wine quality simultaneously.

The number of nodes retained on a grapevine depends to some degree on vine vigor, spacing, and training system, with recommendations usually given in terms of pruning level or shoot density. Several reports have provided pruning level guidelines with the objective of balancing vine vigor, yield, and fruit quality. Among these are recommendations for *Vitis labruscana* Bailey (Partridge, 1925; Shaulis and Oberle, 1948; Shaulis and Robinson, 1953; Tomkins and Shaulis, 1955) and French–American hybrids (Morris et al., 1984; Reynolds et al., 1986). Few reports have investigated optimizing shoot density levels for *Vitis vinifera* (Basler 1980, 1981; Kiefer and Crusius, 1984; Murisier and Ziegler, 1991; Nikov, 1987; Smart, 1988). Reynolds (1988) found that 25 shoots/m (of row) was equivalent to 30 + 10 balanced pruning of moderately vigorous ‘Riesling’ vines in terms of vine size, yield, and fruit composition. Recommendations for *Vitis vinifera* in British Columbia are based partly on these data.

Based on an interpolation of several research reports (Basler 1980, 1981; Kiefer and Crusius, 1984; Murisier and Ziegler, 1991; Nikov, 1987; Smart, 1988), shoot densities between 15 and 25 shoots/m may lead to improved canopy microclimate, with high bud fruitfulness, optimum bud hardiness, higher soluble solids, lower titratable acidity and pH, enhanced varietal character, minimized vegetative flavors, and improved color than shoot densities >25 shoots/m. Furthermore, recent research has investigated the relationship between viticultural practices such as shoot density and crop-thinning level on aroma compounds in grapes and wines. Monoterpenes increased in response to crop-thinning level reductions in ‘Riesling’ (McCarthy, 1986) and ‘Müller-Thurgau’ (Eschenbruch et al., 1987). High N fertilization reduced monoterpenes in ‘Riesling’ wines (Webster et al., 1993). Basal leaf

removal increased monoterpenes in ‘Gewürztraminer’ (Reynolds and Wardle, 1989a), ‘Riesling’ (Reynolds et al., 1991), and ‘Sauvignon blanc’ (Smith et al., 1988). However, demonstrating a relationship between sensory data and monoterpene concentration has been less successful. With regard to wine aging, transformations of monoterpenes such as decreases in linalool and corresponding increases in linalool oxides have been reported (DiStefano and Castino, 1983; Nicolosi-Asmundo et al., 1988; Rapp, 1990).

Currently, shoot density guidelines for *V. vinifera* under North American environmental conditions are not available. Furthermore, research addressing interactions between shoot density and crop-thinning level has not been published. The objectives of the first part of this study (Reynolds et al., 1994) was to assess the effects of moderate to high shoot densities and their interactions with crop-thinning level in terms of vine performance, canopy microclimate, and fruit composition of ‘Riesling’ grapes. The objectives of this portion of the study were to examine some of the major aroma constituents in the wines relative to the vineyard treatments, observe possible changes in these compounds during wine aging, and relate the levels of these constituents to wine aroma and flavor descriptors.

Materials and Methods

Experimental design and plant material: winemaking procedures. Detailed aspects of the experimental design can be found in Reynolds et al. (1994). The experimental design was a randomized complete block with four blocks and five vine treatment replicates. Three shoot densities (16, 26, and 36 shoots/m) were combined in a factorial treatment arrangement with three crop-thinning levels (1, 1.5, and 2 clusters/shoot) to provide nine treatment combinations. Treatment combinations indicating a specific shoot density and crop-thinning level will be designated as shoot density/crop-thinning level numbers (16/1, 26/1.5, 36/2, etc.). Analysis of all data was performed by the SAS statistical package (SAS Institute, Cary, N.C.) using the PROC GLM and PROC CORR procedures.

About 15 kg of fruit per treatment replicate was retained at harvest in 1989 (16 Oct.) for winemaking. Grapes were stored at 2°C for 24 h, crushed in a crusher–destemmer, allowed 48-h skin contact without sulfite at 2°C, and pressed in a hydraulic rack-and-cloth press. Musts from the individual treatment replicates from blocks 1 and 2 and those from blocks 3 and 4, were blended, respectively, into 20-liter glass carboys to give two fermentation

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replicates for each treatment combination. Musts were sulfited to 50 mg·liter⁻¹ free SO₂, settled for 24 h at 2C, racked, and placed into a fermentation room maintained at 15C. After 24 h, a yeast inoculum (*Saccharomyces cerevisiae* Hansen, strain Montrachet; Red Star Co., Milwaukee), grown for 3 days in 'Riesling' juice was added to each carboy at a rate of 3% (v/v). Fermentation proceeded until wines reached ≈1.5% residual sugar (confirmed by Clinitest tablets), at which point they were sulfited to 50 mg·liter⁻¹ free SO₂, racked, cold-stabilized at -2C for ≈30 days, racked again, and stored at 2C until bottling in March 1990.

Wine composition. Wine pH was measured as described previously for berries (Reynolds et al., 1994). Wine TA was measured on 10-ml samples using a titroprocessor (Brinkmann 672; Metrohm, Herisau, Switzerland) according to Amerine and Ough (1980). Ethanol was measured on the wines using a gas chromatograph (model 5700; Hewlett-Packard, Mississauga, Ont.).

Wine aroma volatiles. Two 250-ml samples of wine per treatment × fermentation replicate were taken at time of bottling (nonaged) and 11 months thereafter (aged) and stored at -40C until analysis. Extraction and quantitation of aroma volatiles were performed as described by Webster et al. (1993). Two six-carbon alcohols (trans-3-hexen-1-ol, and cis-3-hexen-1-ol) and five free monoterpenes (citronellol, linalool, α-terpineol, linalool oxide 1, and linalool oxide 2) were identified by gas chromatography-mass spectroscopy (Webster et al., 1993).

Sensory evaluation. Wines were tasted in February 1991 after 11 months of bottle storage. Three aroma descriptors (ripe fruit, green fruit, and corky-musty) and four flavor descriptors (ripe fruit, green fruit, sweetness, and acidity) were developed through consensus by a trained 12-member taste panel. Intensity of each aroma and flavor descriptor was assessed on a 100-point line scoresheet. The two fermentation replicates were assessed at two

Table 1. Composition of 'Riesling' wines (1989) in response to three shoot densities and three crop-thinning levels.

Factor	Wine		
	TA (g·liter ⁻¹)	pH	Ethanol (%)
Shoot density (shoots/m row)			
16	8.7	3.08	14.75
26	9.3	3.03	14.59
36	9.0	3.06	15.86
Significance	Q*	Q*	L***, Q
Crop thinning level (cluster/shoot)			
1	8.8	3.08	14.85
1.5	9.0	3.06	14.86
2	9.2	3.03	15.55
Significance	NS	NS	L***, Q**

NS, ***, **** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively. L = linear, Q = quadratic.

VOLATILE COMPOUNDS IN NON-AGED RIESLING WINES

Fig. 1. Concentration of some volatile compounds (µg·liter⁻¹) of nonaged 'Riesling' wines in response to three shoot densities, 1989. NS, ***, **** Nonsignificant or significant at $P < 0.05$, 0.01, or 0.001, respectively. Linear or quadratic trends were not estimable. Axis length = 80 µg.

separate tastings. All treatments were presented as 30-ml samples in clear tulip-shaped glasses and were randomized for each taster. Results were analyzed by analysis of variance and by principal components analysis (PCA).

Results

Wine composition. Wines in 1989 tended to show the same trends displayed by the berry samples in 1987–90 and the juice samples in 1989. Wine TA displayed a slight quadratic increase relative to increasing shoot density (Table 1), a trend supported by a significant correlation ($P \leq 0.008$) between shoots per vine and wine TA. Wine pH was lowest at 26 shoots/m (Table 1). Ethanol increased relative to increasing shoot density and clusters per shoot

(Table 1), a trend supported by significant correlations ($P \leq 0.0001$) between ethanol and shoots per vine and clusters per vine. Crop-thinning level had no significant effect on wine TA or pH, and there were no interactions between the two factors for these variables. Significant correlations ($P \leq 0.01$) occurred, however, between clusters per vine and wine TA (positive) and wine pH (negative). A significant shoot density $\times$ crop-thinning interaction (data not shown) indicated that ethanol did not increase with clusters per shoot at the highest shoot density.

Wine aroma volatiles. Trends in aroma volatile concentration relative to shoot density and crop-thinning level were similar for nonaged and aged wines. Concentrations of trans-3-hexen-1-ol, linalool, and linalool oxides 1 and 2 in nonaged wines decreased with increasing shoot density (Fig. 1). In aged wines, linalool and linalool

VOLATILE COMPOUNDS IN AGED RIESLING WINES

Fig. 2. Concentration of some volatile compounds ($\mu\text{g}\cdot\text{liter}^{-1}$) of aged 'Riesling' wines in response to three shoot densities, 1989. NS, *, **, *** Nonsignificant or significant at $P < 0.05$, 0.01, or 0.001 respectively; L = linear, Q = quadratic. Axis length = 80 μg .

oxide 2 displayed the same trend, but trans-3-hexen-1-ol and linalool oxide 1 displayed quadratic responses to shoot density. Cis-3-hexen-1-ol and citronellol also increased linearly with increasing shoot density in aged wines, while α -terpineol decreased (Fig. 2).

Increasing clusters per shoot decreased trans-3-hexen-1-ol in nonaged wines (Fig. 3) and citronellol and linalool in aged wines (Fig. 4). Cis-3-hexen-1-ol and linalool oxide 1 in nonaged and aged wines increased relative to increasing clusters per shoot. α -Terpineol in nonaged wines and trans-3-hexen-1-ol, α -terpineol, and linalool oxide 2 in aged wines showed quadratic trends in response to crop-thinning level, with lowest concentrations detected at 1.5 clusters/shoot.

Shoot density $\times$ crop-thinning interactions occurred for trans- and cis-3-hexen-1-ol, α -terpineol, and linalool oxide 1 in nonaged wines (Fig. 5) and for all but cis-3-hexen-1-ol and linalool in aged wines (Fig. 6). Trends in the concentrations of these compounds varied greatly in their magnitude and direction of response to the two factors, and no simple, consistent pattern of response was apparent. However, lowest concentrations of all aroma compounds always occurred in treatment combinations consisting of moderate to high clusters per shoot (1.5 or 2 clusters/shoot) and/or shoot densities of 36 shoots/m. Furthermore, when concentrations of these aroma compounds were examined within treatment groups containing equal cluster numbers but different shoot densities, the two hexenols increased relative to increasing shoot density, while

the monoterpenes tended to decrease.

Cis-3-hexen-1-ol and all monoterpenes except linalool increased in concentration after 11 months of bottle storage (Table 2). There were significant interactions for age $\times$ shoot density (cis-3-hexen-1-ol, citronellol, and linalool oxide 2), age $\times$ crop thinning (cis-3-hexen-1-ol and linalool oxide 1), and age $\times$ shoot density $\times$ crop thinning (linalool oxide 1). Age $\times$ shoot density and age $\times$ crop-thinning interactions suggested that the magnitude of response of each aroma compound to age increased with increasing shoot density or clusters per shoot (data not shown). The three-way interaction for linalool oxide 1 indicated that increases in this compound in response to bottle age were least apparent at the 16/1 treatment combination. Highest concentrations ($66 \mu\text{g}\cdot\text{liter}^{-1}$) were found in aged wines of the 26/2 combination, while lowest concentrations ($25 \mu\text{g}\cdot\text{liter}^{-1}$) were found in the nonaged wines of the 16/1.5 and 26/1.5 combinations.

Sensory evaluation. Tasters found no effect of shoot density on any of the aroma descriptors (Fig. 7), but perceived a reduction in ripe-fruit character relative to increased clusters per shoot (Fig. 8). Linear reductions in ripe-fruit flavor and sweetness and increases in green-fruit flavor and perceived acidity were associated with increased shoot density and clusters per shoot (Figs. 7 and 8).

Interactions showed that tasters found the highest levels of negative flavor descriptors (green fruit and acidity) and the lowest ripe-fruit flavor in the 36 shoots/m treatments and in the 26/2

VOLATILE COMPOUNDS IN NON-AGED RIESLING WINES

Fig. 3. Concentration of some volatile compounds ($\mu\text{g}\cdot\text{liter}^{-1}$) of nonaged 'Riesling' wines in response to three crop-thinning levels, 1989. NS,*,*** Nonsignificant or significant at $P < 0.05$, 0.01, or 0.001 respectively. Linear or quadratic trends were not estimable. Axis length = $80 \mu\text{g}$.

VOLATILE COMPOUNDS IN AGED RIESLING WINES

Fig. 4. Concentration of some volatile compounds ($\mu\text{g}\cdot\text{liter}^{-1}$) of aged 'Riesling' wines in response to three crop-thinning levels, 1989. **,*,***Nonsignificant or significant at $P < 0.05$, 0.01, or 0.001 respectively; L = linear, Q = quadratic. Axis length = 82 μg .

treatment combination (data not shown). Highest level of ripe-fruit flavor and lowest level of green-fruit flavor were found in the 16/1 treatment. Increased clusters per shoot decreased ripe-fruit flavor linearly at 16 shoots/m but had no impact at 36 shoots/m. Green-fruit flavor also was unaffected by crop-thinning level at the highest shoot density. Perceived sweetness and acidity followed the same patterns as ripe fruit and green fruit, respectively. These patterns were clearly shown by PCA (Fig. 9), which separated the 36 shoots/m treatments and the 26/2 treatment from the other combinations. Comparisons between treatments within treatment groups A (16/1.5 and 26/1) and C (26/2 and 36/1.5) showed no

apparent effect of shoot density at equal cluster number, but, within treatment group B (16/2, 26/1.5, and 36/1), the 26/1.5 combination seemed to be favored in terms of highest ripe-fruit flavor and perceived sweetness and lowest green-fruit flavor and perceived acidity. Most shoot density effects implied by the main effects were present at each crop-thinning level among the interactions.

Correlations existed between the seven sensory descriptors, between the aroma compounds, and between the flavor descriptors and concentration of aroma compounds in the aged wines (Table 3). Ripe-fruit aroma was positively correlated with sweetness and negatively correlated with musty aroma. Ripe-fruit flavor and

Fig. 5. Shoot density $\times$ crop-thinning level interactions and significance levels for nonaged 'Riesling' wines, 1989. Trans-2-hexen-1-ol, cis-3-hexen-1-ol, and α -terpineol significant at $P < 0.05$; linalool oxide 1 significant at $P < 0.01$.

sweetness were positively correlated, and these descriptors were negatively correlated with green-fruit flavor. Descriptors of similar aroma and flavor characteristics (e.g., ripe-fruit aroma vs. ripe-fruit flavor) were highly correlated. Many of the monoterpenes

were positively correlated with each other and negatively correlated with the hexenols. Cis-3-hexen-1-ol and linalool oxide 1 were positively correlated with green-fruit flavor and negatively correlated with ripe-fruit flavor and sweetness. Linalool was

Fig. 6. Shoot density $\times$ crop-thinning level interactions and significance levels for aged 'Riesling' wines, 1989. Trans-2-hexen-1-ol and citronellol significant at $P < 0.05$; α -terpineol significant at $P < 0.01$; linalool oxide 1 significant at $P < 0.001$; linalool oxide 2 significant at $P < 0.01$.

positively correlated with ripe-fruit flavor and sweetness and negatively correlated with green-fruit flavor. Citronellol was negatively correlated with sweetness, while linalool oxide 2 was negatively correlated with green-fruit flavor.

Discussion

Increasing nodes retained per vine (shoot density) leads to more clusters per vine, hence higher yield, but also increases canopy

Table 2. Concentration of some volatile compounds ($\mu\text{g}\cdot\text{liter}^{-1}$) of 'Riesling' wines in response to wine age. Means are pooled across nine vineyard treatments imposed in 1989.

Compound	Wine age		Significance ^z			
	Bottling	11 Months	A	A $\times$ SD	A $\times$ CL	A $\times$ SD $\times$ CL
		postbottling				
Trans-3-hexen-1-ol	66.37	67.81	NS	NS	NS	NS
Cis-3-hexen-1-ol	65.45	68.59	*	*	*	NS
Linalool	32.02	23.02	***	NS	NS	NS
Citronellol	17.74	21.40	*	***	NS	NS
α -Terpineol	20.37	31.33	***	NS	**	NS
Linalool oxide 1	33.15	52.72	***	**	NS	**
Linalool oxide 2	27.46	38.01	***	NS	**	NS

^zA = age; SD = shoot density; CL = crop-thinning level.

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

SENSORY ATTRIBUTES OF AGED RIESLING WINES

Fig. 7. Mean intensity plot of aroma (lowercase) and flavor (uppercase) descriptors for 'Riesling' wines in response to three shoot densities, 1989. NS, **, *** Nonsignificant or significant at $P < 0.01$ or 0.001, respectively; L = linear, Q = quadratic. Axis length = 60 points.

SENSORY ATTRIBUTES OF AGED RIESLING WINES

Fig. 8. Mean intensity plot of aroma (lowercase) and flavor (uppercase) descriptors for 'Riesling' wines in response to three crop-thinning levels, 1989. ^{ns,*,***} Nonsignificant or significant at $P < 0.01$ or 0.001 , respectively; L = linear, Q = quadratic. Axis length = 60 points.

density (Shaulis, 1982; Shaulis and May, 1971; Smart, 1988). Results of these phenomena are higher crop loads (yield : vine size ratio), increased canopy shade, and reduced light interception in the canopy interior (Shaulis, 1982). Reductions in clusters per shoot by cluster thinning or as a result of shade-induced decline in fruitfulness may partly mitigate the debilitating effects of high crop load on yield components. Lowering clusters per shoot by cluster thinning may increase cluster weight, berries per cluster, and berry weight and may also significantly advance fruit maturity (Fisher et al., 1977; Reynolds, 1989; Reynolds et al., 1986).

The shoot densities imposed in this experiment ranged from 16 to 36 shoots/m of row. Sixteen shoots/m of row (6.8 shoots/m² in this trial) is a level considered about optimal by some (Kiefer and Crusius, 1984; Reynolds et al., 1986; Smart, 1988), high by others (Basler, 1980, 1981; Murisier and Ziegler, 1991), but low by grower standards (J. Vielvoye, personal communication). Twenty-six shoots/m of row (10.4 shoots/m²) is close to the present British Columbia recommendation based on local research (Reynolds, 1988, 1989), while 36 shoots/m of row (14.9 shoots/m²) is within the expected range for mechanized pruning.

SHOOT DENSITY X CROP LEVEL AGED 1989

Fig. 9. Principal component analysis plot for aroma (lowercase) and flavor descriptors (upper case) of aged 'Riesling' wines, 1989. Factors 1 and 2 account for 59% and 23% of the variability, respectively. Octagons, squares, and triangles represent 16, 26, and 36 shoots/m row, respectively; open, boldface, and solid symbols represent 1, 1.5, and 2 clusters/shoot, respectively.

Impact of shoot density and crop-thinning level on wine aroma compounds was consistent with the response of other measurements of fruit, juice, and wine composition. In most cases, hexenols increased with increasing shoot density and crop-thinning level, while monoterpenes decreased. Shoot density effects were clearest when comparisons were made between treatment combinations containing similar cluster numbers but differing shoot densities. These results are consistent with those of Smith et al. (1988), who observed higher levels of monoterpenes in 'Sauvignon blanc' juices obtained from leaf-plucked vines compared to non-leaf-plucked vines. The large magnitude of increase during bottle storage in wine terpenes in the 26 and 36 shoots/m treatments may have been a consequence of the trend toward increased berry and juice free volatile terpenes with increasing shoot density.

The trends in fruit composition observed in response to shoot density and crop-thinning level were clearly evident in the sensory analysis. Ranges in soluble solids, TA, pH, and monoterpenes in the juices used in winemaking were quite small, and maximum and minimum values did not correspond to treatment combinations with highest and lowest yields. Major differences between treatment combinations were nonetheless observed in the wine descriptors. Shoot density seemed to have the greatest impact on the degree of ripe- and green-fruit flavor in the wines. Relatively small differences existed between the 16 shoots/m combinations and the 26/1 and 26/1.5 treatments in terms of ripe and green-fruit flavors,

but all 36 shoots/m combinations were dramatically different from the rest. This suggests that the large increases in canopy density observed between 26 and 36 shoots/m may have a major impact on wine quality, despite negligible differences in juice composition. It also provides evidence that substantial crop load ranges (6.4 to 19.7 for the 16/1 and 26/1.5 combinations, respectively) may be tolerated without large measurable differences in fruit composition or wine quality.

The impact of wine aging on aroma compounds and, ultimately, sensory response has received some attention. Simpson and Miller (1983) found small increases in trans-3-hex-1-ol, cis-hexanol, and cis-furan-linalool oxide in 'Riesling' wines as they aged, but these increases may have simply been effects of season. Similarly, Rapp and Mandery (1986) reported on changes in aroma volatiles of 'Riesling' wines made between 1964 and 1982. In general, free terpene alcohols such as linalool and geraniol decreased, while linalool oxides, nerol oxides, and hotrienol increased. The major group of constituents associated with aging of 'Riesling' wines has been the carotenoid degradation products (C_{13} norisoprenoids) such as damascenone and 1,1,6-trimethyl-1,2-dihydronaphthalene (Marais et al., 1992; Rapp and Mandery, 1986; Simpson and Miller, 1983). Marais et al. (1992) also correlated an increase in kerosene character and a decrease in young wine character with the changes in monoterpenes and norisoprenoids during aging of 'Riesling' wines. This is the first study of which we are aware that

Table 3. Correlation matrix of taster scores and concentrations of aroma compounds in 'Riesling' wines pooled across nine vineyard treatments in 1989.

	Green fruit aroma	Musty aroma	Ripe fruit flavor	Green fruit flavor	Sweetness	Acidity	Trans- hexenol	Cis- hexenol	Linalool	Citronellol	α -Terpineol	Linalool oxide 1	Linalool oxide 2
Ripe fruit aroma	-0.14 *	-0.24 ***	0.38 ***	0.00	0.18 **	0.04	0.07	-0.03	0.05	0.02	-0.06	-0.06	0.04
Green fruit aroma		0.31 ***	0.10	0.18 **	0.20 **	0.10	-0.10	0.00	0.00	-0.04	0.08	0.05	-0.01
Musty aroma			0.10	0.09	0.15 *	0.09	-0.06	-0.02	0.03	0.03	0.11	0.09	0.01
Ripe flavor				-0.31 ***	0.63 ***	-0.12	0.05	-0.20 **	0.19 **	-0.13	0.03	-0.17 **	0.02
Green flavor					-0.18 **	0.49 ***	-0.08	0.22 ***	-0.25 ***	0.09	-0.06	-0.18 **	-0.15 *
Sweetness						-0.14 *	0.01	-0.21 ***	0.15 *	-0.14 *	0.03	-0.15 *	0.05
Acidity							0.01	0.23 ***	-0.12	-0.04	-0.02	0.18 **	0.02
Trans-hexenol								0.58 ***	0.35 ***	-0.02	0.06	0.30 ***	0.44 ***
Cis-hexenol									-0.08	-0.27 ***	0.17 **	0.68 ***	0.32 ***
Linalool										0.15 *	0.45 ***	0.06	0.42 ***
Citronellol											0.34 ***	0.07	-0.04
α -Terpineol												0.59 ***	0.43 ***
Linalool oxide 1													0.52 ***

*, **, ***Significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

examines effects of viticultural practices on the changes in aroma compounds during wine aging.

Taster response was most closely related to levels of aroma compounds in the aged wines, specifically the hexenols (responsible for the green-fruit flavor) and linalool (responsible for the ripe-fruit flavor). The hexenols also were related to the tasters' perception of acidity in the wines, while linalool may have increased the tasters' perception of sweetness.

Our recommendations of 20 to 25 shoots/m of row for 'Riesling' and similar medium-clustered *V. vinifera* ('Chardonnay', 'Pinot blanc', etc.) seem reasonable based on data presented here. Significant light attenuation in the canopies, coupled with reduced wine quality, takes place somewhere at ≈ 20 to 30 shoots/m of row. Substantial increases in crop load seem to have little impact on wine sensory quality unless accompanied by major increases in canopy shading.

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