AJEV Papers in Press. Published online March 19, 2019.

AJEV PAPERS IN PRESS • AJEV PAPERS IN PRESS

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

Research Article

Impacts of Early Leaf Removal and Cluster Thinning on Grüner Veltliner Production, Fruit Composition, and Vine Health

Maria S. Smith[1,2] and Michela Centinari[1]*

[1]Department of Plant Science, The Pennsylvania State University, University Park, PA 16802; and [2]Present address: Department of Horticulture and Crop Science, Ohio Agricultural Research and Development Center, The Ohio State University, Wooster, OH 44691.

*Corresponding author (mzc22@psu.edu; tel: 814-867-0514)

Acknowledgments: The project was supported by the USDA Northeast Sustainable Agriculture Research & Education program under award No. 2017-38640-26822, the USDA National Institute of Food and Agriculture Federal Appropriations under Project PEN0 4628 and Accession number 1014131, and the Pennsylvania Wine Marketing and Research Board. The authors thank Dr. Charles Zaleski, MD, at Fero Vineyards and Winery for providing and maintaining the vineyard experimental site and Donald Smith for technical support. The critical reading of the manuscript by Kathy Kelley, Richard Marini, and Ryan Elias is gratefully acknowledged.

Manuscript submitted Dec 3, 2018, revised Feb 24, 2019, accepted Feb 28, 2019

Abstract: A traditional crop load regulation technique, cluster thinning (CT), was compared to a more innovative technique, early leaf removal (ELR) applied either at trace bloom (TBLR) or fruit set (FSLR), on high-yielding and vigorous *Vitis vinifera* Grüner Veltliner. Treatment effects on key production parameters, *Botrytis* bunch rot, tolerance to winter temperatures, and production costs were evaluated and compared to an untreated control over two years. Compared to CT, we hypothesized that ELR would improve fruit composition, reduce *Botrytis* bunch rot, and decrease grower costs. Yield regulation imposed by CT was significantly higher (39.3%) than that of TBLR (12.6%) or FSLR (13.3%), but neither CT nor ELR consistently improved fruit chemistry.

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

Our results suggest that the number of leaves removed (five) at trace bloom or fruit set were insufficient to induce a carbohydrate-limiting response, as ELR vines did not have lower fruit set or bud fruitfulness. Concurrently, TBLR and FSLR vines did not show recovery mechanisms such as greater production of lateral leaves or higher shoot efficiency. Although the overall level of bunch rot severity was lower than 5%, ELR consistently decreased bunch rot intensity (TBLR, FSLR) and severity (FSLR). TBLR also improved bud freezing tolerance during vine acclimation in both years. CT was the most expensive treatment, and the lack of a consistent improvement in fruit chemical composition or tolerance to winter temperatures indicated that Grüner Veltliner can properly ripen more than one cluster per shoot.

Key words: canopy management, cold hardiness, crop level, economic sustainability, grape production, viticultural practice

Introduction

Grüner Veltliner (*Vitis vinifera*) is a white grape cultivar widely planted in Austria, representing about 47% of the total grape acreage (Austria Wine Marketing Board 2015). Grüner Veltliner has historically been grown in the neighboring countries of the Czech Republic and Hungary, and more recently, in areas of southern New Zealand (Robinson et al. 2012). In Pennsylvania, it was first planted in 2003 (G. Troxell, personal communication, 2014) and, based on anecdotal observations from Pennsylvania commercial grape growers, Grüner Veltliner plantings have expanded throughout the state due to its suitability to regional growing conditions. Because of its recent introduction, very little is known about the best production practices for Grüner Veltliner under eastern US environmental conditions. A study conducted in

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

Virginia, which has a warm and humid climate, suggests that Grüner Veltliner is a fruitful cultivar capable of ripening high crop yields (5.0 kg/m of cordon; Wolf and Warren 2000). The reported levels of bunch rot were similar to Chardonnay, a cultivar with known susceptibility to bunch rot, but higher than other white grape cultivars such as Petit Manseng and Viognier (Wolf and Warren 2000). However, there is still uncertainty on how crop load (fruit versus vegetative biomass) management can be adjusted for optimum fruit production and quality while minimizing potential for bunch rot infection.

Cluster thinning (CT) is a crop load management practice traditionally used to reduce crop level and enhance fruit ripening of wine grape cultivars that tend to overcrop (Dami et al. 2006 and 2013, Gatti et al. 2012). Despite growers need for high fruit yield to maximize economic return, excessively high crop levels can lead to delayed fruit ripening and wood maturation, decreased carbohydrates storage, and potentially increased vine susceptibility to winter injury (Dami et al. 2006). While CT may improve fruit composition (Dami et al. 2006) and wine quality (Prajitna et al. 2007), the improvement in wine sensory perception might be not sufficient to justify the costs associated with the treatment (Preszler et al. 2013). Therefore, the additional costs of labor and yield loss associated with CT might discourage some producers from adopting it.

Alternatively, removing leaves in the fruit-zone shortly before or at beginning of bloom through fruit set (early leaf removal; ELR) has shown promise as a crop regulation technique mainly in European countries where grape yield is regulated by law (Poni et al. 2006, Intrieri et al. 2008, Tardaguila et al. 2010, Gatti et al. 2012). Early leaf removal reduces crop yield by imposing a carbohydrate limitation during bloom and early stages of fruit development (Poni et

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

al. 2006). Mechanisms behind ELR-induced yield reduction depend on the timing of application. Limiting carbohydrate supply shortly before or at beginning of bloom may decrease fruit set through increased flower abscission (Lebon et al. 2008), thus decreasing the total number of berries per cluster. When basal leaves are removed at the onset of fruit set, lower carbohydrate supply may limit cellular division during the initial stages of berry growth, thereby decreasing final berry size (Jona and Botta 1988). In some cases, but not always, ELR applied at pre-bloom reduced berry weight in addition to fruit set (Poni et al. 2006, Gatti et al. 2012).

Grapevines can exhibit mechanisms of physiological recovery from ELR, such as increased leaf carbon assimilation (A), greater production of lateral leaves (i.e., younger mean leaf age), and similar or greater leaf area-to-yield ratio as compared to undefoliated vines (Poni et al. 2006, Palliotti et al. 2011). Those recovery mechanisms might improve post-veraison canopy efficiency and in part explain why carbohydrate limitation imposed by ELR does not typically have a negative impact on fruit ripening and might even improve secondary metabolite composition in juice (Tardaguila et al. 2010, Bubola et al. 2017) and wine (Sivilotti et al. 2016, Hickey et al. 2018).

Although previous work often reports data on ELR effects on fruit chemical composition, to our knowledge, those data have not been related to the position of the cluster on the shoot (i.e., basal versus distal nodes). Several studies on ELR analyzed fruit composition of the basal cluster only, despite wine chemistry reflects the composition of both basal and distal clusters (Intrieri et al. 2008, Tardaguila et al. 2010, Gatti at al. 2012). Other work analyzed berry samples from all clusters regardless of their position on the shoot (Silvestroni et al. 2016, Bubola et al. 2017). Bloom typically begins in the basal inflorescence of a shoot (Vasconcelos et al. 2009); therefore,

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

when ELR is applied, distal inflorescences might be at an earlier phenological stage compared to those developed from basal nodes. Currently, it is unclear how ELR influences cluster morphology and chemical composition of distal clusters and the resulting impact on total fruit biomass used for winemaking.

When compared with CT, ELR has several potential advantages and drawbacks. Early leaf removal might reduce cluster compactness (Poni et al. 2006, Tardaguila et al. 2010) and therefore decrease fruit susceptibility to bunch rot (*Botrytis cinerea*), a major fungal disease in humid regions (Hed et al. 2015). In contrast, CT tends to increase berry growth and consequently cluster compactness, a compensatory result from removal of carbohydrate sinks (Ferree et al. 2003). Additionally, ELR improves canopy microclimate by increasing fruit-zone sunlight exposure, air flow, and pesticide spray penetration (Hed and Centinari 2018, Hickey and Wolf 2018). This might contribute to reducing bunch rot and improving primary and secondary metabolites to desirable levels in the harvested fruit (Bubola et al. 2017).

To its detriment, repeated use of ELR over multiple years has unintentionally reduced bud fruitfulness (i.e., number of clusters per shoot) in some cultivars despite increased sunlight exposure during bud formation (Sabbatini and Howell 2010, Hickey and Wolf 2018). Moreover, it is still uncertain how carbohydrate source-sink manipulation from ELR might impact storage of soluble carbohydrates (e.g., sucrose, fructose, glucose, and raffinose oligosaccharides) that play a critical role in vine freeze tolerance. Potential effects of ELR on vine susceptibility to winter injury is an important consideration for grape growing regions that experience low winter temperatures capable of damaging dormant tissues of *Vitis vinifera* cultivars.

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

The overall goal of this study was to provide targeted crop load management recommendations for Grüner Veltliner production under cool and humid growing conditions. We compared CT, a traditional crop load regulation practice, to a more innovative and still experimental practice, ELR, imposed at two different phenological stages. We hypothesized that, regardless of timing of application, ELR would be effective at reducing yield and improving fruit composition, while reducing cluster compactness and bunch rot compared with CT and an un-thinned, non-early defoliated control. Due to the expense and time required to perform crop load management practices, an economic assessment was developed to determine whether ELR would be a less expensive practice for yield reduction as compared to CT. We expected CT to have higher economic costs due to a longer application time required relative to ELR. To investigate effects of ELR on vine susceptibility to winter low-temperature, we estimated bud freeze tolerance using differential thermal analysis (DTA) during vine acclimation, maximum winter hardiness, and de-acclimation.

Materials and Methods

Vineyard site and experimental design. The study was conducted in 2015 and 2016 on Grüner Veltliner cl. 01 (*Vitis vinifera*) at a commercial vineyard in Lewisburg (40°59′N; 76°5′W; elevation: 171 m above sea level), Pennsylvania, US. The vineyard soil was classified as Elliber silt-loam (https://websoilsurvey.sc.egov.usda.gov/). The vines were grafted on 101-14 Mgt (*V. riparia* × *V. rupestris*) rootstock and planted in 2010. The vine spacing was 1.5 m within rows and 2.4 m between rows for a density of 2778 vines per hectare with rows oriented north-south. Vines were trained to a bilateral cordon at 0.8 m height and vertically shoot positioned. Winter

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

pruning was performed to retain eight two-bud spurs (16 nodes) per meter. Shoot density was adjusted to an average of 15 shoots per meter of cordon on 25 May 2015 and 26 May 2016 when shoots reached an average growth stage E-L 14 according to the modified Eichhorn-Lorenz system (E-L; Coombe 1995). Shoot hedging was performed two to three times per season between mid-July and late-August. Standard disease and insect control practices for *V. vinifera* cultivars in the eastern US were used (Wolf 2008).

Four adjacent rows were selected for the study. The experimental design was a complete randomized block design with four blocks per treatment that were assigned across the four rows. Each experimental unit consisted of 12 contiguous vines, with 10 inner vines used for data collection and the outer two serving as guard vines. The treatments consisted of a control (un-thinned and non-early defoliated vines); ELR performed at E-L 19, when flowers began to open (trace bloom leaf removal; TBLR); ELR performed at E-L 27 representing the onset of fruit set with clusters at 90° angle from the shoot (fruit set leaf removal; FSLR); and CT performed at E-L 32, bunch closure. Phenological assessment was not conducted separetely for basal and distal inflorescences. Three shoots from each one of the four central vines of each experimental unit (12 shoots per experimental unit) were flagged on the same day of shoot thinning for data collection.

Early leaf removal treatments were implemented on both sides of the canopy by hand-removing the first five well-developed basal main leaves on each shoot and any associated lateral shoots that developed from the same nodes. Treatments were applied on 3 Jun 2015 and 9 Jun 2016 (TBLR) and 18 Jun 2015 and 21 Jun 2016 (FSLR). Cluster thinning was performed by removing distal clusters and retaining only one cluster per shoot on 1 Jul 2015 and 13 Jul 2016.

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

The day CT was performed, three basal leaves were removed on both side of the fruit-zone of control and CT vines in accordance with standard grower practice. Treatments were applied on the same vines in 2015 and 2016. No additional passes of leaf removal were applied to any of the treatments during the season to mimic the grower's practice.

Weather conditions. Air temperature was recorded every 30 min throughout the study period using wireless temperature data loggers (iButton Fob, Model DS9093Fl; Embedded Data Systems, Lawrenceburg, KY). One temperature sensor was placed on the first set of catch wires at the height of the fruit-zone in each experimental unit of the control treatment. Growing degree days (GDD, base 10 °C) were calculated for each sensor from 1 Apr to harvest as GDD = [(maximum daily temperature + minimum daily temperature)]/2] – 10. Daily precipitation from 1 Apr to harvest for the town of Lewisburg was acquired from the National Center for Environmental Information (https://www.ncdc.noaa.gov/cdo-web/datasets#GHCND).

Vegetative growth measurements. To determine treatment impacts on canopy density and light availability in the fruit-zone, enhanced point quadrat analysis (EPQA, Meyers and Vanden Heuvel 2008) was assessed twice per season. EPQA measurements were performed preveraison on 16 Jul 2015 and 28 Jul 2016 and post-veraison on 25 Aug 2015 and 7 Sep 2016. Point quadrat analysis was conducted using a thin metal rod and an insertion guide marked with 20 cm intervals to make 36 insertion points per experimental unit. Photosynthetically active radiation (PAR) was measured with a LI-250A ceptometer (LI-COR Bioscience, Lincoln, NE) within 2 hrs of solar noon on the same day under full-sun conditions. Ambient PAR was measured for each experimental unit by averaging one measurement per second over 15 sec with the ceptometer positioned above the canopy in the middle of the row and the sensors oriented

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

parallel to the sky. Ten intracanopy PAR measurements per experimental unit were taken with the ceptometer placed parallel to the vine row in the interior of the canopy at fruit-zone height with the sensor directly facing upward. In-canopy photon flux was calculated as the ratio of intracanopy canopy PAR and ambient PAR. Canopy density and in-canopy flux measurements were analyzed with Canopy Exposure Mapping Tools (v. 1.7, freeware from J.M. Meyers, Cornell University, Ithaca, NY), which was developed to calculate occlusion layer number, leaf and cluster exposure flux availability (Meyers and Vanden Heuvel, 2008).

All flagged shoots were collected one day prior to harvest to assess end-of-season shoot leaf area. Main and lateral leaves were measured separately using a scanning leaf area meter (LI-3100c, LI-COR Bioscience, Lincoln, NE). Pruning weights were taken on the 10 inner vines of each experimental unit during the dormant season (9 Mar 2016 and 9 Mar 2017) with a 0.01 kg accuracy hanging scale (Pelouze 7710, Rubbermaid, Inc., Huntersville, NC).

Fruit set, yield parameters, and fruit composition. Fruit set was estimated in 2016 for each inflorescence of the control and ELR flagged shoots at stage E-L 18, as reported by Poni et al. (2006). The basal and distal inflorescence of each flagged shoot, as well as 50 inflorescences from non-experimental Grüner Veltilner vines, were photographed on a flat, white background on the same day. The number of visible flowers in each photo was counted using MS Paint (Microsoft, Bellevue, WA). After taking the photos, the 50 inflorescences from the non-experimental vines were collected, transported to the laboratory, and the actual number of flowers per inflorescence were counted. The regression equation ($y = 1.404x + 11.347$; $r^2 = 0.831$) established between the actual number of flowers per inflorescence and that counted on the 50 photos was used to estimate the number of flowers on the inflorescences of the flagged

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

shoots. The percentage of fruit set was then determined at harvest as ratio between the total number of berries per cluster and the number of estimated flowers at stage E-L 18. Because of lack of personnel resources, we were unable to take pictures of the inflorescences at stage E-L 18 in 2015; therefore, fruit set was not estimated in the first year of the study.

Vines were harvested by hand on 24 Sep 2015 and 28 Sep 2016 the day before commercial harvest. Immediately prior to harvest, 30 randomly selected basal and distal clusters per experimental unit were visually assessed for bunch rot incidence (percentage of clusters infected) and severity (percentage of infected cluster area; Horsfall and Barratt 1945). Clusters from the 10 inner vines of each experimental unit were counted and weighted using a hanging scale accurate to 0.01 kg (Pelouze 7710). The average cluster weight was calculated by dividing yield by the number of clusters per experimental unit. Ravaz index was calculated as the ratio of yield to pruning weight collected in the following dormant season.

In both years, basal and distal clusters of flagged shoots were collected separately two days prior to harvest. Cluster compactness was rated for each cluster using a scale from 1 to 5, where 1 described a cluster as “very loose; no berry contact; bending of the stem to 90° possible” and 5 as “very compact; berries not flexible; bending of the stem not possible” (Ipach 2005). Harvested clusters were then frozen at – 20 °C until they were deconstructed to count the number of berries per cluster and measure average berry weight. Frozen berries were divided in the following categories: full size and healthy berries, berries infected by rot, small seedless berries (< 5 mm diameter, ‘chicken’ berries), and live green ovaries (small, firm, green, seedless berries; Iland 2011). Berries were counted and weighted by category, thawed in a water bath at 60 °C, crushed, and strained to remove skin and seeds for juice chemistry analysis. Total soluble solids (TSS)

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

were measured using a hand-held refractometer (Master, Atago USA, Inc., Bellevue, WA), pH using a pH-meter (Orion Star A111, Thermo Fisher Scientific, Waltham, MA), and titratable acidity (TA) was measured using an autotitrator (G20, Mettler Toledo, Columbus, OH). Titrations were made using a 10 mL juice sample size titrated with 0.1 N NaOH to an endpoint pH of 8.2. Juice chemistry analysis was conducted for basal and distal clusters separately but also for both clusters combined.

Bud freeze tolerance and fruitfulness. Primary bud freeze tolerance was estimated monthly throughout the dormant season from November to March. The differential thermal analysis (DTA) method was used in accordance to Mills et al. (2006). Eight canes were collected randomly across the 10 inner vines of each experimental unit and stored at 4 °C until analysis. DTA analysis was performed twice over the following 48 hrs; four canes for each experimental unit were used for each DTA run: five buds per cane were excised from nodes two through six with approximately 2 mm of intact surrounding tissue and placed on a thermoelectric module (Melcor Corporation, Trenton, NJ). Six trays, each containing nine cell modules each, were placed in a programmable temperature-controlled freezer (Tenney, Thermal Products Solutions, New Columbia, PA). The temperature was lowered from 4 °C to – 40 °C at a rate of 4 °C hr^{-1}, held at – 40 °C for 1 hr, and then increased to 4 °C at the rate of 4 °C hr^{-1}. Lethal bud temperature was expressed as median low temperature exotherm (LT_{50}) or the temperature at which 50% of primary buds died. Bud fruitfulness was evaluated as number of inflorescences per shoot the spring following treatments application. Measurements were taken prior to shoot thinning on 25 May 2016 and 9 May 2017.

Economic analysis. An economic analysis was conducted to estimate the additional price per

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

tonne of Grüner Veltilner grapes and retail price per 750 mL bottle of wine if CT, TBLR, and FSLR were adopted compared no additional crop load management practices except shoot thinning (Preszler et al. 2013). The time necessary to apply each treatment was recorded for each experimental unit in 2015 and 2016 and averaged across the two years. The additional labor costs per hectare were estimated according to Yeh et al. (2014). Expected revenue per hectare was calculated by multiplying yield by the average industry price per tonne for Grüner Veltliner for 2015 and 2016 (https://flgp.cce.cornell.edu). The additional production cost per tonne, the additional price per tonne (i.e., grower preferred price), and retailed price per 750 mL bottle of wine required to provide the same grower revenue were estimated.

Statistical analyses. Data analyses were performed using JMP statistical software (v. 12.1, SAS Institute, Cary, NC). All data were analyzed using a mixed-effects analysis of variance (ANOVA) model with year and treatment as fixed-effects and block as a random-effect. Treatment differences were assessed using Tukey's honestly significant difference (HSD) pair-wise comparison test. In the instance of a treatment by year interaction effect, parameters were analyzed separately within each year. We chose to use a more liberal critical value to test our hypotheses (probability value of 10% rather than 5%). Data collected under field condition could be quite variable and, therefore, it would require a very large sample size to detect difference at the 5% level (Marini 1999). We also elected to report exact *P*-values to help the reader with data interpretation.

Results

Weather conditions. Seasonal GDD calculated from 1 Apr to harvest was similar between the two growing seasons. Cumulative GDD was 53 GDD higher in 2015 than 2016

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

(1884 *vs.* 1831). However, 2015 was a wetter year with 161 mm more precipitation than 2016 (555 *vs.* 394 mm). Cumulative precipitation from Apr 1 to harvest was close to the past 10-year average (589 mm) in 2015, but much lower in 2016.

Vine vegetative growth. Overall, ELR had modest effects on canopy density and no impact on the amount of sunlight reaching the clusters and the leaves in the fruit-zone (Cluster and leaf exposure flux availability; Table 1). Results were consistent between the two years; differences were mainly observed preveraison, while tended to disappear later in the season, after veraison. As expected, ELR reduced the number of leaf layers (TBLR, FSLR), the number of shade-producing leaves and clusters (occlusion layers; TBLR), and the percentage of interior leaves and clusters (FSLR) preveraison when compared to the control (Table 1). Main, lateral, and total leaf area did not differ amongst treatments in 2015; however, in 2016, FSLR vines had lower main and total leaf area than CT vines (Table 2). Pruning weight was lowest in the TBLR and highest in the CT treatment (Table 3).

Yield parameters, fruit set and composition. The crop load management treatments had lower yield compared to control vines in both years (Table 3). Cluster thinned vines had the lowest yield and Ravaz index; on average, CT vines had 39.3% lower yield than control vines. Yield reductions were less severe for TBLR and FSLR vines; they averaged to 13.3% and 12.6%, respectively, compared with the control. As expected, the lower yield of CT vines was due to a lower number of clusters per vine compared to the control and ELR (Table 3). Cluster thinned vines had the greatest average cluster weight when compared to basal and distal clusters combined of C and ELR vines (Table 3). However, when comparing basal clusters only, berry weight of CT was not higher than that of the control or TBLR vines (Table 4). Although TBLR

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

and FSLR vines exhibited lower yield than control vines, they did not have lower cluster weight, as we predicted, or fewer clusters (Table 3). Regardless of the timing, ELR did not affect fruit set of either the basal (P = 0.477) or distal cluster (P = 0.378) when compared to the control; fruit set averaged to 49.2% for the control, 45.1% for TBLR, and 48.6% for FSLR. Similarly, total number of berries per cluster, percentage of 'chicken' berries, and percentage of live green ovaries were similar between ELR and control for both basal or distal clusters (Table 4).

Early leaf removal, either applied at trace bloom or fruit set, consistently reduced the percentage of clusters infected by bunch rot (Table 3). When compared to the control, FSLR vines also had lower bunch rot severity and cluster compactness. The percentage of berries infected with bunch rot in basal and distal clusters confirmed the visual assessment of bunch rot conducted at harvest. The lowest percentage of infected berries was in the basal cluster of the FSLR vines and distal cluster of the TBLR vines (Table 4).

Juice chemistry was affected differently by treatments in the two vintages (Table 5). When combining juice from basal and distal clusters, the only consistent effect across the two years was that FSLR had lower TSS than CT. Concurrently, FSLR had the lowest shoot efficiency, defined as total sugar per shoot or unit of leaf area, and lower leaf area-to-yield ratio compared to CT (Table 6). When analyzing juice chemistry of the basal cluster alone, CT fruit had higher TSS than control in both years, but differences were not consistent across vintages when analyzing the total fruit produced by the shoot (i.e., combined basal and distal clusters for the control treatment).

Bud freeze tolerance and fruitfulness. Differences in bud freeze tolerance (i.e., LT_{50}) amongst treatments were mainly found in November, during the acclimation period (Table 7). In

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

both years, TBLR vines had higher bud freeze tolerance than the control in November; the LT_{50} of TBLR buds was 0.34 °C (2015) and 0.91 °C (2016) lower than that of the control. However, LT_{50} was lower in FSLR (0.35 °C) and CT (0.37 °C) compared with the control only in November 2015. There were no differences in LT_{50} amongst treatments during mid-winter, when buds reached maximum winter freeze tolerance, except for January 2016 when FSLR vines had higher bud freeze tolerance as compared to CT and TBLR vines. Bud freeze tolerance was not affected by CT or ELR in March, as the vines start to de-acclimate. The minimum winter temperatures during the two dormant seasons were –19.5 °C on 14 Feb 2016 and –11.7 °C on 9 Jan 2017, which may have not reached critical values likely to have caused extensive damage on Grüner Veltliner (Shellie et al. 2014). Although there were no differences in bud fruitfulness between the crop load management treatments and the control in either year, TBLR vines had fewer clusters per shoot (1.44) than CT (2.04) after two years of treatments application. Overall, bud fruitfulness ranged from 1.60 (control) to 1.88 (TBLR) in 2015 and from 1.44 (TBLR) to 2.04 (CT) in 2016.

Economic analysis. Unsurprisingly, crop load management practices increased grower costs and reduced expected revenue in both years (Table 8). Cluster thinning was the most expensive treatment; if CT was applied, the expected revenue ($/ha) for Grüner Veltliner growers would have been reduced by 44% in 2015 and 46% in 2016. Applying TBLR would have generated 26% (2015) and 16% (2016) less revenue, while applying FSLR would have resulted in 23% (2015) and 19% (2016) less revenue. As a result, Grüner Veltliner producers would have had to increase the retail price for a 750 mL bottle of wine by approximately $0.33

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

(FSLR) to \$1.18 (CT) in 2015 and \$0.17 (TBLR) to \$1.34 (CT) in 2016 to maintain revenue similar to that of the control (Table 8).

Discussion

The primary objective of this study was to understand how CT and ELR at trace bloom and fruit set impact key production parameters and tolerance to winter temperatures of Grüner Veltliner under humid, cool-climate conditions. Early leaf removal, regardless of timing, and CT reduced yield in both years of the study. However, the extent of yield reduction was much higher in CT vines than in those defoliated either at trace bloom or fruit set.

Yield reduction induced by CT was predictable and has been well-documented (Dami et al. 2006 and 2013, Gatti et al. 2012, Preszler et al. 2013). When comparing basal clusters, CT vines had a slight but not significant increase in berry weight (50 mg), which was not enough to counter balance yield-reduction effects from CT, as it occurs when clusters are removed at earlier phenological stages (Ferree et al. 2003). Low yield and crop load of the CT vines indicated that Grüner Veltliner can support more than one cluster per shoot. Crop load of CT vines was below the Ravaz index range, 4 to 10, and above the leaf area-to-yield ratio, 8 to 12 cm^2/g, suggested for optimal *V. vinifera* wine quality and vine balance (Kliewer and Dokoozlian 2005). Furthermore, CT had inconsistent effects on fruit ripeness at harvest, increasing TSS and pH only in one of the two years.

Yield reduction induced by ELR is much less predictable than CT and, in our study, was less severe than expected. Defoliation of the first six nodes of the shoot just prior to bloom reduced yields anywhere from 20% to 50% on several *V. vinifera* cultivars (Gatti et al. 2012,

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

Silvestroni et al. 2016, Hed and Centinari 2018, Hickey and Wolf 2018). In our study, yield reduction averaged to 12.6 % (TBLR) and 13.3 % (FSLR). More than five leaves would likely need to be removed from vigorous Grüner Veltliner vines under our environmental conditions to significantly decrease fruit set and reduce yield to levels comparable to previous work.

Although crop regulation was less severe than what anticipated, yield of ELR vines was significantly lower than that of control vines. The mechanism behind yield reduction remains unclear as ELR vines did not have lower fruit set, number of berries per cluster, or cluster weight. However, it should be noted that yield data was collected for all the experimental vines, which included a greater and more diverse population of shoots compared to the 12 shoots selected per experimental unit for fruit set and berry data collection. We cannot exclude that ELR might have significantly reduced fruit set and berry development when applied on shorter shoots with lower total leaf area than those selected. It also possible that, although not significant at the $P = 0.1$ level, a numerical reduction of average cluster weight for both ELR treatments (10.5%), berry weight for FSLR (basal cluster: 5.5%; distal cluster: 4.5%), and number of berries per cluster for TBLR (basal cluster: 12.5%; distal cluster: 14.7%) might have contributed to the lower overall yield of the ELR vines.

Removing five leaves likely did not limit the availability of carbohydrates in a way that could induce recovery mechanics that improve fruit chemical composition. Contrary to our hypothesis, all fruit reached similar technological maturity in both years regardless of crop load management. Previous studies indicated that improved fruit maturity of ELR vines was related to source-sink recovery mechanisms, which included higher late-season canopy efficiency due to greater production of lateral leaves, higher or similar leaf area-to-yield ratio, and greater leaf A

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

rate as compared to undefoliated vines (Poni et al. 2006, Palliotti et al. 2011). Grüner Veltliner vines exhibited vegetative recovery from ELR as main and lateral leaf area and leaf area-to-yield ratio were similar to that of the control vines. However, ELR vines did not have a younger and more efficient canopy (i.e., greater lateral leaf area and/or shoot efficiency) as reported in previous studies (Poni et al. 2008, Palliotti et al. 2011). Under our growing conditions, vines were hedged multiple times until late-August, which might explain why the lateral leaf area was similar amongst treatments. We don't exclude, however, that the effects of CT and ELR on fruit maturity, would be different in cooler and rainy years, since weather conditions during ripening influence the efficacy of CT and leaf removal (Frioni et al. 2007).

Our results also indicated that leaf removal would need to be applied multiple times throughout the season to maintain an open fruit-zone in vigorous Grüner Veltliner vines. Lateral shoot growth was observed in the fruit zone after applying ELR treatments but was not quantified. Removing five leaves at bloom or fruit set only temporarily improved canopy density and did not increase sunlight availability to leaves and clusters a few weeks after treatment application. This result contrasted with what was found in Riesling (*V. vinifera*) in a similar grape growing region, where lower canopy density and increased cluster and leaf sunlight exposure effects from mechanical and hand-applied ELR were still present after veraison (Hed and Centinari 2018).

Although ELR did not affect fruit set or berry weight, FSLR vines had lower cluster compactness and bunch rot severity. It might be possible that a numerical decrease in average berry weight for the basal and distal cluster (average to 5%), which was not significant at the P = 0.1 level, was enough to cause a visible reduction in cluster compactness. Cluster loosening is

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

typically a desirable effect from ELR, as it can reduce susceptibility to late-season bunch rot especially in humid climates and for cultivars with compact clusters. The fewer leaf layers in TBLR (preveraison) and FSLR (pre- and post-veraison) compared to the control could have also improved fungicide penetration resulting in lower bunch rot infections. However, overall levels of bunch rot severity were below 5% in both years. Rainfall in September 2015 (41 mm) and 2016 (23 mm) was lower than the 10-year average (116 mm) and likely resulted in low late-season disease pressure. Under those weather conditions, implementation of standard canopy management practices (shoot thinning, shoot positioning, hedging, and basal leaf removal at bunch closure) were sufficient to adequately control bunch rot.

Overall, ELR effects on cluster morphology or chemical composition were not influenced by the cluster position on the shoot. However, comparing basal clusters of CT shoots with both basal and distal clusters produced by control and ELR shoots instead of the basal cluster only, provided more accurate information on the effect of CT on juice chemistry. When comparing basal clusters, CT fruit had higher TSS than the control in both years, but the difference disappeared in 2015 when combining basal and distal clusters for the control.

One of the objectives of this study was to investigate the effects of source-sink manipulation on vine susceptibility to winter injury and bud fruitfulness. The most relevant result was a higher bud freeze tolerance during fall acclimation for the TBLR vines as compared to the control in both year; however, by December, buds amongst all treatments had similar ability to withstand low temperatures. Decreasing crop load resulted in increased bud freeze tolerance in overcropped vines (Dami et al. 2006), but it had also no effect on freeze tolerance when vines were already in balance before crop load adjustments (Dami et al. 2013, Preszler et al. 2013).

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

The higher freeze tolerance during the acclimation period of TBLR vines may have not been caused by a lower crop load but, instead, related to a temporary increase in bud sunlight exposure early in the season during bud development. Bud sunlight exposure can improve bud maturation (Fennell and Hoover 1991) and freeze tolerance during cold temperature acclimation (*V. labrusca*; Howell and Shaulis 1980). Crop load management treatments did not impact bud fruitfulness compared to the control in either 2015 or 2016. While the carbohydrate-limiting effect from ELR may negatively impact the development of the inflorescence primordia within the bud, which occurs between bloom and veraison (Sabbatini and Howell 2010, Hickey and Wolf 2018), in our study the amount of leaves removed, as previously stated, were likely insufficient to induce a stress (lower fruit set or bud fruitfulness) or recovery response.

When crop load management is implemented, a grape grower might be able to recover economic losses from reduced yield and increased labor costs by harvesting healthier fruit and improving wine quality. Under our experimental conditions, CT generated the greatest loss in revenue among the crop load management treatments because of the lowest yield and highest labor costs but did not improve fruit health or chemistry. Although applying ELR might cause economic losses under relatively dry late-summer conditions, we recognized that outcomes can change under different weather conditions. Costs associated with ELR may be recovered in wet season with higher disease pressure through the reduction of bunch rot severity (FSLR) and intensity (TBLR and FSLR). In our study, secondary metabolites in juice or wine were not analyzed; hence, we cannot determine if an improvement in wine quality due to either ELR or CT might have justified an increase in the retail price per bottle of wine. Estimating costs of crop load management practices can be challenging since many variables can influence the outcomes.

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

Our estimates should be used as an example, and we suggest growers to develop their own cost analysis based on their specific situation.

Conclusion

For two consecutive seasons, ELR applied either at trace bloom or fruit set on vigorous Grüner Veltliner vines did not reduce carbohydrate availability in a way that could decrease fruit set or improve fruit quality as reported in previous studies on other *V. vinifera* cultivars. Although significant, yield reduction from ELR was overall less than 15% and much lower than that imposed CT. The most relevant and consistent effects of ELR included higher bud freeze tolerance during fall acclimation (TBLR) and lower bunch rot incidence (TBLR and FSLR) and severity (FSLR) as compared to the control. Therefore, in humid climates, costs associated with ELR may be justified by a greater amount of healthy fruit at harvest. The lower yield of CT vines did not translate to a consistent improvement in fruit chemical composition, suggesting that Grüner Veltliner can be cropped to more than one cluster per shoot to minimize or avoid loss in revenue.

Literature Cited

Austria Wine Marketing Board. 2015. Austrian Wine Statistics Report. Retrieved from: https://www.austrianwine.com/press-multimedia/statistics/

Bubola M, Sivilotti P, Janjanin D, and Poni S. 2017. Early leaf removal has larger effect than cluster thinning on cv. Teran grape phenolic composition. Am J Enol Vitic 68:234-242.

Coombe BG. 1995. Adoption of a system for identifying grapevine growth stages. Aus J Grape Wine Res 1:100-110.

Dami I, Ferree D, Prajitna A, and Scurlock D. 2006. A five-year study on the effect of cluster thinning on yield and fruit composition of 'Chambourcin' grapevines. HortSci 4:586-588.

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

Dami I, Ennahli S, and Scurlock D. 2013. A five-year study on the effect of cluster thinning and harvest date on yield, fruit composition, and cold-hardiness of ‘Vidal Blanc’ (*Vitis* spp.) for ice wine production. HortSci 48:1358-1362.

Fennell A and Hoover E. 1991. Photoperiod influences growth, bud dormancy, and cold acclimation in *Vitis labruscana* and *V. riparia*. J Amer Soc Hort Sci 116:270-273.

Ferree DC, Cahoon GA, Scurlock DM, and Brown MV. 2003. Effects of time of cluster thinning grapevines. Small Fruits Rev 2:3-14.

Frioni T, Zhuang S, Palliotti A, Sivilotti P, Falchi R, and Sabbatini P. 2017. Leaf removal and cluster thinning efficiencies are highly modulated by environmental conditions in coold climate viticulture. Am J Enol Vitic 68:325-335.

Gatti M, Bernizzoni F, Civardi S, and Poni S. 2012. Effects of cluster thinning and preflowering leaf removal on growth and grape composition in cv. Sangiovese. Am J Enol Vitic 63:325-331.

Hed B, Ngugi HK, and Travis JW. 2015. Short- and long-term effects of leaf removal and gibberellin

on Chardonnay grapes in the Lake Erie region of Pennsylvania. Am J Enol Vitic 66:22-29.

Hed B and Centinari M. 2018. Hand and mechanical fruit-zone leaf removal at prebloom and fruit set was more effective in reducing crop yield than reducing bunch rot in ‘Riesling’ grapevines. HortTech 28:296-303.

Hickey CC and Wolf TK. 2018. Leaf removal effects on Cabernet franc and Petit Verdot: I. crop yield components and primary fruit composition. Am J Enol Vitic 69:221-230.

Hickey CC, Kwasniewski MT, and Wolf TK. 2018. Leaf removal effects on Cabernet franc and Petit Verdot: II grape carotenoids, phenolics, and wine sensory analysis. Am J Enol Vitic 69:231-246.

Horsfall JG and Barratt RW. 1945. An improved grading system for measuring plant disease. Phytopath 35:655.

Howell GS and Shaulis N. 1980. Factors influencing within-vine variation in the cold resistance of cane and primary bud tissues. Am J Enol Vitic 31:158-161.

Iland P. 2011. The Grapevine: From the science to the practice of growing vines for wine. Patrick Iland Wine Promotions Pty Ltd, Adelaide.

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

Intrieri C, Filippetti I, Allegro G, Centinari M, and Poni S. 2008. Early defoliation (hand vs mechanical) for improved crop control and grape composition in Sangiovese (*Vitis vinifera* L.). Aus J Wine Res 14:25-32.

Ipach R, Huber B, Hofmann H, and Baus O. 2005. Richtlinie zur Prü- fung von Wachstumsregulatoren zur Auflockerung der Traubenstruktur und zur Vermeidung von Fäulnis an Trauben. Outline for an EPPO-Guideline (European and Mediterranean Plant Protection Organization: Paris, France).

Jona R and Botta R. 1988. Fruit set and early berry development in two grapevine cultivars. Israel J Bot 307:203-216.

Keller M. 2015. The Science of Grapevines: Anatomy and Physiology. 2nd ed. Elsevier Academic Press, London.

Kliewer WM and Dokoozlian NJ. 2005. Leaf area/crop weight ratios of grapevines: influence on fruit composition and wine quality. Am J Enol Vitic 56:170-181.

Lebon G, Wojnarowiez G, Holzapfel B, Fontaine F, Vaillant-Gaveau N, and Clement C. 2008. Sugars and flowering in the grapevine (*Vitis vinifera* L.). J Exp Bot 59:2565-2578.

Marini RP. 1999. Are nonsignificant differences really not significant? HortSci 34:761-762.

Meyers JM and Vanden Heuvel JE. 2008. Enhancing the precision and spatial acuity of point quadrat analyses via calibrated exposure mapping. Am J Enol Vitic 59:425-431.

Mills LJ, Ferguson JC, and Keller M. 2006. Cold-hardiness evaluation of grapevine buds and cane tissues. Am J Enol Vitic 57:194-200.

Palliotti A, Gatti M, and Poni S. 2011. Early leaf removal to improve vineyard efficiency: gas exchange, source-to-sink balance, and reserve storage responses. Am J Enol Vitic 62:219-228.

Poni S, Casalini L, Bernizzoni F, Civari S, and Intrieri C. 2006. Effects of early defoliation on shoot photosynthesis, yield components, and grape composition. Am J Enol Vitic 57:397-407.

Poni S, Bernizzoni F, and Civardi S. 2008. The effect of early leaf removal on whole-canopy gas exchange and vine performance of *Vitis vinifera* L. 'Sangiovese'. Vitis 1:1-6.

Prajitna A, Dami IE, Steiner TE, Ferree DC, Scheerens JC, and Schwartz SJ. 2007. Influence of cluster thinning on phenolic composition, resveratrol, and antioxidant capacity in Chambourcin wine. Am J Enol Vitic 58:346-350.

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

Preszler T, Schmit TM, and Vanden Heuvel JE. 2013. Cluster thinning reduces the economic sustainability of Riesling production. Am J Enol Vitic 64:333-341.

Robinson J, Harding J, and Vouillamoz J. 2012. Wine Grapes: a complete guide to 1,368 vine varietals including origins and flavours. Harper Collins, New York.

Sabbatini P and Howell GS. 2010. Effects of early defoliation on yield, fruit composition, and harvest season cluster rot complex of grapevines. HortSci 45:1804-1808.

Shellie K, Cragin J, and Serpe M. 2014. Performance of alternative European wine grape cultivars in Southwestern Idaho: cold hardiness, berry maturity, and yield. HortTech 24:138-147.

Silvestroni O, Lanari V, Lattanzi T, Palliotti A, and Sabbatini P. 2016. Impact of crop control strategies on performance of high-yielding Sangiovese grapevines. Am J Enol Vitic 66:407-417.

Sivilotti P, Herrera JC, Lisjak K, Česnik HB, Sabbatini P, Peterlunger E and Castellarin SD. 2016. Impact of leaf removal, applied before and after flowering, on anthocyanin, tannin, and methoxypyrazine concentrations in 'Merlot' (*Vitis vinifera* L.) grapes and wines. J Agric Food Chem. 64:4487-4496.

Tardaguila J, Martinez de Toda F, Poni S and Diago MP. 2010. Impact of early leaf removal on yield and fruit and wine composition of *Vitis vinifera* L. Graciano and Carignan. Am J Enol Vitic 61:372-380.

Vasconcelos MC, Greven M, Winefield CS, Trought MCT and Raw V. 2009. The Flowering Process of *Vitis vinifea*: A review. Am J Enol Vitic 60:411-434.

Wolf TK and Warren MK. 2000. Crop yield, grape quality, and winter injury of eight wine grape cultivars in Northern Virginia. J Am Pom Soc 54:34-43.

Wolf TK. 2008. Wine grape production guide for eastern North America. Natural Resources Agricultural Engineering Service, New York.

Yeh AD, Gomez MI and White GB. 2014. Cost of establishment and production of *V. vinifera* grapes in the Finger Lakes region of New York-2013. Cornell University Department of Applied Economics and Management, Ithaca, NY.

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

Table 1 Enhanced point quadrat analysis (EPQA) characteristics of Grüner Veltilner vines with different crop load management treatments. Measurements were taken at preveraison (16 Jul 2015 and 28 Jul 2016) and post-veraison (25 Aug 2015 and 7 Sep 2016).

	Percent gaps (%)	Leaf layer number (n)	Occlusion layers (n)	Interior clusters (%)	Interior leaves (%)	Cluster exposure flux availability (%)	Leaf exposure flux availability (%)
				Preveraison			
Treatment (T)[a]							
Control	11.46	1.01 a[b]	1.86 a	18.2 a	20.4 a	57.1	53.1
CT	12.50	0.84 ab	1.59 ab	11.8 ab	10.2 b	59.5	56.9
TBLR	14.93	0.42 c	1.39 b	14.3 ab	12.2 ab	64.0	54.4
FSLR	17.24	0.58 bc	1.50 ab	13.7 b	5.9 b	64.1	57.5
P-value (T)	0.318	< 0.001	0.009	0.079	0.008	0.208	0.627
Year (Y)							
2015	12.09	0.78	1.62	10.7	13.1	62.4	56.6
2016	15.97	0.65	1.55	14.8	11.3	59.9	54.3
P-value (Y)	0.109	0.777	0.475	0.064	0.496	0.363	0.627
P-value (TxY)	0.781	0.647	0.720	0.680	0.100	0.674	0.966
				Post-veraison			
Treatment (T)							
Control	13.20	0.98 ab	1.78	22.0	13.9	55.3	57.1
CT	12.85	1.15 a	1.73	19.5	13.6	53.0	53.6
TBLR	9.38	1.12 a	1.88	23.4	14.3	60.5	53.4
FSLR	12.85	0.78 b	1.62	16.0	13.7	53.9	59.9
P-value (T)	0.669	0.019	0.128	0.253	0.995	0.133	0.075
Year (Y)							
2015	11.98	1.08	1.80	21.9	17.0	56.4	56.2
2016	12.15	0.94	1.71	18.5	10.8	54.9	55.8
P-value (Y)	0.945	0.105	0.224	0.253	0.007	0.544	0.846
P-value (TxY)	0.677	0.581	0.541	0.665	0.822	0.241	0.790

[a]CT = cluster thinning; TBLR = trace bloom leaf removal; FSLR = fruit set leaf removal.
[b]Treatment means followed by different letters within a column are significantly different (Tukey's HSD test, $P < 0.10$).

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

Table 2 Main, lateral, and total leaf area at harvest for Grüner Veltilner vines with different crop load management treatments. Data are separated by year due to significant treatment by year interaction.

	Main leaf area (cm^2)	Lateral leaf area (cm^2)	Total leaf area (cm^2)
		2015	
Treatment (T)[a]			
Control	1836.6	1691.2	3527.8
CT	1884.5	1582.7	3467.2
TBLR	1724.8	1758.6	3483.4
FSLR	1805.8	1878.6	3684.3
P-value (T)	0.951	0.666	0.955
		2016	
Treatment (T)			
Control	1823.5 ab[b]	2026.6	3850.1 ab
CT	2009.8 a	2427.2	4437.0 a
TBLR	1894.7 ab	2217.6	4112.3 ab
FSLR	1556.4 b	1840.9	3397.3 b
P-value (T)	0.072	0.128	0.015

[a]CT = cluster thinning; TBLR = trace bloom leaf removal; FSLR = fruit set leaf removal.
[b]Treatment means followed by different letters within a column are significantly different (Tukey's HSD test, $P < 0.10$).

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

Table 3 Effects of treatment and year on yield components, bunch rot, pruning weight, and crop load for Grüner Veltliner vines.

	Yield/ vine (kg)	Clusters/ vine (n)	Cluster wt (g)	Pruning wt/ vine (kg)	Ravaz index (yield/prun. wt [kg/kg])	LA/yield (cm^2/g)	Cluster compactness (1-5)[b]	Rot severity (% cluster area)	Rot intensity (% clusters)
Treatment (T)[a]									
Control	8.89 a[c]	49 a	190 b	1.18 ab	7.91 a	8.11 b	3.50 ab	4.42 a	71.7 a
CT	5.40 c	36 b	220 a	1.35 a	3.78 b	14.65 a	3.75 a	4.10 ab	69.2 a
TBLR	7.77 b	46 a	170 b	1.07 b	6.99 a	8.82 b	3.13 bc	2.81 ab	55.8 b
FSLR	7.71 b	45 a	170 b	1.19 ab	6.56 a	9.85 b	2.88 c	2.69 b	57.1 b
P-value (T)	< 0.001	< 0.001	< 0.001	0.031	< 0.001	< 0.001	0.001	0.012	0.005
Year (Y)									
2015	7.54	47 a	210 a	1.22	6.44	11.45 a	3.19	4.81 a	76.7
2016	7.34	35 b	160 b	1.18	6.17	9.27 b	3.44	2.19 b	50.2
P-value (Y)	0.418	< 0.001	< 0.001	0.469	0.588	0.005	0.048	< 0.001	< 0.001
P-value (TxY)	0.477	0.110	0.149	0.635	0.534	0.870	0.542	0.436	0.467

[a]CT = cluster thinning; TBLR = trace-bloom leaf removal; FSLR = fruit set leaf removal.
[b]Scale range is from 1= very loose clusters, no berry contact, bending of the stem to 90° possible to 5 = very compact, berries not flexible, bending of the stem not possible (Ipach et al. 2005).
[c]Treatment means followed by different letters within a column are significantly different (Tukey's HSD test, $P < 0.10$).

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

Table 4 Effects of treatment and year on berry weight, total number of berries per cluster, and percentage of normal size, 'chicken' and infected berries, and live green ovaries for basal and distal clusters of Grüner Veltliner vines.

	Berry wt (g)	Total berries /clusters (n)	Normal size berries (%)	'Chicken' berries (%)	Rot-infected berries (%)	Live green ovaries (%)
			Basal cluster			
Treatment (T)[a]						
Control	1.65 ab[b]	160	89.02	3.91	4.58 a	1.81
CT	1.70 a	157	90.66	3.78	3.06 ab	2.17
TBLR	1.63 ab	140	89.36	3.46	4.16 ab	1.90
FSLR	1.56 b	157	89.41	4.91	2.67 b	2.40
P-value (T)	0.024	0.161	0.529	0.255	0.070	0.635
Year (Y)						
2015	1.57	138	87.19	6.14	5.29	0.02
2016	1.70	170	92.03	1.89	1.95	4.12
P-value (Y)	< 0.001	0.161	< 0.001	< 0.001	< 0.001	< 0.001
P-value (T x Y)	0.270	0.933	0.600	0.102	0.465	0.629
			Distal cluster			
Treatment (T)						
Control	1.68	109	88.02	4.71 ab	4.44 a	2.32
CT	NA[c]	NA	NA	NA	NA	NA
TBLR	1.65	93	91.17	3.56 b	2.41 b	2.12
FSLR	1.60	105	88.52	5.83 a	4.07 ab	1.46
P-value (T)	0.215	0.097	0.145	0.073	0.073	0.167
Year (Y)						
2015	1.56	86	86.69	7.30	5.09	0.02
2016	1.71	118	91.79	2.10	2.19	3.92
P-value (Y)	0.001	< 0.001	0.002	< 0.001	0.001	< 0.001
P-value (T x Y)	0.913	0.097	0.696	0.344	0.338	0.162

[a]CT = cluster thinning; TBLR = trace bloom leaf removal; FSLR = fruit set leaf removal.
[b]Treatment means followed by different letters within a column are significantly different (Tukey's HSD test, $P = 0.10$).
[c]Distal cluster removed from CT vines.

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

Table 5 Effects of treatment and year on Grüner Veltliner juice composition for basal cluster, distal cluster, and combined basal and distal cluster at harvest 2015 and 2016.

	TSS (Brix)	pH	TA (g/ L)	TSS (Brix)	pH	TA (g/L)	TSS (Brix)	pH	TA (g/L)
	2015								
	Basal cluster			***Distal cluster***			***Basal + distal cluster***		
Treatment (T)[a]									
Control	21.4 b[b]	3.63	4.16	21.8	3.61	4.26	21.6 ab	3.61	4.20
CT	22.1 a	3.61	4.27	NA[c]	NA	NA	22.1 a	3.62	4.27
TBLR	21.3 b	3.64	4.29	21.9	3.61	4.43	21.7 ab	3.61	4.35
FSLR	22.1 a	3.62	4.25	21.4	3.61	4.44	21.3 b	3.62	4.33
P-value (T)	0.001	0.719	0.850	0.143	0.919	0.636	0.033	0.959	0.744
	2016								
	Basal cluster			***Distal cluster***			***Basal + distal cluster***		
Treatment (T)									
Control	21.1 bc	3.62 b	4.12	21.5	3.61	4.11	21.0 b	3.60 b	4.12
CT	23.0 a	3.77 a	4.07	NA	NA	NA	23.0 a	3.77 a	4.07
TBLR	21.9 ab	3.72 ab	4.24	22.2	3.72	4.10	22.1 ab	3.74 ab	4.10
FSLR	20.5 c	3.63 ab	4.21	21.2	3.64	4.10	20.8 b	3.63 ab	4.09
P-value (T)	0.005	0.025	0.959	0.261	0.110	0.989	0.009	0.016	0.999

[a]CT = cluster thinning; TBLR = trace bloom leaf removal; FSLR = fruit set leaf removal.

[b]Treatment means followed by different letters within a column are significantly different (Tukey's HSD $P < 0.10$).

[c]Distal cluster removed from CT treatment.

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

Table 6 Effects of treatment and year on Grüner Veltliner shoot efficiency, or source-sink balance.

	Total sugar (g)			Leaf area-to-yield ratio
	per shoot	per berry	per cm^2 leaf area	cm^2/g
Treatment (T)[a]				
Control	95.9 a[b]	0.355	0.026 a	8.11 b
CT	93.6 a	0.357	0.025 ab	14.65 a
TBLR	83.2 a	0.357	0.024 ab	8.82 b
FSLR	56.5 b	0.357	0.016 b	9.85 b
P-value (T)	< 0.001	0.998	0.089	< 0.001
Year (Y)				
2015	95. 5	0.371	0.028	11.45 a
2016	69.1	0.341	0.018	9.27 b
P- value (Y)	< 0.001	< 0.001	< 0.001	0.005
P- value (T x Y)	0.412	0.073	0.473	0.870

[a]CT = cluster thinning; TB = trace-bloom leaf removal; FSLR = fruit set leaf removal.

[b]Treatment means followed by different letters within a column are significantly different (Tukey's HSD test, $P < 0.10$).

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

Table 7 Bud median low-temperature exotherm (LT_{50}; °C) of Grüner Veltliner vines with different crop load management treatments from November 2015 through March 2016 and from November 2016 through March 2017.

	November 2015	December 2015	January 2016	February 2016	March 2016
Treatment (T)[a]					
Control	-12.72 a[b]	-21.13	-22.91	-22.58	-19.82
CT	-13.09 b	-21.48	-22.78	-22.56	-19.68
TBLR	-13.06 b	-20.97	-22.94	-22.61	-19.95
FSLR	-13.07 b	-21.32	-22.87	-23.03	-19.70
P-value (T)	0.039	0.181	0.913	0.360	0.659
Treatment (T)					
Control	-13.20 a	-20.50	-22.53 ab	-21.92	-19.95
CT	-13.82 ab	-20.36	-22.17 a	-21.90	-19.79
TBLR	-14.11 b	-20.36	-22.24 a	-22.50	-20.01
FSLR	-13.46 ab	-20.82	-22.91 b	-22.52	-20.21
P-value (T)	0.030	0.543	0.035	0.210	0.556

[a]CT = cluster thinning; TBLR = trace bloom leaf removal; FSLR = fruit set leaf removal.

[b]Treatment means followed by different letters within a column are different based are significantly different (Tukey's HSD test, $P < 0.10$).

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2019.18100
AJEV Papers in Press are peer-reviewed, accepted articles that have not yet been published in a print issue of the journal or edited or formatted, but may be cited by DOI. The final version may contain substantive or nonsubstantive changes.

Table 8 Production cost associated with early leaf removal and cluster thinning and price analysis of Grüner Veltliner.

	Additional cost of crop load management ($/ha)[a]	Additional production cost ($/t)	Yield (t/ha)	Expected revenue[a] ($/ha)	Preferred price to maintain revenue ($/t)	Additional cost[b] ($/bottle)
Treatment (T)[c]				**2015**		
Control	0	0	25	36,969	1,361	0.00
CT	133	9	15	20,760	2,207	1.18
TBLR	102	5	20	27,381	1,672	0.43
FSLR	96	5	21	28,641	1,598	0.33
				2016		
Control	0	0	23	35,764	1,406	0.00
CT	133	9	14	19,309	2,372	1.34
TBLR	102	5	21	29,923	1,533	0.17
FSLR	96	5	21	29,098	1,579	0.23

[a]The average industry price per tonne for Grüner Veltliner was $1,361 in 2015 and $1,406 in 2016.

[b]The additional retail price for a 750 mL bottle of wine under the assumptions of 491.4 L wine (655.2 bottles) per tonne of grapes, and that the producer uses the grapes for winemaking instead of selling the grapes at market price.

[c]CT = cluster thinning; TBLR = trace bloom leaf removal; FSLR = fruit set leaf removal.