Shoot Density Affects ‘Riesling’ Grapevines

I. Vine Performance

A.G. Reynolds,¹ C.G. Edwards,² D.A. Wardle,³ D.R. Webster,⁴ and M. Dever⁵

Agriculture Canada Research Station, Summerland, B.C. V0H 1Z0, Canada

Additional index words. *Vitis vinifera*, cluster thinning, pruning, canopy management, aroma, flavor, monoterpenes

Abstract. ‘Riesling’ grapevines (*Vitis vinifera* L.) were subjected for 4 years (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/shoot) in a factorialized treatment arrangement. Weight of cane prunings per vine (vine size) decreased linearly with increasing shoot density and clusters per shoot. Cane periderm formation (in terms of percent canes per vine with >10 ripened internodes) was inhibited by increased shoot density, while vine winter injury (primarily bud and cordon) increased slightly in a linear fashion with increasing clusters per shoot. Canopy density and leaf area data suggested that fruit clusters were most exposed to sunlight at a shoot density of 26 shoots/m of row due to reduced lateral shoot growth and a trend toward slightly smaller leaves. Yield, clusters per vine, and crop load (yield per kilogram of cane prunings) increased with increasing shoot density and clusters per shoot, while other yield components (cluster weight, berries per cluster, and berry weight) decreased. Soluble solids and pH of berries and juices decreased with increasing shoot density and clusters per shoot, but titratable acidity was not substantially affected. Free volatile terpenes increased in berries and juices in 1989 with increasing shoot density, as did potentially volatile terpenes in 1990. Shoot densities of 16 to 26 shoots/m of row are recommended for low to moderately vigorous ‘Riesling’ vines to achieve economically acceptable yields and high winegrape 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. Although several reports provide guidelines with the objective of balancing vine vigor, yield, and fruit quality of *Vitis labruscana* Bailey and French-American hybrids (Morris et al., 1984; Partridge, 1925; Reynolds et al., 1986; Shaulis and Oberle, 1948; Shaulis and Robinson, 1953; Tomkins and Shaulis, 1955), few reports have investigated optimizing shoot density levels for *Vitis vinifera* L. Basler (1980, 1981) concluded that 5 to 6 and 6 to 7 shoots/m² [≈ 12 to 17 shoots/m (of row) at a 1.4 $\times$ 2.4-m (vine $\times$ row) spacing] were optimal for vertically trained ‘Müller-Thurgau’ and ‘Blauburgunder’, respectively. Kiefer and Crusius (1984) recommended higher shoot densities for similarly trained ‘Riesling’ (21 to 29 shoots/m), ‘Müller-Thurgau’ (14 to 22 shoots/m), and ‘Silvaner’ (14 to 17 shoots/m). Although ‘Merlot’ winegrape quality was reduced little at 22 to 37 shoots/m (Nikov, 1987), major decreases in winegrape quality were noted between 37 and 52 shoots/m. Based on canopy microclimate data, Smart (1988) indicated that 15 shoots/m of row was probably ideal for ‘Gewürztraminer’, although these data were collected on very dense vines that had been shoot-adjusted at veraison. Thus, the possible effects of lateral shoot growth at different shoot densities could not be observed. Reynolds (1988) found that 25 shoots/m of row (10 shoots/m²) 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 reports (Basler, 1980, 1981; Kiefer and Crusius, 1984; Murisier and Ziegler, 1991; Smart, 1988), shoot densities of 15 to 25 shoots/m may improve canopy microclimate, with higher bud fruitfulness, better 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, crop level, and aroma compounds in grapes and wines. Monoterpenes increased in response to crop level reductions in ‘Riesling’ (McCarthy, 1986) and ‘Müller-Thurgau’ (Eschenbruch et al., 1987). High N fertilization reduced monoterpene concentration in ‘Riesling’ wines (Webster et al., 1993). Basal leaf removal has 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.

Currently, shoot density guidelines for growing *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 first objective of this study 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, fruit composition, and wine descriptors of ‘Riesling’ grapes. The second objective was to examine some of the major aroma constituents in the wines relative to the vineyard treatments and to observe possible changes in these compounds during wine aging. Aspects of this study relating to wine composition and sensory attributes are presented in Reynolds et al. (1994).

Materials and Methods

Experimental design and plant material. This trial was located at Pioneer Vineyards, Kelowna, B.C. ‘Riesling’ (clone 21B Weis) vines on 5C rootstock, planted in 1978, were trained to 0.7-m-high bilateral cordons and pruned to two-node spurs. Spacing was 1.4

Received for publication 27 Sept. 1993. Accepted for publication 17 Jan. 1994. We gratefully acknowledge the cooperation and interest of Daniel Dulik, Pioneer Vineyards, Kelowna, B.C. We also thank Jean Hogue for technical assistance in the field, 1987–90. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked *advertisement* solely to indicate this fact.

¹Research scientist, Pomology and Viticulture Section.

²Assistant professor, Dept. of Food Science and Human Nutrition, Washington State Univ., Pullman, WA 99164.

³Research assistant, Pomology and Viticulture Section.

⁴Research assistant, Dept. of Food Science and Human Nutrition, Washington State Univ., Pullman, WA 99164.

⁵Research assistant, Food Processing Section.

× 2.4 m (vine × row) in east–west-oriented rows. Vines were hedged once each summer when the berries were 9 to 12 mm in diameter. Based on dry-weight measurements (A.G. Reynolds, unpublished data) of summer prunings in a prior experiment at this site, the amount of biomass removed at hedging (<0.05 kg dry weight/vine) was not significant. Soil was a Glenmore clay loam (Kelley and Spilsbury, 1949). Irrigation was provided by overhead sprinklers. Soil management and pest control practices were carried out according to published recommendations (British Columbia Ministry of Agriculture and Fisheries, 1987).

The experimental design was a randomized complete block with four blocks and five vine treatment replicates confined to two vineyard rows. All vines were pruned each season to 60 nodes per vine. 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. Theoretical clusters per vine at the three shoot densities were 23, 36, and 50 (1 cluster/shoot); 35, 54, and 75 (1.5 clusters/shoot); and, 46, 72, and 100 (2 clusters/shoot). Shoot density levels were established ≈14 to 21 days after budburst by shoot thinning. Treatment combinations indicating a specific shoot density and crop-thinning level will be hereafter designated as shoot density/crop 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.

Growth, periderm, and winter injury. Cane pruning weight data were collected for the 1987 to 1990 growing seasons, inclusive. Canes per vine were counted in March 1988 and allocated into one of four categories based on internodes per cane with fully formed (ripened) periderm: 0 to 3 internodes; 4 to 5 internodes; 6 to 9 internodes; and >10 internodes. Data were expressed as a percentage of total canes per vine. Following Winter 1989, during which temperatures fell to –25°C, vine winter injury was assessed in late May 1989. Four subjective categories were used: 0, minor bud injury only; 1, one cordon injured; 2, both cordons injured; 3, both cordons completely killed plus one trunk injured; and 4, vine killed to the soil level.

Canopy assessment. Canopy density was assessed in late August 1987 and 1990 by point quadrat analysis (Smart, 1982) by inserting a 1-m-long needle at regular intervals into the fruit zone at a ≈30° angle to the soil level. Twenty insertions per treatment replicate were made. The number and nature of the canopy contacts for each insertion were recorded and, from these data, information was generated on exposed cluster faces, partially exposed cluster faces, and shaded (interior) leaves.

One shoot per treatment replicate was chosen in late August 1990 for measuring leaf area components. In all cases, a hedged shoot from the middle of the third vine in each treatment replicate was sampled. Nodes per shoot were recorded, and the main leaves and those on lateral shoots were removed. Leaf areas per main shoot and on lateral shoots were measured using a leaf area meter (LI-3000; LI-COR, Lincoln, Neb.). Leaf areas per vine were estimated from the product of leaf area per shoot and shoots per vine data.

Mean cluster photon fluence rate (PFR) was measured hourly on 20 clusters per treatment replicate on 28 Aug. 1990 using an integrating quantum–radiometer–photometer (model 188-B; LI-COR) equipped with a quantum sensor (model 190SB; LI-COR). Measurements were taken from 0900 to 1200 HR, inclusive. The sensor was held parallel to the surface of each cluster sampled.

Yield components. Yield per vine and clusters per vine were recorded each season at harvest, and an estimate of cluster weight

was calculated. A 100-berry sample was randomly collected at harvest from each five-vine replicate for measuring berry weight; an estimate of berries per cluster was calculated from the cluster weight and berry weight data. The number of clusters per shoot was calculated from clusters per vine and shoots per vine, while crop load (kilogram yield per kilogram cane prunings) was calculated from yield per vine and vine size data. Harvest dates were 28 Sept. 1987, 14 Oct. 1988, 16 Oct. 1989, and 17 Oct. 1990.

Berry composition. All berry samples were stored at –40°C until analysis. A 50-g subsample from each berry sample was subjected to the nonvolatile acid extraction procedure described by Mattick (1983). The rest of each sample was juiced, and soluble solids (°Brix) and pH were measured using an temperature-compensated refractometer (Abbé; AO Scientific, Buffalo, N.Y.) and a pH meter (model 825MP; Fisher Scientific, Vancouver, B.C.), respectively. Titratable acidity (TA) was measured on the extracts using a titroprocessor ensemble (Brinkman 672; Metrohm, Herisau, Switzerland). Additional 300-berry samples were collected randomly from each treatment replicate at harvest in 1989 and 1990 for measuring monoterpenes. Concentrations of free volatile terpenes (FVT) and potentially volatile terpenes (PVT) were measured colorimetrically on a spectrophotometer [DMS 100; Varian (Canada), Georgetown, Ont.] on distillates derived from two 100-g subsamples of berry homogenate. The FVT and PVT quantitation method was a modification of the method of Dimitriadis et al. (1984), described by Reynolds and Wardle (1989b).

Juice composition. About 15 kg of fruit per treatment replicate was retained at harvest in 1989 for winemaking. Grapes were stored at 2°C for 24 h, crushed in a crusher–destemmer, allowed a 48-h skin contact without sulfite at 2°C, and pressed in a hydraulic rack-and-cloth press. Juice samples (two × 250 ml) were collected from each treatment replicate to determine °Brix, TA, pH, FVT, and PVT before inoculation. Juice °Brix and pH were measured as described for the berries. Juice TA was measured on 10-ml samples using a titroprocessor, according to Amerine and Ough (1980). Juice FVT and PVT were quantitated as previously described for berries on two 100-ml subsamples per 250-ml juice sample.

Results

Growth, periderm, and winter injury. Weight of cane prunings (vine size) for the 4 years of observation was 0.27 to 0.53 kg/vine (0.19 to 0.38 kg/m of row), a range representing low to moderate vigor. Increasing shoot density and clusters per shoot decreased vine size linearly in two of four seasons (Table 1). These trends were confirmed by significant negative correlations ($P \leq 0.01$) between shoots and clusters per vine and vine size in 1989. Means of 4 years averaged across the three shoot densities (0.45, 0.40, and 0.39 kg/vine) and three crop-thinning levels (0.44, 0.40, and 0.39 kg/vine) suggested that increasing shoot density and clusters per shoot may slightly decrease vine size long term. Since all vines were initially pruned to equal node numbers, these vine size data reflect cane quality rather than quantity of cane prunings removed in accordance with the differing shoot density levels.

Crop-thinning level had no apparent significant effect on cane periderm formation (Table 1), and shoot density had no effect on the percentage of canes with 4 to 5 or 6 to 9 ripened internodes (data not shown). However, as shoot density increased, the percentage of canes with 0 to 3 ripened internodes increased and the percentage of canes with >10 ripened internodes decreased (Table 1). This trend was confirmed by highly significant correlations ($P \leq 0.0001$) between shoots per vine and these two variables. Actual cane

number per vine increased linearly with increasing shoot density for the 0 to 3 group (5 to 17 canes; $P \leq 0.001$), 4 to 5 group (2 to 4 canes; $P \leq 0.001$), and 6 to 9 group (6 to 10 canes; $P \leq 0.001$), but remained constant in the >10 group (12 canes). Shoot density had no apparent effect on vine winter injury (Table 1). However, increasing clusters per shoot increased winter injury, although injury levels were low (mainly confined to bud and cordon) considering the severity of the winter. There were no shoot density $\times$ crop-thinning interactions for vine size, shoots retained per vine, cane periderm formation, or winter injury.

Canopy assessment. In 1987, increasing shoot density led to significantly denser canopies (2.2, 3.0, and 4.2 contacts/insertion for 16, 26, and 36 shoots/m, respectively), but crop-thinning level had no effect. Lowering shoot density also led to significantly more canopy gaps and more fruit exposure (data not shown). Increasing clusters per shoot increased fruit exposure (data not shown), perhaps due to more clusters per vine combined with lower individual shoot vigor. In 1990, crop-thinning level seemed to have no effect (Table 2). Shoot density had effects similar to those in 1987 on total contacts and number of shaded leaves, but had quadratic effects on fruit exposure. All canopies in 1990 were too shaded. An increase from 16 to 26 shoots/m did not markedly increase canopy shade; in fact, the large range of shoot densities tested in this experiment produced a relatively small range of

canopy densities. Maximum fruit exposure occurred at the moderate (26 shoots/m) density, perhaps due to reduced leaf size and lateral shoot growth. There were no shoot density $\times$ crop-thinning interactions.

Increasing shoot density increased total leaf area per vine and leaf area per vine on main shoots. A trend toward smaller leaves in response to increased shoot density was also apparent. Leaf area per lateral shoot, leaf area on lateral shoots (expressed on a per main shoot basis), and the ratio of main leaf : lateral leaf area decreased with increasing shoot density (Table 3). This seemed to be a result of individual shoot devigoration and could account for the increased fruit exposure at 26 shoots/m of row observed with point quadrat analysis. These relationships between shoot density and components of lateral shoot growth were supported by negative correlations ($P \leq 0.0001$) between shoots per vine and these variables. The 16 shoots/m of row treatments therefore produced longer laterals due to their vigorous shoots; because their internodes were longer (data not shown), their shoots were hedged somewhat more severely (≈ 14 leaves/shoot). Thus, lateral shoot growth at low shoot densities (≈ 16 shoots/m) may lead to attenuation in canopy light levels equal to the addition of 10 more shoots/m of row. Crop-thinning level had no impact on leaf area components, and there were no shoot density $\times$ crop-thinning interactions.

Crop-thinning level had no independent effect on cluster PFR

Table 1. Growth, winter injury, and cane periderm formation of 'Riesling' vines subjected to three shoot densities and three crop-thinning levels during 1987–90.

Factor	Wt of cane prunings (kg/vine)				Shoots retained/vine				Winter injury ²	Canes/vine (% , 1988)	
	1987	1988	1989	1990	1987	1988	1989	1990	(1989)	0–3 Ripened internodes	>10 Ripened internodes
Shoot density (shoots/m row)											
16	0.47	0.43	0.36	0.52	23	24	23	23	0.1	18.4	49.6
26	0.48	0.38	0.29	0.43	34	36	37	37	0.2	30.7	37.2
36	0.48	0.35	0.29	0.44	47	49	48	49	0.3	37.8	31.1
Significance	NS	L ^{**}	L [*]	NS	L ^{***}	L ^{***}	L ^{***}	L ^{***}	NS	L ^{***}	L ^{***}
Crop-thinning level (clusters/shoot)											
1	0.48	0.41	0.36	0.53	34	37	36	37	0.0	28.1	40.9
1.5	0.46	0.37	0.30	0.45	36	36	37	37	0.3	30.7	37.4
2	0.51	0.36	0.27	0.41	36	37	36	36	0.3	29.1	38.7
Significance	NS	NS	L ^{**}	L ^{**}	NS	Q [*]	NS	NS	L [*]	NS	NS

²0 = Minor bud injury only; 1 = one cordon injured; 2 = both cordons injured; 3 = both cordons killed plus one trunk injured; 4 = vine killed to soil level.

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively. Shoot density $\times$ crop-thinning level interactions were nonsignificant. L = linear, Q = quadratic.

Table 2. Canopy characteristics of 'Riesling' vines subjected to three shoot densities and three crop-thinning levels determined by point quadrat analysis in August 1990.

Factor	Contacts/insertion	Exposed clusters/insertion	Partially exposed clusters/insertion	Shaded leaves/insertion
Shoot density (shoots/m row)				
16	4.3	0.07	0.27	1.4
26	4.3	0.14	0.44	1.4
36	5.2	0.05	0.20	2.1
Significance	L ^{***} , Q [*]	Q ^{**}	Q ^{***}	L ^{***} , Q [*]
Crop-thinning level (clusters/shoot)				
1	4.7	0.06	0.27	1.8
1.5	4.5	0.09	0.30	1.7
2	4.5	0.11	0.34	1.5
Significance	NS	NS	NS	NS

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively. Shoot density $\times$ crop-thinning level interactions were nonsignificant. L = linear, Q = quadratic.

(data not shown), and shoot density had no effect at three of the four samplings. At 1100 HR, a significant shoot density $\times$ crop-thinning interaction occurred. Percentages of ambient PFR for the three crop-thinning levels (1, 1.5, and 2 clusters/shoot) at each shoot density were 35, 16, and 8 (16 shoots/m); 7, 14, and 9 (26 shoots/m); and 19, 45, and 36 (36 shoots/m). These data suggest that high fruit exposure may occur at high shoot densities, especially if cluster thinning is not used, perhaps simply because of more clusters per vine, but also due to shoot devigoration and low lateral shoot development. The relatively low cluster exposure (1.5 and 2 clusters/shoot crop-thinning levels) at 16 shoots/m could also be related to lateral shoot growth.

Yield components. In general, increasing shoot density and clusters per shoot levels increased yield, clusters per vine, and crop load (Table 4) and reduced cluster weight, berries per cluster, and berry weight (Table 5). These trends were supported by highly significant correlations ($P \leq 0.0001$) between shoots per vine, clusters per vine, and these yield components. Increasing shoot density also sometimes led to fewer clusters per shoot, a result suggesting that the increased canopy shade resulted in reduced fruitfulness (Table 5).

Several shoot density $\times$ crop-thinning interactions occurred among the yield components including yield (1987 and 1990), clusters per vine (1987, 1988, and 1990), cluster weight (1988), berries per cluster (1987 and 1988), and clusters per shoot (1989) (data not shown). As expected, the 16/1 and 36/2 combinations consistently gave the lowest and highest yields, respectively.

Although the remaining seven treatment combinations had theoretical clusters per vine ranging from 35 to 72, yield compensation apparently led to equivalent yields. Treatment combinations with similar clusters per vine but different shoot densities [16/1.5 and 26/1 (group A); 16/2, 26/1.5, and 36/1 (group B); and 26/2 and 36/1.5 (group C)] did not differ from one another within these groups. Interactions for clusters per vine seemed to be based on the large differences in clusters per vine between the 36/1.5 and 36/2 combinations. Cluster weights were highest for the 16/1 and 16/1.5 combinations in 1988, and the 36/1.5 and 36/2 treatments produced the lightest clusters. Increasing shoot density reduced cluster weight most substantially at 1 and 1.5 clusters/shoot and within treatment group A. Berries per cluster decreased linearly with increasing shoot density in 1987 at 1.5 clusters/shoot only; in 1988, berries per cluster decreased linearly with increasing shoot density at each crop-thinning level and within treatment groups A and C. Overall, reducing crop-thinning level by cluster thinning to 1.5 clusters/shoot was not effective for increasing cluster weight or berries per cluster at 26 and 36 shoots/. Clusters per shoot decreased with increasing shoot density in 1989 at 2 clusters/shoot only, a result suggesting reduced fruitfulness at the higher shoot densities.

Berry composition. Increasing shoot density and clusters per shoot reduced °Brix (1989 excepted) and pH (Table 6). TA increased with increasing shoot density in 1987 and with increasing clusters per shoot in 1987 and 1988. These trends were confirmed by significant correlations between shoots per vine,

Table 3. Leaf area components of 'Riesling' vines subjected to three shoot densities and three crop-thinning levels in 1990.

Factor	Leaf area on main shoots (cm ²)/			Leaf area on lateral shoots (cm ²)/			L : M ratio ²	Total (cm ²)
	Leaf	Shoot	Vine	Lateral shoot	Main shoot	Vine		
Shoot density (shoots/m row)								
16	129.8	1689	38,713	159.1	1959	45,046	1.24	83,760
26	113.4	1668	61,018	69.9	1027	37,131	0.60	98,149
36	120.0	1922	94,849	76.3	1259	62,378	0.64	157,227
Significance	NS	NS	L ***	L **	L *	NS	L **	L ***
Crop-thinning level (clusters/shoot)								
1	125.5	1888	68,906	87.7	1268	44,168	0.66	113,075
1.5	114.4	1688	62,982	96.3	1443	49,627	0.86	112,610
2	123.1	1718	65,323	119.4	1527	52,249	0.95	117,572
Significance	NS	NS	NS	NS	NS	NS	NS	NS

²L : M ratio = leaf area per vine on lateral shoots : leaf area per vine on main shoots.

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively. Shoot density $\times$ crop-thinning level interactions were nonsignificant. L = linear.

Table 4. Yield, clusters per vine, and crop load of 'Riesling' vines subjected to three shoot densities and three crop-thinning levels during 1987–90.

Factor	Yield (t·ha ⁻¹)				Clusters/vine				Crop load (kg yield/kg cane prunings)			
	1987	1988	1989	1990	1987	1988	1989	1990	1987	1988	1989	1990
Shoot density (shoots/m row)												
16	7.8	14.3	9.2	10.9	35	35	34	34	6.0	13.1	9.3	8.6
26	10.4	16.8	11.4	14.4	50	52	51	53	9.3	19.9	16.5	14.1
36	14.0	19.4	12.0	16.5	72	71	63	68	11.0	22.3	17.2	14.6
Significance	L **	L ***	L ***	L ** , Q **	L ** , Q **	L ***	L ** , Q *	L ***	L ***	L ***	L ** , Q **	L ** , Q **
Crop-thinning level (clusters/shoot)												
1	8.4	13.5	10.2	12.4	36	37	36	37	6.8	12.8	11.0	9.7
1.5	10.2	17.2	11.7	14.3	54	53	52	54	8.9	22.0	16.4	13.2
2	13.8	20.0	10.9	15.4	69	69	61	66	10.8	21.4	16.1	14.7
Significance	L ***	L ***	NS	L ***	L ***	L ***	L ** , Q *	L ***	L ***	L ***	L ** , Q *	L ***
Interaction	*	NS	NS	**	***	***	NS	**	NS	NS	NS	NS

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.0001, respectively. L = linear, Q = quadratic.

clusters per vine, and these three maturity indices (data not shown). Ranges of maturity indices over 4 years were 20.7 to 22.4 °Brix, 9.0 to 13.0 g·liter⁻¹ TA, and 2.94 to 3.14 pH.

There were shoot density × crop-thinning interactions in 1988 and 1989 for pH (data not shown). Within each crop-thinning level in both seasons, lowest pH occurred at the 26 shoots/m of row level and decreased linearly with increasing clusters per shoot in 1988 at each shoot density. Within treatment groups B and C, pH increased in both seasons with increasing shoot density.

Increasing shoot density increased berry FVT in 1989 and berry PVT in 1990 (Table 7). Significant positive correlations ($P \leq 0.001$) between shoots per vine and FVT in 1989 and between shoots per vine and PVT in 1990 confirmed these trends. Crop-thinning level had no apparent effect on berry monoterpenes levels in either 1989 or 1990. Significant positive correlations ($P \leq 0.0001$) occurred between clusters per vine and FVT in 1989 and between clusters per vine and FVT ($P \leq 0.04$) and PVT ($P \leq 0.001$) in 1990.

Juice composition. Juices in 1989 showed the same trends displayed by the berry samples (Table 7). Juice °Brix was not affected by shoot density but was reduced linearly with increasing clusters per shoot. This relationship was confirmed by a significant negative correlation ($P \leq 0.0001$) between clusters per vine and juice °Brix. Juice TA was not influenced by either factor, but significant positive correlations existed between juice TA and shoots per vine ($P \leq 0.04$) and clusters per vine ($P \leq 0.0002$). Juice pH was influenced in a quadratic manner by shoot density, with the

lowest pH at the 26 shoots/m of row level. Increasing clusters per shoot decreased pH linearly. Significant negative correlations occurred between juice pH and shoots per vine ($P \leq 0.03$) and between juice pH and clusters per vine ($P \leq 0.0001$). Juice FVT, as with the berries, increased linearly with increasing shoot density but was unaffected by crop-thinning level. A significant positive correlation between shoots per vine and juice FVT ($P \leq 0.0003$) confirmed this trend. Juice PVT was not influenced by shoot density but displayed a quadratic trend in response to crop-thinning level. There were no interactions between the two factors.

In general, differences in juice composition between treatment combinations were very small, and ranges of soluble solids, TA, pH, FVT, and PVT were very narrow: 22.4 to 23.3 °Brix; 9.3 to 10.2 g·liter⁻¹ TA; 2.82 to 2.98 pH; 1.11 to 1.32 mg·liter⁻¹ FVT; and 1.53 to 1.77 mg·liter⁻¹ PVT. These maximum and minimum values for each measurement did not necessarily correspond to highest- and lowest-yielding treatment combinations.

Discussion

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

Table 5. Cluster weight, berries per cluster, clusters per shoot, and berry weight of 'Riesling' vines subjected to three shoot densities and three crop-thinning levels during 1987–90.

Factor	Cluster wt (g)				Berries/cluster				Clusters/shoot				Berry wt (g)			
	1987	1988	1989	1990	1987	1988	1989	1990	1987	1988	1989	1990	1987	1988	1989	1990
Shoot density (shoots/m row)																
16	74.0	139.2	95.2	113.4	53	86	61	72	1.5	1.5	1.5	1.5	1.36	1.60	1.54	1.58
26	71.4	111.2	78.1	96.3	51	72	52	65	1.5	1.4	1.4	1.4	1.36	1.53	1.49	1.49
36	66.4	94.8	67.5	84.3	50	62	46	59	1.5	1.4	1.3	1.4	1.30	1.51	1.45	1.43
Significance	NS	L***	L***	L***	NS	L***	L***	L***	NS	NS	L***	L*	NS	L**	L**	L***
Crop-thinning level (clusters/shoot)																
1	75.8	127.2	97.7	118.0	55	79	62	77	1.0	1.0	1.0	1.0	1.36	1.61	1.56	1.54
1.5	67.5	115.3	80.3	92.2	49	73	53	61	1.5	1.5	1.4	1.5	1.33	1.55	1.50	1.51
2	67.9	101.1	60.7	82.4	50	68	43	57	1.9	1.9	1.8	1.8	1.33	1.49	1.42	1.44
Significance	NS	L***	L***	L***	NS	L***	L***	L***, Q*	L***	L***	L***, Q*	L***	NS	L***	L***	L**
Interaction	NS	*	NS	NS	*	*	NS	NS	NS	NS	**	NS	NS	NS	NS	NS

NS, ***, ***, ***, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS. NS, ***, ***, ***, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS. NS, ***, ***, ***, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS.

Table 6. Composition of 'Riesling' berries in response to three shoot densities and three crop-thinning levels during 1987–90.

Factor	°Brix				Titrateable acidity (g·liter ⁻¹)				pH			
	1987	1988	1989	1990	1987	1988	1989	1990	1987	1988	1989	1990
Shoot density (shoots/m row)												
16	22.4	21.9	22.4	21.4	9.0	10.7	10.4	12.8	3.14	3.07	3.07	3.00
26	22.0	21.1	22.0	20.7	9.4	11.1	10.5	13.0	3.10	3.02	3.02	2.94
36	21.9	21.0	22.4	20.9	9.8	11.1	10.8	13.0	3.10	3.05	3.05	2.97
Significance	L*	L***	NS	L*, Q	L***	NS	NS	NS	L**	Q**	Q**	L*, Q**
Crop-thinning level (clusters/shoot)												
1	22.4	22.0	22.4	21.4	9.3	10.6	10.6	12.8	3.14	3.09	3.07	3.01
1.5	22.2	21.2	22.1	20.8	9.5	11.2	10.6	13.0	3.11	3.05	3.04	2.96
2	21.8	20.7	22.2	20.8	9.5	11.1	10.5	12.9	3.09	3.01	3.03	2.94
Significance	L**	L***	Q*	L**	L*	L*	NS	NS	L**	L***	L**	L***
Interaction	NS	NS	NS	NS	NS	NS	NS	NS	NS	**	NS	NS

NS, ***, ***, ***, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS. NS, ***, ***, ***, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS, NS.

Table 7. Monoterpene content² of 'Riesling' berries and juices (1989–90) and composition of 'Riesling' juices (1989) in response to three shoot densities and three crop-thinning levels.

Factor	Berries				Juice				
	FVT (mg·liter ⁻¹)		PVT (mg·liter ⁻¹)		TA		FVT	PVT	(mg·liter ⁻¹)
	1989	1990	1989	1990	°Brix	(g·liter ⁻¹)	pH	(mg·liter ⁻¹)	
Shoot density (shoots/m row)									
16	0.73	0.65	2.33	1.99	23.1	9.6	2.96	1.17	1.66
26	0.87	0.65	2.25	2.08	22.8	10.0	2.89	1.17	1.59
36	1.07	0.66	2.35	2.25	22.9	9.8	2.93	1.27	1.64
Significance	L ***	NS	NS	L **	NS	NS	Q ***	L *	NS
Crop-thinning level (clusters/shoot)									
1	0.92	0.63	2.36	2.09	23.2	9.6	2.95	1.22	1.67
1.5	0.86	0.64	2.34	2.11	22.9	9.8	2.92	1.17	1.58
2	0.90	0.69	2.23	2.13	22.7	9.9	2.91	1.22	1.64
Significance	NS	NS	NS	NS	L **	NS	L **	NS	Q *

²FVT = free volatile terpenes, PVT = potentially volatile terpenes.

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively. Shoot density $\times$ crop-thinning level interactions were nonsignificant. L = linear, Q = quadratic.

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).

Although increasing shoot density increases canopy shade and crop load, separating the shade and crop load effects imposed by differing shoot densities has rarely been attempted. Reynolds et al. (1986) increased yield and delayed 'Seyval blanc' fruit maturity as shoot density increased from 7 to 20 shoots/m, despite similar crop loads and cluster numbers per vine. In that study, delayed fruit maturity and increased *Botrytis* bunch rot were clearly related to fruit exposure reductions associated with increasing shoot density. Murisier and Ziegler (1991), however, showed that cluster thinning 'Chasselas' vines with shoot densities of 8.5 to 10.2 shoots/m increased fruit soluble solids equivalent to vines with 5.1 shoots/m, despite a significant attenuation in canopy light levels at the higher shoot densities. Consequences of the high shoot densities, such as reduced fruitfulness, were not overcome by cluster thinning, but yield per shoot was improved as a result of heavier clusters. This suggests, contrary to the results of Reynolds et al. (1986), that shading effects on yield and fruit composition may be overcome by adjusting crop-thinning level.

The shoot densities imposed in the present study ranged from 16 to 36 shoots/m. By comparing these with studies using vertical canopy-trained vines, 16 shoots/m (7 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 (10 shoots/m²) is close to the current recommendation for growers in British Columbia based on local research (Reynolds, 1988, 1989), while 36 shoots/m (15 shoots/m²) is within the expected range for mechanized pruning.

Increasing shoot density reduced cane pruning weight slightly and decreased the percentage of canes with fully formed periderm. The actual number of canes per vine with fully formed periderm neither increased nor decreased with increasing shoot density. This phenomenon is consistent with previously reported trends (Reynolds, 1989; Reynolds et al., 1986) and is assumed to be a shade-related response. Although yield increases relative to increasing shoot density could be ascribed to more clusters per vine,

shoot density $\times$ crop-thinning interactions suggested that, at nearly equal cluster numbers per vine, increasing shoot density could still reduce cluster weights and berries per cluster. These shoot density effects on yield components were also noticed within each crop level, i.e., at theoretically equivalent leaf area : crop ratios.

Measurements of leaf area components suggested that vines adjusted to 16 shoots/m had equal or greater canopy density than those maintained at 26 shoots/m. Point quadrat analysis seemed to confirm this and also suggested that cluster exposure was greater at 26 shoots/m. Because shoot adjustment occurred ≈ 20 days before bloom, reduced shoot number increased individual shoot vigor. Consequently, internodes from 16 shoots/m treatments were longer than at the other shoot density levels, hence node number per shoot was lower on the hedged shoots. Therefore, as shoot density decreased, hedging severity increased slightly and the potential for lateral shoot growth (hence canopy shade) was magnified. At 16 shoots/m, more leaf area could be attributed to lateral shoot leaves than to main shoot leaves. Main shoot leaves also tended to be larger than at other levels, but this did not seem to be an important factor. Although lateral shoot growth was inhibited at 36 shoots/m, canopy density was appreciably increased by this reduced shoot spacing.

These results contrast with those of Smart (1988), who imposed treatments on 'Gewürztraminer' vines at veraison from 5 to 74 shoots/m. In doing so, the effects on lateral shoot growth and canopy density resulting from early season shoot adjustment could not be measured. Average length of individual shoots in Smart's trial was $\approx 60\%$ of that in our study, with main and lateral leaf areas of 30% to 50% of that reported here. There was also $\approx 30\%$ leaf loss due to shade in the vines used by Smart and none in our study. Under these conditions, Smart demonstrated a linear relationship between shoot density and cluster exposure, percent sunflecks, percent canopy gaps, and leaf layer number for shoot densities from 5 to 20 shoots/m. He therefore concluded that shoot densities from 15 to 20 shoots/m were probably optimal. Our results are somewhat at odds with these conclusions due to the shading effects from enhanced lateral shoot growth at low shoot densities under our conditions.

Increased shoot density seemed to delay fruit maturity. The duration of this delay is unknown because all treatments were harvested on the same day. Soluble solids were affected more than TA, a result suggesting that the effect could have been a conse-

quence of higher yields. It is also possible that since the 26 and 36 shoots/m levels produced many small lateral shoots, the sink strength of the fruit on those vines was diminished. The pH response, however, suggested that higher fruit exposure and lower canopy density at 26 shoots/m may have accounted for slightly lower pH values. Increases in FVT and PVT in response to increasing shoot density may be a concentration effect associated with lower berry weight, but this trend was not observed in response to crop level, despite similar effects on berry weight. Photon fluence rate measurements of clusters gave some evidence of more cluster exposure at the highest shoot density, which could account for the higher FVT and PVT concentrations, consistent with previous work with 'Gewürztraminer' (Reynolds and Wardle, 1989a, 1989b).

Effects of crop-thinning level on vine size, yield components, and fruit composition are consistent with trends reported in the literature (Fisher et al., 1977; Reynolds, 1989; Reynolds et al., 1986). In general, the increased crop stress resulting from increasing clusters per shoot produced slightly smaller vines and slightly increased winter injury. The increase in clusters retained per vine reduced cluster weight, berry weight, and clusters per vine and delayed fruit maturity except for monoterpenes.

Our shoot density recommendations of 20 to 25 shoots/m 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 takes place somewhere from 20 to 30 shoots/m.

Literature Cited

- Amerine, M.A. and C.S. Ough. 1980. Methods of analysis of musts and wines. Wiley, New York.
- Basler, P. 1980. Zur optimalen Belastung der Reben beim Riesling x Sylvaner am Zurichsee. Schweiz. Z. Obst-und Weinbau 116(3):56-64.
- Basler, P. 1981. Zur optimalen Belastung der Reben beim Blauburgunder in der Ostschweiz. Schweiz. Z. Obst-und Weinbau 117(13):354-364.
- British Columbia Ministry of Agriculture and Fisheries. 1987. Grape production guide. British Columbia Ministry of Agr. and Fisheries, Victoria.
- Dimitriadis, E. and P.J. Williams. 1984. The development and use of a rapid analytical technique for estimation of free and potentially volatile monoterpene flavorants of grapes. Amer. J. Enol. Viticult. 35:66-71.
- Eschenbruch, R., R.E. Smart, B.M. Fisher, and J.G. Whittles. 1987. Influence of yield manipulations on the terpene content of juices and wines of Müller-Thurgau, p. 89-93. In: T. Lee (ed.). Proc. 6th Austral. Wine Ind. Tech. Conf., Australian Industrial Publishers, Adelaide.
- Fisher, K.H., O.A. Bradt, J. Wiebe, and V.A. Dirks. 1977. Cluster thinning 'De Chaunac' French hybrid grapes improves vine vigor and fruit quality in Ontario. J. Amer. Soc. Hort. Sci. 102:162-165.
- Kelley, C.C. and R.H. Spilsbury. 1949. Soil survey of the Okanagan and Similkameen Valleys, British Columbia. B.C. Dept. of Agr. Rpt. 3, B.C. Survey, Victoria.
- Kiefer, W. and P. Crusius. 1984. Beziehungen zwischen Anschnitt, Mengenertrag und Qualität bei verschiedenen Rebsorten. Mitt. Klosterneuburg 34:51-63.
- Mattick, L.R. 1983. A method for the extraction of grape berries used in total acid, potassium, and individual acid analysis. Amer. J. Enol. Viticult. 34:49.
- McCarthy, M.G. 1986. Influence of irrigation, crop thinning, and canopy manipulation on composition and aroma of Riesling grapes. MS thesis. Waite Agr. Inst., Glen Osmond, Australia.
- Morris, J.R., C.A. Sims, J.E. Bourque, and J.L. Oakes. 1984. Influence of training system, pruning severity, and spur length on yield and quality of six French-American hybrid grape cultivars. Amer. J. Enol. Viticult. 35:23-27.
- Murisier, F. and R. Ziegler. 1991. Effets de la charge en bourgeons et de la densité de plantation sur le potentiel de production, sur la qualité du raisin et sur le développement végétatif. Essais sur Chasselas. Revue Suisse Viticult. Arboricult. Hort. 23:277-282.
- Nikov, M. 1987. Influence de la charge sur la production et la croissance de la vigne (c.v. Merlot). Connaissance Vigne Vin 21:81-91.
- Partridge, N.L. 1925. Growth and yield of Concord grape vines. Proc. Amer. Soc. Hort. Sci. 22:84-87.
- Reynolds, A.G. 1988. Response of Riesling vines to training system and pruning strategy. Vitis 27:229-242.
- Reynolds, A.G. 1989. 'Riesling' grapes respond to cluster thinning and shoot density manipulation. J. Amer. Soc. Hort. Sci. 114:364-368.
- Reynolds, A.G., C.G. Edwards, D.A. Wardle, D.R. Webster, and M. Dever. 1994. Shoot density affects 'Riesling' grapevines. II. Wine composition and sensory response. J. Amer. Soc. Hort. Sci. 119:881-892.
- Reynolds, A.G., R.M. Pool, and L.R. Mattick. 1986. Effect of shoot density and crop control on growth, yield, fruit composition, and wine quality of 'Seyval blanc'. J. Amer. Soc. Hort. Sci. 111:55-63.
- Reynolds, A.G. and D.A. Wardle. 1989a. Impact of several canopy manipulation practices on growth, yield, fruit composition, and wine quality of Gewürztraminer. Amer. J. Enol. Viticult. 40:121-129.
- Reynolds, A.G. and D.A. Wardle. 1989b. Influence of fruit microclimate on monoterpene levels of Gewürztraminer. Amer. J. Enol. Viticult. 40:149-154.
- Reynolds, A.G., D.A. Wardle, and J. Hogue. 1991. Impact of training system, vine spacing, and basal leaf removal on the performance of Riesling vines. Amer. Soc. Enol. Viticult., 42nd Annu. Meeting, Seattle. (Abstr.)
- Shaulis, N.J. 1982. Responses of grapevines and grapes to spacing of and within canopies, p. 353-361. In: A.D. Webb (ed.). Proc. Centennial Symp. Grapes and Wines, Univ. of California, Davis. Univ. of California Press, Berkeley.
- Shaulis, N.J. and P. May. 1971. Response of 'Sultana' vines to training on a divided canopy and to shoot crowding. Amer. J. Enol. Viticult. 22:215-222.
- Shaulis, N.J. and G.D. Oberle. 1948. Some effects of pruning severity and training on Fredonia and Concord grapes. Proc. Amer. Soc. Hort. Sci. 51:263-270.
- Shaulis, N.J. and W.B. Robinson. 1953. The effect of season, pruning severity, and trellising on some chemical characteristics of Concord and Fredonia grape juice. Proc. Amer. Soc. Hort. Sci. 62:214-220.
- Smart, R.E. 1982. Vine manipulation to improve wine grape quality, p. 362-375. In: A.D. Webb (ed.). Proc. Centennial Symp. Grapes and Wines, Univ. of California, Davis. Univ. of California Press, Berkeley.
- Smart, R.E. 1988. Shoot spacing and canopy light microclimate. Amer. J. Enol. Viticult. 39:325-333.
- Smith, S., I.C. Codrington, M. Robertson, and R.E. Smart. 1988. Viticultural and oenological implications of leaf removal for New Zealand vineyards, p. 127-133. In: R.E. Smart, R.J. Thornton, S.B. Rodrigues, and J.E. Young (eds.). Proc. 2nd Intl. Symp. Cool Climate Viticult. Oenol., N.Z. Soc. Viticult. Oenol., Auckland.
- Tomkins, J. and N.J. Shaulis. 1955. The Catawba grape in New York. II. Some effects of severity of pruning on the production of fruit and wood. Proc. Amer. Soc. Hort. Sci. 66:214-219.
- Webster, D., C.G. Edwards, S. Spayd, J.C. Peterson, and B.J. Seymour. 1993. Influence of nitrogen fertilization on the concentrations of monoterpenes, higher alcohols and esters in aged White Riesling wines. Amer. J. Enol. Viticult. 44:275-284.