Cluster Thinning Reduces the Economic Sustainability of Riesling Production

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Abstract: Crop levels of 1 (low), 1.5 (medium), and 2 (high) clusters per shoot established by cluster thinning (CT) were compared to nonthinned (control) Riesling vines over a three-year period. Yields ranged from 5.2 to 12.4 t/ha in 2008 and from 4.0 to 9.3 t/ha in 2009, while crop loads (yield/pruning weight) ranged from 2.9 to 8.7 in 2008 and 2.9 to 9.9 in 2009. By 2010, yield and crop load (yield/pruning weight) did not differ among treatments. Cluster weight was unaffected by CT in 2008 and 2009 but in 2010 control clusters weighed 39% less than low crop. There was little or no CT effect on berry size, pH, titratable acidity, pruning weight, cluster light exposure, or bud cold hardiness. Soluble solids at harvest ranged from 18.2 Brix in control to 22.3 Brix in low crop in 2008, from 18.9 to 22.1 Brix, respectively, in 2009, and from 20.5 to 22.0 Brix, respectively, in 2010. A consumer wine aroma sorting trial revealed that the low crop wine, and the low and medium crop wines, differed in aromatic attributes from the other treatments in 2008 and 2009, respectively. Grower financial net return per hectare ranged from $2,832 in low crop to $16,055 in control in 2008, from -$115 to $8,596, respectively, in 2009, and from $1,938 to $4,242, respectively, in 2010. Financial losses associated with CT could be recouped only by increases of up to 143% over base market price for grapes.

Key words: canopy management, crop load, fruit composition, wine aroma, yield components

The belief that low-yielding grapevines produce higher quality wines has a foothold among wine critics in the popular press, and grapevine yield restrictions have long been codified by law in the quality appellations of some European countries. In many regions, wine producers face a dilemma trying to maximize both grapevine yields and wine quality simultaneously (Keller et al. 2008). Balancing these two objectives requires a quantitative approach to understanding all aspects of yield management, including financial returns and vine balance.

The Ravaz index, or crop load (yield/pruning weight), is one of the most important indicators of vine balance (Ravaz 1911), and its usefulness is enhanced when measurements are calibrated with fruit and/or wine quality. Crop load between 5 and 10 is thought to be ideal for quality winemaking (Bravdo et al. 1985), a hypothesis subject to numerous investigations on various cultivars in climates both warm (Chapman et al. 2004, Keller et al. 2005) and cool (Reynolds et al. 2007). But the crop load metric does not encompass the full spectrum of decision making required to determine sustainable target yields, especially in regions where grape prices are pegged to parameters other than soluble solids at harvest.

Commercial growers commonly reduce crop load by cluster thinning (CT), assuming it will improve fruit composition and/or wine aromas or enhance consumer perception of quality, either of which may enable the grower to recoup lost revenue through higher prices. Cluster thinning has demonstrated positive effects on the timing of fruit maturity or soluble solids accumulation in red cultivars such as Cabernet Sauvignon (Nuzzo and Matthews 2006), Pinot noir (Reynolds et al. 1994b), and Merlot (Bowen et al. 2011) and in white cultivars such as Riesling (Reynolds et al. 1994a), Chasselas (Murisier and Ziegler 1991), and Trebbiano (Arfelli et al. 1996). Wines made from lower cropped vines exhibited increased herbaceousness in Chardonnay Musqué (Reynolds et al. 2007) and more vegetal aromas in Cabernet Sauvignon (Chapman et al. 2004). There were no CT effects on consumer perception of wine quality in studies of Gewürztraminer at one cluster per shoot (Reynolds and Wardle 1989), Sangiovese at three crop levels (Filippetti et al. 2007), and Cabernet Sauvignon at ~30% crop reduction (Ough and Nagaoka 1984); however, CT reduced consumer quality ratings in Sauvignon blanc (Gal et al. 1996, Naor et al. 2002). In the aforementioned studies, no economic analyses were conducted to link yield and quality with changes in grower financial returns.

Few quantitative tools exist to help growers calculate costs and benefits of CT. There are two primary costs associated with CT: skilled human labor and lost revenue from reduced yield. The cost of CT in Spain was determined to be $520

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Acknowledgments: This manuscript is based on work financially supported by the Total Quality Focus and Sustainability Program of the New York Wine & Grape Foundation. The authors thank Pete Saltonstall and Thom Bechtold at King Ferry Winery for providing and maintaining the vineyard site, Steve Lerch for technical support in the vineyard, Jim Meyers for statistical analyses and EPQA methodology, and Kathy Arnink for winemaking assistance. The authors also gratefully acknowledge Gavin Sacks, Associate Professor of Food Science, Cornell University, for intellectual contributions made to this work.

Manuscript submitted Oct 2012, revised Feb 2013, accepted Mar 2013

Publication costs of this article defrayed in part by page fees.

doi: 10.5344/ajev.2013.12123

to $650/ha by hand and $220/ha by machine (Tardaguila et al. 2008), but the impact of lower yields on net returns was not examined. Other reports have stated CT is economically feasible only as a temporary solution when vines are overcropped or when environmental conditions impede ripening (Keller et al. 2005, Nuzzo and Matthews 2006), but no economic analyses were presented to support these statements.

A model published by this research group was the first to position grapevine yield within a quantitative economic decision-making framework (Preszler et al. 2010). In this study, the model is applied to data from a field trial of varying crop levels in a mature commercial Riesling vineyard. The goal was to elucidate the effects of CT on yield components, fruit composition, wine similarities or differences, and financial net returns, and by doing so, enhance decision-making acuity among winegrape growers considering cluster thinning.

Materials and Methods

Vineyard site and experimental design. This field experiment was conducted from 2008–2010 at a commercial vineyard on the east side of Cayuga Lake in King Ferry, New York, in the Finger Lakes AVA (42.38°N; 76.38°W; 213 m elev.), on a soil type classified as Cazenovia series with a silt loam structure (USDA-NRCS soil maps). Vines were *Vitis vinifera* L. cv. Riesling cl. 239, grafted on 3309C rootstock, planted in 1998 in an east-west row orientation on a westward facing slope, with 1.5 m spacing between vines and 3.0 m between rows. Vines were cane pruned and trained to the Pendelbogen vertical shoot-positioned system. The vineyard was managed by the cooperating commercial grower according to the standard viticultural and disease control practices for *V. vinifera* in the Finger Lakes region. Growing degree days for the research site were estimated from mean daily temperatures, calculated with a base temperature or lower threshold of 10°C, using data recorded at the nearest weather station maintained by the Cornell University Network for Environment and Weather Applications (newa.cornell.edu), which is located in Lansing, New York, 9.2 km south of the vineyard trial block (42.57°N; 76.60°W; 124 m elev.). Precipitation data from the same nearby weather station was also used to estimate annual and growing season rainfall amounts at the research site.

The research plot spanned three adjoining vineyard rows and the experiment was designed with a nonthinned control plus three cluster thinning (CT) treatments: 1.0 (low crop), 1.5 (medium crop), and 2.0 (high crop) clusters retained per shoot. Treatments were arranged in a randomized complete block with four replicates. Each CT treatment was nine contiguous vines, the outer two serving as guard vines and the inner seven used for data collection, for a total of 112 experimental units. When at least two-thirds of the vines reached or exceeded Eichhorn–Lorenz (E–L) stage 9 (two or three leaves unfolded) secondary shoots were removed by hand and in 2008 primary shoots were thinned to 27 per vine, the lowest density counted before thinning. In 2009 and 2010, primary shoots were thinned to 36 per vine. Cluster thinning treatments were applied when at least two-thirds of the vines had reached or exceeded E–L stage 31 (pea-sized berries). Clusters located distally nearest the shoot apex were removed first, and the basal clusters were left intact.

Canopy characterization. Grapevine canopy characteristics relating to light environment and vegetative growth were recorded on a per vine basis when at least two-thirds of the vines had reached or exceeded E–L stage 35 of shoot development (early berry ripening, veraison). Enhanced point quadrat analysis (EPQA) was used to quantify the light environment (Meyers and Vanden Heuvel 2008). A thin rod was inserted through the fruiting zone perpendicular to the row direction, at 20 cm intervals, and sequential contact of the rod with leaves, clusters, and wires was recorded. Photon flux measurement was performed using a ceptometer (model AccuPAR LP-80; Decagon, Pullman, WA) for each vine between 11:00 and 14:00 hr EST on the same day as insertion data was collected. The ceptometer measurements were obtained by holding the probe (90 cm long with 80 photosensors) within the vine fruit zone and parallel to the row while simultaneously holding a photosynthetically active radiation sensor above the canopy, which was connected to the integrated controller. For each vine, 10 measurements were made over a period of 10 seconds, and the mean value for above- and within-canopy photon flux was recorded. The resulting data was analyzed by EPQA and Canopy Exposure Mapping (CEM) Tools (ver.1.7; Cornell University, Ithaca, NY) to calculate occlusion layer number (OLN), the number of shade-producing contacts; cluster exposure layer (CEL), the number of shading layers between clusters and the nearest canopy boundary; and cluster exposure flux availability (CEFA), the percentage of above-canopy light that reaches clusters.

Harvest and yield components. Vegetative and yield component data were collected on a per vine basis. Harvest date was based on a 22 Brix threshold determined using the average soluble solids of a random sampling of 100 berries from the low crop vines, as measured by a temperature compensating Brix scale (0–30) refractometer (Leica, Buffalo, NY). Experimental vines were harvested by hand on 9 Oct 2008, 7 Oct 2009, and 13 Oct 2010. Clusters were snipped, counted, and weighed with a hanging scale accurate to 0.01 kg (model SA3N340; Salter Brecknell, Fairmont, MN) to determine yield per vine, total yield, and average cluster weight. A subsample of 100 berries was collected randomly in duplicate from each treatment replicate and weighed to determine average berry weight. After being weighed on the day of harvest, the duplicate 100 berry subsamples were combined with their respective CT treatment field replicates for pressing and winemaking.

Differential thermal analysis and pruning. The low-temperature exotherm (LTE_{50}) at which 50% of buds are killed through freezing was measured by differential thermal analysis (DTA). A freezing chamber design and methodology was used (similar to Mills et al. 2006) that incorporated a computer-controlled freezing and data acquisition module, environmental test chamber (model BTC; Tenney Thermal Product Solutions, New Columbia, PA), digital temperature controller (model 942; Watlow Electric, St. Louis, MO), multimeter datalogging system (model 2701; Keithley Instruments, Cleveland, OH), and output computer (model 745; Dell Optiplex, Round Rock, TX).

Four vines were selected from each CT treatment replicate and in February of each year one cane was cut from each data vine, weighed, and brought to the lab for same-day DTA data collection. Canes collected for study were in an exterior canopy position, were representative of the approximately modal cane diameter for the vine, and exhibited uniformly dark periderm (Wolf and Cook 1992). Buds were excised from the second through sixth nodes on each cane, leaving 2 mm of surrounding tissue intact. Ten buds from each CT treatment replicate were randomly assigned and loaded into each thermoelectric module (TEM) on the freezing tray and the chamber temperature was reduced from 4°C to -40°C and back to 4°C at a rate of 4°C/hr (Mills et al. 2006). Signals (mV) produced by the heat of fusion upon freezing of the buds were detected by the TEMs and output was recorded every 15 seconds in Excel (Microsoft, Redmond, WA). Median LTEs were determined for each TEM and then averaged to derive a single mean LTE for each treatment replicate (Wolf and Cook 1992).

In mid-March of each year, vines were pruned to three remaining canes with 40 nodes per vine, and the prunings were weighed on a per vine basis with a hanging scale accurate to 0.01 kg (model SA3N340; Salter Brecknell). Cane weights collected earlier for DTA were added back into the pruning weights for each vine and crop load (yield/pruning weight) was calculated for each vine.

Winemaking and basic juice chemistry. All grapes were brought to the Cornell Orchards Teaching Winery to undergo processing on the day of harvest. Grapes from each separate CT treatment field replicate were whole-cluster pressed in a 40 L stainless-steel hydraulic bladder press (model Zambelli Hydro 40 Inox; Gino Pinto, Hammonton, NJ). Duplicate 200 mL juice samples were collected from each separate CT treatment field replicate and frozen at -20°C for later analysis. Pressed juice from the field replicates were then combined with their like CT treatments, treated with 50 mg/L sulfur dioxide added as potassium metabisulfite, and allowed to settle for 12 hr at 4°C. After settling, the juice was racked according to CT treatment into duplicate 19 L glass carboys for a total of eight fermentation lots. Carboys were chaptalized to the same level of soluble solids, 22 Brix, if necessary, and juice was inoculated with 0.25 g/L *Saccharomyces cerevisiae* strain R-HST yeast (Lallemand, Toulouse, France) previously rehydrated in GoFerm (Lallemand) according to manufacturer's instructions. Carboys were moved to a 16°C room and stirred daily. FermAid K (Lallemand) was added (0.15 g/L) at inoculation and again when wines reached 10 Brix. Wines fermented until residual sugar was measured at less than 0.5% using Clinitest tablets (Bayer, West Haven, CT), were racked into clean carboys, adjusted to 40 mg/L free sulfur dioxide, and moved to a 2°C storage room for approximately four months. Wines did not undergo any acid adjustments or malolactic fermentation and were screened for faults by an expert panel prior to being bottled manually using standard 750 mL green glass bottles and natural corks and then stored at 16°C. Wine aroma consumer sorting trials were conducted approximately one year after bottling.

Fruit composition data were collected from composite samples of previously frozen juice from each CT treatment field replicate, with duplicate analytical replicates. Juice soluble solids content was analyzed with a temperature-compensating Brix scale (0–30) refractometer (Leica). Juice pH was measured with a benchtop pH meter (model SB80P1; VWR SympHony, Radnor, PA) and titratable acidity was measured by titrating a 50 mL aliquot of juice against 0.10 M NaOH to pH 8.2 using an automatic titrator (model DL22; Mettler Toledo, Columbus, OH).

Wine aroma sorting trial. Wines made in 2008, 2009, and 2010 were evaluated for aromatic similarities approximately one year after bottling by an aroma sorting panel consisting of faculty, staff, and students at Cornell University who consume white wine at least once per month and were between 21 and 55 years of age. In each year of the study, 60, 40, and 48 people, respectively, participated in the trial and were seated in a room illuminated with fluorescent lighting and separated by white partitions. Wines were served in 30 mL aliquots at room temperature in clear tulip-shaped (ISO) 220 mL wine glasses covered with petri dish lids. Wines from all three CT treatments and nonthinned control were poured in duplicate for a total of eight glasses per panelist presented simultaneously. Each glass was coded with a random three-digit identification number and the presenting order of wines was randomized. Panelists were asked to sort wines into groups based on wine aromatic properties, using only their own sorting criteria and sensory experience of the aromas, without tasting. To minimize imposed researcher bias, panelists were not trained in advance and there was no predetermination or rating of attributes that would discriminate among wines (Lawless and Heymann 1998).

After the free sorting task was complete, wines placed in the same group were given a similarity rating of 1 and wines placed in different groups were assigned a similarity rating of zero. The number of times each pair of samples was sorted into the same group was summed across panelists to create a similarity square matrix for each year which was analyzed by the multidimensional scaling (MDS) statistical methodology (Kruskal 1964) in SAS software (ver. 8.0; SAS Institute, Cary, NC). Sorting data was summed across all panelists rather than inspecting for possible subsegments because more data points per stimulus pair correlates to a more precise fit to the data by MDS (Giguère 2007). MDS is a perceptual mapping technique used to structure data and reveal patterns of similarity among samples when underlying attributes are not well understood (Lawless and Heymann 1998). This statistical tool represents multivariate information in geometric maps corresponding closely to the input matrix, thus more frequently paired samples are placed close to each other while objects with stronger negative correlations are set farther apart (Nestrud and Lawless 2010). MDS has been widely applied in food science and sensory studies (Lawless and Glatter 1990, Tang and Heymann 2002) and to classify wine aroma in Chardonnay (Lee and Noble 2006) and Cabernet Sauvignon (Preston et al. 2008).

The appropriate dimensionality of MDS configurations was determined by calculating the squared correlation (RSQ), a direct measure of the proportion of variance accounted for by MDS, and badness-of-fit (i.e., stress value) at varying levels of dimensionality for the aroma sorting matrix (Schiffman and Knecht 1993). An RSQ between 0.90 and 1 and a stress value between 0 and 0.15 indicate a good fit of the model to the data and significance of the consensus plot (Wilkinson 1990). Analysis in two dimensions created a model with RSQ and stress value within the acceptable ranges for significance, and adding a third dimension provided little reduction in stress, little increase in RSQ, and made visual interpretation of the output configuration more difficult. Thus the analysis was completed under two dimensions, which is the most common and readily interpretable level (Giguère 2007) also used in prior MDS studies of wine aroma (Lee and Noble 2006, Preston et al. 2008).

Economic analysis. Input parameter data for yield (t/ha) before and after CT, fixed and variable production costs ($/t) before and after CT, and Riesling market price ($/t) were entered into the CT economic model (Preszler et al. 2010). Calculated output parameters were actual net returns ($/t) and constant net returns expressed as the minimum grape price ($/t) that must be received in order to adopt CT practices at varying levels. The model assumed net returns per tonne increase with higher per tonne price requirements, but were offset due to lower yields and higher production costs.

Statistical analysis. SAS software (ver. 8.0) was used to analyze viticulture and juice data for statistically significant differences. Data was analyzed using SAS general linear model procedure (GLM Proc) and means were separated using the Fisher's least significant difference (LSD) test at the 5% significance level. A p value of ≤ 0.05 was necessary for results to be reported as significant. Canopy light environment data were analyzed using EPQA and CEM Tools (ver. 1.7; Cornell University, Ithaca, NY). Consumer wine aroma sorting trial data were analyzed using the MDS Proc in SAS. Microsoft Excel was used for basic descriptive statistics. Economic data were analyzed using a previously published model (Preszler et al. 2010).

Results

Reproductive growth and fruit composition. Yield per vine and hectare was reduced by CT in 2008 and 2009 but no significant differences existed in 2010 (Table 1). Yields in 2008 ranged from 5.7 kg/vine in the control vines to 2.4 kg/vine in low crop, corresponding to 12.4 and 5.2 t/ha, respectively, or a 58% decrease in yield from CT. In 2009 yields ranged from 4.3 kg/vine in control to 1.9 kg/vine in low crop, corresponding to 9.3 and 4.0 t/ha, respectively, or a 57% decrease. In 2010 yields ranged from 3.0 kg/vine in control to 2.5 kg/vine in low crop, corresponding to 6.5 and 5.3 t/ha, respectively, with no significant differences among treatments. In 2008 and 2009 there was no CT effect on cluster weight, and yield differences were due to the number of clusters per vine after thinning. In 2010 clusters in the control weighed 39% less than low crop, and cluster weight differed among low, medium, and high crop treatments. Berry count per cluster in 2010 was separated into two groups: low (49.0) and medium (43.6) in one and high (30.8) and control (31.5) in another. There was little or no CT effect on berry weight in any year. In 2008 soluble solids ranged from 18.2 Brix in control up to 22.3 Brix in low crop. In 2009 soluble solids ranged from 18.9 Brix in control up to 22.1 Brix in low crop, while medium and high crop did not differ from one another. In 2010 soluble solids did not differ among medium, high, and control treatments (Table 1). Juice acid levels at harvest were highest in 2009, but CT had little or no effect on pH and TA in any year.

Vegetative growth and canopy characterization. Pruning weight of low crop vines was higher than the control in 2009 only (Table 1). Crop load differed among CT treatments in 2008, ranging from 2.9 in low crop to 8.7 in control, and in 2009, ranging from 2.9 to 9.9, respectively. In 2010 crop load of the low treatment was significantly lower than control but all other treatments did not differ. Low and medium crop load remained generally consistent all three years, but crop load in the high crop vines was 6.1 in 2008 and 7.1 in 2009 and fell to 4.3 in 2010. Likewise crop load in the control vines was 8.7 in 2008 and 9.9 in 2009 but fell to 5.8 in 2010. Bud cold hardiness as measured by mean LTE_{50} of buds sampled in February was -22.5, -23.1, and -23.1°C in each respective year of the study, with no significant CT effects among treatments. In each respective year of the study, OLN averaged 2.92, 2.97, and 2.75 and CEFA averaged 0.35, 0.28, and 0.32, with no significant CT treatment effects on either parameter. In 2008, CEL ranged from 0.62 in the control to 0.91 in the low crop vines, an increase of 47% that indicated more shading layers between clusters and their nearest canopy boundary as cluster thinning increased. Average CEL was 0.85 in 2009 and 0.78 in 2010, with no difference among CT treatments.

Wine aroma sorting. Calculated RSQ and stress values for MDS consensus plots indicated an acceptable fit of the two-dimensional model to the aroma sorting data all three years, and panelists reported significant differences among crop levels in all three years. In 2008 low crop was separated as the only wine above zero on the first dimension, while medium and high crop aromas more closely resembled the control, since those three samples were all below zero in the first dimension (Figure 1). In 2009 low and medium crop aroma clustered together as the only two wines above zero in both the first and second dimensions, while high crop and control were in separate groups. In 2010 data plots were spaced relatively equidistant in all four quadrants, thus panelists discerned differences among aromas of all crop levels.

Economic analysis. Yield and price parameters were obtained from data collected in the field trial or derived from published sources and entered in the CT economic model (Table 2). Yield of control vines was 12.4 t/ha in 2008, 9.3 t/ha in 2009, and 6.5 t/ha in 2010. Average market price for Finger Lakes Riesling was $1,773/t in 2008, $1,562/t in 2009, and $1,565/t in 2010, as found on the Finger Lakes Grape Program website (flg.cce.cornell.edu). Because yield and price decreased each year, potential revenue before CT (based on yield per hectare of the control plots) decreased from $21,985/ha in 2008 to $14,527/ha in 2009 and to $10,173/ha in 2010.

Variable and fixed production costs for managing one hectare of Riesling in the Finger Lakes, including additional labor costs of implementing cluster thinning, were derived from a published survey of vineyard management costs (White 2008) and entered into the model. Lost revenue from thinned fruit was calculated according to actual yields and market prices. Total costs were subtracted from potential revenue before CT to calculate grower net return, which in 2008 ranged from $2,832/ha in low crop to $16,055/ha in control, in 2009 ranged from -$115/ha in low crop to $8,596 in control, and in 2010 ranged from $1,938/ha in low crop to $4,242 in control. Compared to the base market price of $1,773/t, the derived minimum price for a grower to recoup costs of implementing CT for low crop grapes in 2008 was $4,316/t, a 143% price increase. Compared to the base market price of $1,562/t in 2009, the minimum price for low crop grapes was $3,740/t, a 139% price increase. And compared to the base market price of $1,565/t in 2010, the minimum price for low crop grapes was $2,000/t, a 28% price increase.

Table 1 Yield components and fruit composition of Riesling grapevines in the Finger Lakes, NY, 2008 to 2010. Cropping treatments imposed by cluster thinning to varying crop levels at E–L stage 31 (two-thirds of berries reach pea size; ~6 mm diam.) Yield data are shown at harvest. Each value is an average of four field replicates ± standard error.

	Clusters/shoot			Clusters/vine		
Crop level[a]	**2008**	**2009**	**2010**	**2008**	**2009**	**2010**
Low	1.0 ± 0.01 d[b]	1.0 ± 0.03 c	1.0 ± 0.01 c	27.4 ± 0.37 d	35.5 ± 1.06 c	37.1 ± 0.29 c
Medium	1.6 ± 0.01 c	1.5 ± 0.02 b	1.6 ± 0.01 b	43.1 ± 0.36 c	55.2 ± 0.72 b	56.4 ± 0.22 b
High	2.0 ± 0.11 b	2.0 ± 0.05 a	2.0 ± 0.06 a	54.9 ± 2.85 b	70.8 ± 1.87 a	70.5 ± 2.08 a
Control	2.5 ± 0.11 a	2.1 ± 0.12 a	2.0 ± 0.18 a	67.8 ± 2.88 a	74.0 ± 4.21 a	73.0 ± 6.48 a
	Cluster wt (g)			**Berries/cluster**		
	2008	**2009**	**2010**	**2008**	**2009**	**2010**
Low	88.9 ± 1.21 a	52.8 ± 2.96 a	66.1 ± 1.66 a	50.7 ± 1.32 a	34.2 ± 1.26 a	49.0 ± 0.82 a
Medium	80.6 ± 3.25 a	45.9 ± 2.75 a	54.8 ± 5.34 b	45.8 ± 1.28 a	29.2 ± 1.39 b	43.6 ± 3.47 a
High	83.1 ± 1.82 a	50.8 ± 3.35 a	39.6 ± 3.11 c	49.6 ± 3.41 a	32.7 ± 2.86 ab	30.8 ± 2.32 b
Control	84.3 ± 3.97 a	58.3 ± 4.65 a	40.5 ± 2.82 c	52.2 ± 3.87 a	41.9 ± 2.93 a	31.5 ± 1.89 b
	Berry wt (g)			**Yield/ha (t)**		
	2008	**2009**	**2010**	**2008**	**2009**	**2010**
Low	1.76 ± 0.04 a	1.54 ± 0.05 a	1.35 ± 0.06 a	5.2 ± 0.08 d	4.0 ± 0.15 c	5.3 ± 0.14 a
Medium	1.76 ± 0.06 a	1.57 ± 0.03 a	1.25 ± 0.06 a	7.5 ± 0.31 c	5.5 ± 0.30 b	6.7 ± 0.66 a
High	1.69 ± 0.10 a	1.56 ± 0.05 a	1.29 ± 0.02 a	9.8 ± 0.41 b	7.8 ± 0.73 a	6.0 ± 0.59 a
Control	1.63 ± 0.04 a	1.39 ± 0.02 b	1.29 ± 0.04 a	12.4 ± 1.00 a	9.3 ± 1.01 a	6.5 ± 1.01 a
	Yield/vine (kg)			**Pruning wt/vine (kg)**		
	2008	**2009**	**2010**	**2008**	**2009**	**2010**
Low	2.4 ± 0.04 c	1.9 ± 0.07 c	2.5 ± 0.06 a	0.87 ± 0.09 a	0.66 ± 0.04 a	0.75 ± 0.08 a
Medium	3.5 ± 0.14 b	2.5 ± 0.14 b	3.1 ± 0.31 a	0.78 ± 0.05 a	0.56 ± 0.08 ab	0.63 ± 0.13 a
High	4.6 ± 0.19 a	3.6 ± 0.34 a	2.8 ± 0.28 a	0.75 ± 0.04 a	0.53 ± 0.06 ab	0.66 ± 0.07 a
Control	5.7 ± 0.46 a	4.3 ± 0.47 a	3.0 ± 0.47 a	0.67 ± 0.04 a	0.44 ± 0.05 b	0.53 ± 0.07 a
	Crop load (yield/pruning wt)			**Soluble solids (Brix)**		
	2008	**2009**	**2010**	**2008**	**2009**	**2010**
Low	2.9 ± 0.32 d	2.9 ± 0.17 d	3.4 ± 0.27 b	22.3 ± 0.14 a	22.1 ± 0.10 a	22.0 ± 0.04 a
Medium	4.5 ± 0.39 c	4.7 ± 0.64 c	5.5 ± 1.14 ab	20.8 ± 0.08 b	21.0 ± 0.17 b	21.0 ± 0.11 b
High	6.1 ± 0.45 b	7.1 ± 0.97 b	4.3 ± 0.09 ab	20.0 ± 0.09 c	20.3 ± 0.26 b	20.9 ± 0.11 b
Control	8.7 ± 0.80 a	9.9 ± 0.76 a	5.8 ± 0.80 a	18.2 ± 0.03 d	18.9 ± 0.13 c	20.5 ± 0.21 b
	pH			**Titratable acidity (g/L)**		
	2008	**2009**	**2010**	**2008**	**2009**	**2010**
Low	3.64 ± 0.04 a	2.65 ± 0.02 a	2.81 ± 0.01 b	7.0 ± 0.48 a	13.5 ± 0.11 a	8.3 ± 0.04 a
Medium	3.52 ± 0.04 b	2.69 ± 0.02 a	2.89 ± 0.01 a	7.1 ± 0.36 a	13.4 ± 0.22 a	8.4 ± 0.08 a
High	3.48 ± 0.03 b	2.68 ± 0.05 a	2.82 ± 0.02 b	7.3 ± 0.10 a	13.2 ± 0.18 a	8.5 ± 0.12 a
Control	3.42 ± 0.02 b	2.62 ± 0.01 a	2.84 ± 0.03 b	7.3 ± 0.13 a	13.4 ± 0.19 a	8.3 ± 0.06 a

[a]Low: 1 cluster/shoot remains; medium: 1.5 clusters/shoot remain; high: 2 clusters/shoot remain; control: nonthinned.
[b]Analysis of variance was conducted through the GLM procedure in SAS. Within year columns, means followed by different letters are significantly different at $p \leq 0.05$ by Fisher's LSD test.

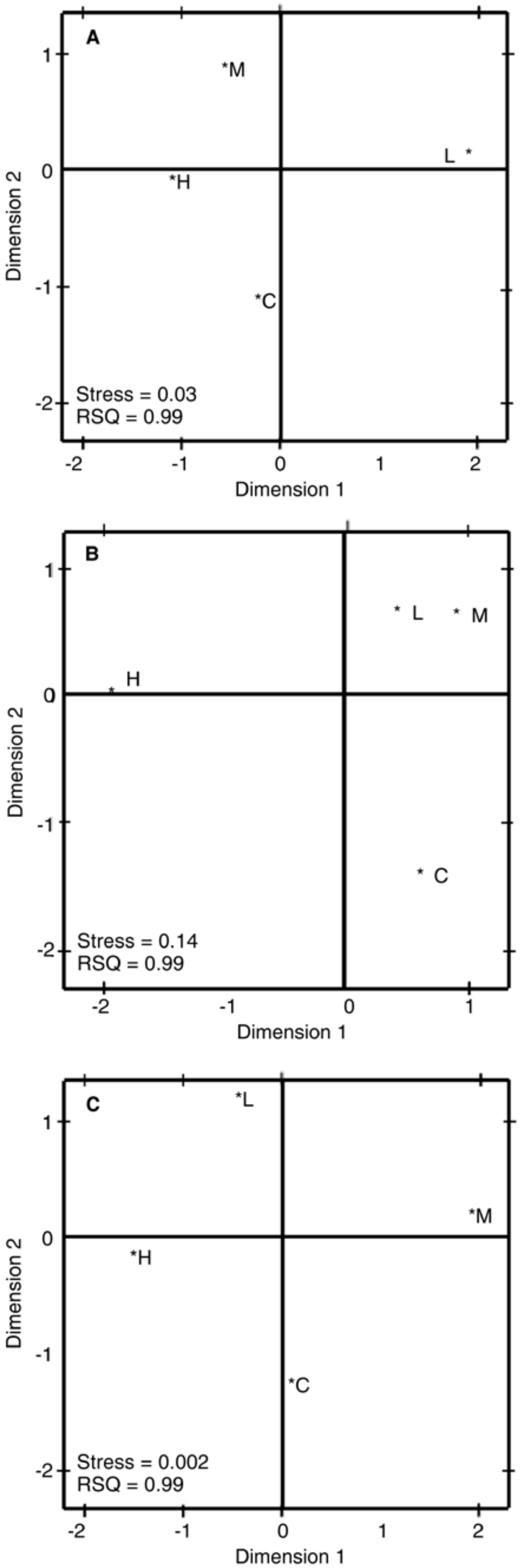

Figure 1 Two-dimensional consensus plots of similarity ratings of Riesling wines made in 2008 (**A**), 2009 (**B**), and 2010 (**C**) from low (L), medium (M), high (H), and control (C) crop vines averaged over responses of 60, 40, and 48 panelists, respectively.

Discussion

Reproductive growth and fruit composition. Cluster thinning improved juice soluble solids accumulation consistent with other observations for *V. vinifera* (Bowen et al. 2011, Nuzzo and Matthew 2006, Reynolds et al. 1994a, 1994b), although the impacts of CT varied by year and were less pronounced in 2010. There seems to be little dispute that CT advances ripening in white cultivars and cool-climate regions. There were little or no CT effects on juice pH and TA at harvest, which is reflected in the literature (Reynolds et al. 1994a). The effects of CT on yield components were mostly predictable with cluster number per shoot and per vine reduced according to severity of CT treatment. There were no direct effects on berry weight from within-year CT treatments. In 2008 and 2009, differences in yield among CT treatments were primarily due to reduced cluster count, but in 2010 cluster weight and berries per cluster were highest at the lower crop levels. The high crop and control exhibited suppressed vigor in 2010 such that yield was equivalent among all treatments (ranging from 5.3 to 6.5 t/ha), which may have been an indicator of vine carbohydrate reserves declining following the two previous years of very high crop level (between 7.8 and 12.4 t/ha).

Vegetative growth and canopy characterization. Control vines had reduced pruning weights in 2009, which is consistent with the literature for white *V. vinifera* (Reynolds and Wardle 1989, Reynolds et al. 1994a); however, in 2008 and 2010 pruning weights were not affected by CT likely as a result of individual vine variation. Wintertime cold acclimation as measured through DTA was not significantly affected by CT in any year, similar to other results (Bravdo et al. 1985, Keller et al. 2008). When compared to the control, CEL was higher in low crop in 2008, indicating more shading layers between clusters and their nearest canopy boundary, likely a result of increased growth of lateral and noncount shoots as a result of CT. However, there was no indication that higher CEL also caused any decrease in cluster sunlight exposure or bud fruitfulness.

While we did not note significant differences in pruning weight and CEFA in the lower cropped vines, these parameters could have other effects on the economic sustainability and health of the vineyard. Particularly in regions with high rainfall, vigorous early season shoot growth and a shaded fruiting zone could increase pressure from powdery mildew. Denser canopies with less cluster sunlight exposure are more susceptible to powdery mildew growth and also experience reduced coverage of fruiting zone fungicide spray materials, and disease severity has been shown to be inversely proportional (and strongly linear) to the degree of sunlight exposure as defined by CEFA (Austin et al. 2011). When compared to linear response curves between CEFA and cluster disease severity in a previous study of Chardonnay in the Finger Lakes (Austin et al. 2011), the actual CEFA decrease in this study would have increased disease severity from ~40% in control to ~50% in low crop in 2008, from ~35% to ~55% in 2009, and from ~40% to ~60% in 2010. As such, lower cropped vines may require additional management tools such as shoot positioning and leaf pulling to expose the fruiting zone and more frequent fungicide spray application; however, these management tools would increase the economic production costs beyond those modeled in this study.

Wine aroma sorting. Aroma sorting trial panelists were able to discern differences among wines from at least two crop levels in all three years of the study as illustrated in the MDS configuration consensus plots with significant RSQ and stress values (Figure 1). In 2008 the low crop wine (crop load 2.9) sorted separately on its own dimension, distinctly different from all other wines (crop load 4.9 to 8.7). In 2009 low and medium wines (crop load 2.9 and 4.7, respectively) clustered together distinctly separate from high and control

Table 2 Production costs and pricing parameters for Riesling in the Finger Lakes, NY, 2008 to 2010. Grower net return analysis expressed by metrics of previously published CT economic sustainability model (Preszler et al. 2010). Cropping treatments imposed by CT to varying crop levels when berries reached pea size. Yield data shown at harvest. Fixed and variable costs are based on maintaining one hectare of *V. vinifera* in the Finger Lakes for one year (White 2008).

	Potential yield before CT (t/ha)[b]			Expected market price before CT ($/t)[c]			Potential revenue before CT ($/ha)[d]		
Crop level[a]	**2008**	**2009**	**2010**	**2008**	**2009**	**2010**	**2008**	**2009**	**2010**
Low	12.4	9.3	6.5	1773	1562	1565	21,985	14,527	10,173
Medium	12.4	9.3	6.5	1773	1562	1565	21,985	14,527	10,173
High	12.4	9.3	6.5	1773	1562	1565	21,985	14,527	10,173
Control	12.4	9.3	6.5	1773	1562	1565	21,985	14,527	10,173

	Actual yield after CT (t/ha)[e]			Actual revenue after CT ($/ha)[f]			Production cost before CT ($/ha)[g]		
	2008	**2009**	**2010**	**2008**	**2009**	**2010**	**2008**	**2009**	**2010**
Low	5.2	4.0	5.3	9,220	6,248	8,295	5,930	5,930	5,930
Medium	7.5	5.5	6.7	13,298	8,591	10,486	5,930	5,930	5,930
High	9.8	7.8	6.0	17,375	12,184	9,390	5,930	5,930	5,930
Control	12.4	9.3	6.5	21,985	14,527	10,173	5,930	5,930	5,930

	Production cost before CT ($/t)[h]			Additional production cost after CT ($/ha)[i]			Additional production cost after CT ($/t)		
	2008	**2009**	**2010**	**2008**	**2009**	**2010**	**2008**	**2009**	**2010**
Low	478	638	912	457	432	426	88	108	80
Medium	478	638	912	420	402	389	56	73	58
High	478	638	912	395	371	0	40	48	0
Control	478	638	912	0	0	0	0	0	0

	Total production cost after CT ($/ha)[j]			Total production cost after CT ($/t)			Change in revenue after CT ($/ha)[k]		
	2008	**2009**	**2010**	**2008**	**2009**	**2010**	**2008**	**2009**	**2010**
Low	6,388	6,363	6,357	566	746	993	-12,766	-8,279	-1,878
Medium	6,350	6,332	6,320	534	711	970	-8,688	-5,936	313
High	6,326	6,301	5,930	519	685	912	-4,610	-2,343	-783
Control	5,930	5,930	5,930	478	638	912	0	0	0

	Change in revenue after CT ($/t)			Grower net return ($/ha)[l]			Grower minimum price ($/t)[m]		
	2008	**2009**	**2010**	**2008**	**2009**	**2010**	**2008**	**2009**	**2010**
Low	-2,455	-2,070	-354	2,832	-115	1,938	4,316	3,740	2,000
Medium	-1,158	-1,079	47	6,947	2,259	4,166	2,987	2,714	1,576
High	-470	-300	-130	11,050	5,883	3,460	2,284	1,910	1,695
Control	0	0	0	16,055	8,596	4,242	1,773	1,562	1,565

[a]Low: 1 cluster/shoot remains; medium: 1.5 clusters/shoot remain; high: 2 clusters/shoot remain; control: nonthinned.
[b]Yield of control field replicates (nonthinned) from Table 1.
[c]Average market price of Riesling as surveyed annually by Cornell Coop. Ext. Finger Lakes Grape Program.
[d]Potential yield before CT multiplied by expected market price before CT.
[e]From Table 1.
[f]Expected market price before CT multiplied by actual yield after CT.
[g]Based on published cost of all viticultural practices on one hectare of *V. vinifera* in the Finger Lakes for one year (White 2008).
[h]Fixed production cost before CT divided by potential yield before CT.
[i]Based on published costs of CT practices for one hectare of *V. vinifera* in the Finger Lakes (White 2008).
[j]Fixed production costs before CT plus variable production costs after CT.
[k]Actual revenue after CT minus potential revenue before CT.
[l]Actual revenue after CT minus total production cost after CT.
[m]Market price a commercial grapegrower would need to charge to maintain constant net return. Calculated as net returns for the control minus net returns for the CT treatment group ($/ha) all divided by reported yield ($/tonne) and added to the base minimum market price.

wines (crop load 7.1 and 9.9, respectively). For 2010 wines there were perceived differences among all four crop levels, with no grouping of wines together in the same quadrant of the MDS map, indicating four stimulus subgroups, even though the wines were made from a relatively limited range of crop load (between 3.4 and 5.8) and yield per hectare among crop levels in 2010 did not differ.

One possible hypothesis for the wine sensory differences could be compositional differences in fruit and/or wine due to a carryover effect of crop load impacts as well as N limitation and reduced carbohydrate storage in this vineyard because of growing season climatic variability. The 2009 growing season was relatively wet and cool and had a lower accumulation of growing degree days from 1 Apr through 31 Oct (1,237 GDD), than either the 2008 (1,306 GDD) or 2010 (1,500 GDD) growing seasons (Cornell University Network for Environment and Weather Applications; newa.cornell.edu). Mean annual precipitation decreased in each successive year of the study, from 74.5 cm in 2008 to 67.2 cm in 2009 and 65.5 cm in 2010. However, during the 2009 growing season (1 Apr through 31 Oct) the research site received more precipitation (53.3 cm) than in the 2008 (48.5 cm) and 2010 (36.2 cm) growing seasons. Other studies have shown that fruit quality in current and subsequent growing seasons can suffer from limited N availability and assimilate supply (Keller 2005), and Riesling wines made from grapes with variable N availability differed in sensory qualities and concentration of aromatic monoterpenes (Webster et al. 1993). Various terpene concentrations have been reported in another thinning study to increase at lower crop levels in Gewürztraminer (Reynolds and Wardle 1989). In a study of Chardonnay Musqué thinned to one cluster per shoot, wines exhibited increased herbaceousness and less tropical fruit (Reynolds et al. 2007), and CT has also been reported to decrease wine quality in Sauvignon blanc (Gal et al. 1996, Naor et al. 2002).

The goal of this sorting trial was to reveal any apparent similarities or differences among the wines without imposing questions of likeability, specific sensory properties, or a quality construct such as fruitiness. It cannot be inferred from this data whether consumers preferred or disliked any specific wines, as that data was not collected and no quality construct was asked of the panelists. The projective mapping technique does not provide any descriptive data, so the MDS output dimensions require additional sensory or chemical data to assist with interpreting the underlying attributes (Kennedy and Heymann 2009, Nestrud and Lawless 2010). However, the meaningful aspect of the MDS configuration is the proximity of points to each other, and the wider relative distances between points indicate more dissimilar wines among varying crop levels. The MDS method is a practical and reliable tool for assessing overall aromatic similarities of white wine (Lee and Noble 2006), and panelists in this study were able to discern differences in aroma of wines made from varying crop levels.

Economic analysis. Commercial growers are motivated to recoup costs incurred from CT and maintain consistent net returns by charging above-market prices for grapes, which is feasible if buyers can discern sensory differences in wines and are willing to pay a premium for them. In 2008 both low and medium crop levels exhibited such low financial returns that to recoup costs of CT the grower would need to charge 143% and 68% more per tonne, respectively, when compared to the control. It is unclear whether discernible sensory differences among crop levels would justify such large price increases. In 2009 the low crop level resulted in negative grower net returns, and the control crop level resulted in 46% greater financial net return than the high crop. In 2010 all crop levels exhibited positive net returns and a relatively small difference in yield, but net returns were maximized at the control crop level. The low crop level resulted in severely reduced financial net returns that would require 143%, 139%, and 28% grape price increases in each respective year of the study. The significant enhancement to fruit ripening caused by CT, although not specifically valued financially in this study, is likely not enough to outweigh the financial costs of implementing the practice or concerns about selling grapes at highly inflated prices.

Conclusion

This study examined the effects of CT on various fruit, wine, sensory, and economic parameters of a commercial Riesling vineyard in the Finger Lakes, New York, to understand how CT is justified as part of an economically sustainable viticulture program. A consumer aroma sorting panel cited differences between 2008 wines made from low crop (5.2 t/ha) and wines made from the higher cropped treatments (7.5 to 12.4 t/ha), but the low crop grapes required a 143% price increase to compensate for lost yields and increased production costs. Panelists found differences among 2009 wines at the higher crop levels, but were not able to discern differences among wines made from grapes at 1.0 and 1.5 clusters per shoot (4.0 and 5.5 t/ha, respectively). Sensory results showed differences for all 2010 wines even though yields did not differ, potentially a result of the compounding of CT treatments from previous years and impacts on vine N storage. There were no detrimental viticultural effects of CT, and despite higher soluble solids at harvest, vines with crop load less than 5 led to major financial losses for the grower at constant market prices. Cluster thinning practices designed to reduce yields for fruit or wine quality purposes also reduced grower net returns. While CT impacts on perceived wine aroma differed among years and crop levels, our results suggest that the substantial price increases necessary to offset losses from cluster thinning may not be warranted.

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