Fruit Zone Leaf Removal Timing and Extent Alters Bunch Rot, Primary Fruit Composition, and Crop Yield in Georgia-grown ‘Chardonnay’ (*Vitis vinifera* L.)

Annie R. Vogel and Rachael S. White

Department of Horticulture, University of Georgia, 322 and 324 Hoke Smith Building, Athens, GA 30602

Clark MacAllister

UGA Cooperative Extension, 298 Academy Avenue, Dawson County, Dawsonville, GA 30534

Cain C. Hickey

The Pennsylvania State University, 318A Tyson Building, University Park, PA 16801

Additional index words. botrytis, canopy management, grape, sour rot

Abstract. Fruit zone leaf removal is a vineyard management practice used to manage bunch rots, fruit composition, and crop yield. We were interested in evaluating fruit zone leaf removal effects on bunch rot, fruit composition, and crop yield in ‘Chardonnay’ grown in the U.S. state of Georgia. The experiment consisted of seven treatments: no leaf removal (NO); prebloom removal of four or six leaves (PB-4, PB-6), post-fruit set removal of four or six leaves (PFS-4, PFS-6), and prebloom removal of two or three leaves followed by post-fruit set removal of two or three leaves (PB-2/PFS-2, PB-3/PFS-3). Although leaf removal reduced botrytis bunch rot and sour rot compared with NO, effects were inconsistent across the two seasons. Fruit zone leaf removal treatments reduced titratable acidity (TA) and increased soluble solids compared with NO. PB-6 consistently reduced berry number per cluster, cluster weight, and thus crop yield relative to PFS-4. Our results show that post-fruit set fruit zone leaf removal to zero leaf layers aids in rot management, reduces TA, increases soluble solids, and maintains crop yield compared with no leaf removal. We therefore recommend post-fruit set leaf removal to zero leaf layers over no leaf removal if crops characterized by relatively greater soluble solids-to-TA ratio and reduced bunch rot are desirable for winemaking goals.

Climate and pests dictate the cultivars that can be sustainably grown within a region, and management practices are used to achieve production goals within those cultivars. Two goals of

vineyard and winery enterprises are to produce economical crop yields and consumer-preferred wines. Cultural practices used to achieve these goals vary by growing region. In humid, subtropical growing regions, such as in the southeastern United States, excessive grapevine canopy growth results in shaded leaves and fruit zones (Giese et al., 2015; Hatch et al., 2011; Hickey et al., 2016). The humidity of the southeastern United States macroclimate is intensified within a shaded fruit zone microclimate. Management strategies are implemented to increase grape cluster exposure by thinning dense canopies that can otherwise exacerbate rot incidence and severity (English et al., 1989; Hed et al., 2009; Hickey et al., 2018b; Wolf et al., 1986). Fruit zone leaf removal is used to decrease rot incidence (Hed et al., 2015; Smith and Centinari, 2019), increase spray penetration (Hed and Centinari, 2018), and promote the development of desirable (Bubola et al., 2017) and reduce the presence of undesirable (Ryona et al., 2008) wine sensory impact compounds.

Fruit zone leaf removal is conventionally implemented after fruit set and before bunch closure (Poni et al., 2006). Removing leaves from only the morning-sun canopy side (e.g., the east side of north/south-oriented rows) has become standard practice in the eastern United States, where the current recommendation is to retain an average of one to two fruit zone leaf layers (Reynolds and Wolf, 2008). In humid regions, more late-season bunch rots are observed in fruit zones with one to two leaf layers relative to fruit zones devoid of leaves (Bubola et al., 2017; Hed et al., 2015), even in ‘Cabernet Sauvignon’ (Hickey and Wolf, 2018), which is generally tolerant to late-season bunch rots compared with ‘Chardonnay’, ‘Vignoles’, and other white-berried winegrape cultivars. However, questions persist regarding optimal timing and degree of fruit zone leaf removal across cultivars and climatically unique growing regions. Optimal leaf removal method is dictated by the radiation and temperatures experienced within a region (Spayd et al., 2002; Tarara et al., 2008).

Leaf removal affects grape soluble solids, TA, and pH (Pallioti et al., 2012), which are important for wine alcohol, acidity, mouthfeel, and microbial stability. As berries are subjected to radiant heat with increased fruit exposure, TA generally decreases as a function of malic acid respiration (Lakso and Kliever, 1975; Jackson and Lombard, 1993). In some regions, lower acidity may be desirable for the production of less astringent wines (Reynolds et al., 2006). Although best fruit zone management practice differs across climatically distinct regions and cultivars (Hickey et al., 2018a; Hickey and Wolf, 2019; Spayd et al., 2002; Tarara et al., 2008), removal of some leaves surrounding clusters can positively affect wine quality potential by increasing or decreasing several metabolites (Crupi et al., 2010; Hunter et al., 1991; Jackson and Lombard, 1993; Lee et al., 2005; Ryona et al., 2008).

Fruit set, berry size, and cluster compactness can be reduced when leaves are removed before bloom (Poni et al., 2006). The reduced fruit set has also been associated with an increase in skin thickness, skin-to-pulp ratio, and phenolics (Diago et al., 2012; Poni et al., 2006, 2009). Reduced fruit set results in a reduction in berry number per cluster, ultimately resulting in looser clusters. Although a decrease in cluster compactness can improve rot management (Hed et al., 2009; Sabbatini and Howell, 2010), prebloom leaf removal may not always result in superior rot management relative to post-fruit set leaf removal (Hickey et al., 2018b; Liggieri et al., 2018). Further, removal of excessive fruit zone foliage before bloom substantially reduces crop yield (Diago et al., 2012; Hickey and Wolf, 2018; Poni et al., 2006, 2009).

Post-fruit set leaf removal has numerous benefits. Like prebloom leaf removal, post-fruit set leaf removal increases airflow and pesticide spray penetration, leading to decreased rot (English et al., 1989; Hickey and Wolf, 2018; Wolf et al., 1986). The resulting

Received for publication 28 Apr. 2020. Accepted for publication 15 July 2020.

Published online 4 September 2020.

We gratefully acknowledge funding for this work from the Georgia Department of Agriculture and U.S. Department of Agriculture, under agreement and award identification no. AM170100XXXXG018. Appreciation is also extended to Ken van Dusen, Hezzie Patrick, Sharon Paul, Steven Patrick, Alyssa Haley, Annika Kohler, Alex Cameli, Zach Bennet, and Emily Currens for their collective vineyard and laboratory assistance.

C.M. is an Extension Agent.

C.C.H. is a Viticulture Extension Educator.

C.C.H. is the corresponding author. E-mail: viticulture@psu.edu.

This is an open access article distributed under the CC BY-NC-ND license (<https://creativecommons.org/licenses/by-nc-nd/4.0/>).

fruit exposure can decrease TA, increase soluble solids, and balance pH compared with no leaf removal (Bavaresco et al., 2008; Bubola et al., 2017; Reynolds et al., 2007). Unlike prebloom leaf removal, which can drastically reduce crop yield (Sabbatini and Howell, 2010), post-fruit set leaf removal maintains crop yield (Hickey and Wolf, 2018; VanderWeide et al., 2018). Post-fruit set leaf removal may offer greater economic sustainability relative to prebloom leaf removal.

Best leaf removal practice should be based on previous findings, optimized for vineyard production goals, and refined for specific cultivars. Further investigation of best fruit zone management practice is required in regions where no formal leaf removal studies have been conducted, such as in the U.S. state of Georgia. The present study evaluated the effect of different leaf removal regimes on crop yield, rot incidence, rot severity, and primary fruit composition of 'Chardonnay' grown in north Georgia, a humid, subtropical region. We hypothesized that prebloom leaf removal would reduce crop yield and that leaf removal to the greatest extent would reduce bunch rot and juice TA.

Materials and Methods

Experimental vineyard and treatments. Our experiment used 'Chardonnay' clone 5 grafted onto C-3309 rootstocks maintained in a commercial vineyard in Dahlonaga, GA. Vines were planted in 1999 with 2.13 m (vine) × 3.05 m (row) spacing in rows oriented east to west. Soil was a Haysville sandy loam (NRCS, USDA, 2020). Vines were trained onto a single canopy system with bilateral cordons and vertical shoot positioning. Vines were spur pruned and thinned to 24 shoots per vine at modified Eichorn-Lorenz (EL) stage 13 (Dry and Coombe, 2004) in each season. Herbicide applications maintained the under-trellis free of vegetation, and vegetation was maintained in vineyard alleyways. Primary shoots were hedged throughout the season before falling over the top catch wire; shoot hedging started around EL stage 31 and continued once every 2 to 3 weeks until the postveraison period. Lateral shoots were hedged from canopy sides at the same frequency as shoots were "topped." Pest management was uniformly applied across treatments and blocks in each year.

Experimental units consisted of four vines between vineyard posts. In some cases, vines were missing or putatively infected with a systemic disease (*Xylella fastidiosa*); laboratory tests were not performed to diagnose symptomatic vines. The result was that there were often fewer than four vines within every experimental unit. In both years, the vines that were excluded at harvest were also excluded at dormant pruning; in 2018, additional vines were missing or infected at dormant pruning. A total of 10% and 7.9% of vines in the entire trial were either missing or infected at harvest in 2017 and 2018,

respectively, whereas a total of 10% and 12.1% of vines in the trial were missing or infected during dormant pruning following each season. Thus, the missing or infected vines precluded our ability to measure crop weight, cluster number, and dormant pruning weight from all four vines in every experimental unit.

Treatments were implemented in a randomized complete block design, replicated in five blocks. Treatment integrity was maintained throughout the season by periodically removing vegetative ingress into the fruit zone after the initial treatment implementation. Secondary vegetative growth was only removed from nodes where treatments were originally implemented; this occurred on a 2- to 3-week basis through the modified EL stage 35 (veraison) growth stage. Primary and lateral shoot hedging was the only canopy maintenance conducted in "NO" plots. Treatments were as follows [note: all modified EL stages in treatment descriptions and the following methods are taken from Dry and Coombe (2004)]:

No leaf removal: NO (no leaves or lateral shoots removed in the fruit zone)

Prebloom leaf removal: PB-4 and PB-6 [removal of leaves and laterals from primary shoot nodes 1 to 4 and 1 to 6, respectively, at modified EL stage 17 (single flowers well separated)]

Post-fruit set leaf removal: PFS-4 and PFS-6 [removal of leaves and laterals from primary shoot nodes 1 to 4 and 1 to 6, respectively, at modified EL stage 31 (pea-sized berries)]

Combined prebloom and post-fruit set leaf removal: PB-2/PFS-2 (removal of leaves and laterals from primary shoot nodes 2 and 3 at modified EL stage 17 followed by removal of leaves and laterals from primary shoot nodes 1 and 4 at modified EL stage 31); PB-3/PFS-3 (removal of leaves and laterals from primary shoot nodes 2–4 at modified EL stage 17 followed by removal of leaves and laterals from primary shoot nodes 1, 5, and 6, at modified EL stage 31)

Meteorology. Temperature and rainfall data were recorded from 1 Apr. to 31 Oct. in 2017 and 2018 using a weather station located on the vineyard site and roughly 180 m from the experimental vineyard blocks. The weather station was comprised of a HMP35 temperature and humidity probe (Vaisala, Helsinki, Finland) and a TB4 rain gauge (Hydrological Services America, Lake Worth, FL), which were logged with a CR1000 data logger (Campbell Scientific, Logan, UT).

Dormant cane pruning weight. The weight of pruned canes was recorded on a per-vine basis using a field scale during the dormant periods between the growing seasons of 2017–18 and 2018–19. Dormant cane weights per vine were then expressed as weight per linear meter of row basis using vine spacing.

Fruit zone architecture. Point quadrant analysis (PQA) data were collected at modified EL stage 35 (veraison; berry softening and sugar accumulation). PQA was collected after vineyard passes were made to remove lateral shoot and leaf growth maintain the integrity of the initially implemented treatments (see "Experimental vineyard and treatments" for explanation of treatments and follow-up maintenance). A probe was inserted through the fruit zone perpendicular to the cordon three times per meter in each experimental unit; ≈22 probe insertions were made through the canopies within each experimental unit. Probe insertions allowed quantification of fruit zone leaf layer number (LLN) (Smart and Robinson 1991). Photosynthetic photon flux density (PPFD) was measured by inserting an LP-80 ceptometer (Decagon Devices, Inc., Pullman, WA) into the fruit zone above, and parallel to, the cordon. Under consistent, ambient conditions on sunny days, two PPFD readings each were taken from the middle two vines in every experimental unit at the veraison. Measurements were averages of PPFD readings taken while orienting the ceptometer in three orientations above the cordon (45° north, vertical, 45° south). The PPFD and probe insertion data were used to generate cluster exposure flux availability (CEFA) using enhanced point quadrant analysis (EPQA version 1.6.2) (Meyers and Vanden Heuvel 2008).

Bunch rot incidence and severity and crop loss due to rot. Botrytis bunch rot (*Botrytis cinerea*) severity and incidence measurements were quantified on three occasions: once after start of veraison, once at an intermediate date between veraison and harvest, and once again immediately before harvest. On each occasion, 25 randomly selected clusters were nondestructively evaluated for botrytis bunch rot and severity. Sour rot (rot complex caused by yeast and bacteria) incidence and severity were rated on the same clusters in which botrytis bunch rot was rated, but only at harvest. Incidence was calculated as the number of clusters visually diagnosed with botrytis bunch rot or sour rot of infection divided by the total number of clusters evaluated. Severity was rated by visual estimation of the percentage of each cluster that was infected by botrytis bunch rot or sour rot. Estimated crop loss due to rot was calculated as the quotient of (1) and (2): 1) the product of rot incidence and severity and 2) 100; crop loss = (incidence × severity)/100.

Components of crop yield. Crop yield was measured with a field scale on a per-vine basis at EL stage 38 on 22 Aug. 2017 and 29 Aug. 2018. Harvest date was determined by the commercial vineyard hosting our experiment. Cluster number per vine was recorded. Average cluster weight was determined as the quotient of crop weight and cluster number per vine. Immediately before harvest on 21 Aug. 2017 and 29 Aug. 2018, a random, composite berry sample of 120 berries, taken equally from both canopy sides (60 berries per side), was collected to calculate average

individual berry weight. Berry number per cluster was determined as the quotient of average cluster weight and average individual berry weight. Crop yield per vine and components thereof were averaged within each experimental unit.

Primary juice composition. After modified EL stage 35, composite samples of 80 berries were equally collected from both canopy sides (40 berries per side); collection dates paralleled those of preharvest botrytis bunch rot ratings to compare rot and soluble solids development over time. The 120-berry composite sample, randomly collected from each experimental unit immediately before EL stage 38, was used for soluble solids, titratable acidity and pH analyses. The fresh berry samples were evenly hand pressed in the plastic sample bag, and expressed juice was centrifuged for 5 m at 4000 rotations per minute. One milliliter of centrifuged juice was then used to measure soluble solids with a PAL-1 Atago digital pocket refractometer (Atago USA Inc., Bellevue, WA). Total TA was measured on 5 mL of juice diluted with 40 mL of distilled water using an 848 Titrino Plus automated titration system (Metrohm USA, Riverview, FL) and titrated to an endpoint of pH 8.2 with a 0.1 M NaOH base. The pH was measured on undiluted juice using the pH probe on the automated titration system.

Statistical analysis. Statistical computation was performed using JMP Pro v. 13. A mixed model was used to evaluate the random block effect and fixed treatment effect using two-way analysis of variance for EPQA, rot incidence, rot severity, primary chemistry, and components of crop yield. Significance ($\alpha \leq 0.05$) was determined with Tukey's honestly significant difference for all treatment effects. All data were analyzed within the time point collected (e.g., "year" was not used as a model effect for data in tables, and "date" was not used as a model effect for the preharvest soluble solids and estimated crop loss data set in Fig. 2). A bivariate linear fit model was used to determine the relationship between LLN and crop loss due to botrytis bunch rot and sour rot, the relationship between LLN and incidence and severity of botrytis and sour rot at harvest, and the relationship between the number of leaves removed before bloom and the change in components of yield relative to treatments in which prebloom leaf removal was not conducted.

Results and Discussion

Meteorology. In 2017, 2276 growing degree days (GDD) accumulated with precipitation of 1088 mm from 1 Apr. to 31 Oct. (Fig. 1). In 2018, 2407 GDD accumulated with precipitation of 1081 mm from 1 Apr. to 31 Oct. The greatest monthly rainfall occurred in May of each year and the greatest GDD number were accumulated in June, July, and August of both years. When considering the harvest dates of 22 Aug. 2017 and 29 Aug. 2018, a relatively greater amount of GDD were accumulated, and more rain fell, before harvest in 2018 relative to 2017.

Fig. 1. Growing degree day (A) and rainfall (B) accumulation for 2017 and 2018 at the experimental vineyard in Dahlenega, GA. Growing degree days were calculated using a base of 10 °C.

Dormant cane pruning weight. Dormant cane pruning weight was unaffected by treatment (Table 1). Vines were hedged multiple times throughout the season in both years; dormant pruning weights were not fully comprehensive of actual vine size, and hedging may have masked treatment effects. Pruning weight was greater in 2017 than in 2018 despite greater precipitation in 2018 compared with 2017 (Fig. 1). The greater pruning weight in 2017 may have been a function of the relatively lower crop yield in 2017 (Table 2) resulting in less resource competition to vegetative growth than in 2018. Smart and Robinson (1991) report that pruning weights from balanced vines are between 0.3 and 0.6 kg/m row in a single canopy system such as the type used in our study. Pruning weights tended to fall within, or above, that range, indicating highly vigorous canopy vegetative growth. Our pruning weight data were reflective of high vine size and was likely a function of ample storage carbohydrates combined with the vigor induced by a humid, subtropical climate.

Fruit zone architecture. All leaf removal treatments resulted in greater fruit zone exposure relative to NO, as demonstrated by the lower LLN and greater CEFA observed in leaf removal plots (Table 1). As more leaves were removed, fruit zone LLN was reduced. Compared with recently recommended fruit zone LLNs (Reynolds and Wolf, 2008), NO resulted in greater fruit zone leaf layers, whereas PB-4, PFS-4, and PB-2/PFS-2 produced similar leaf layers and PB-6, PF-6, and PB-3/PFS-3 produced fewer leaf layers. Fruit zone LLN was generally inversely related to fruit zone CEFA, indicating that greater incident radiation reached the clusters. NO had a significantly lower CEFA than all other treatments (Table 1). PB-6 and PFS-6 resulted in 423.1% and 407.7% greater CEFA than NO. PB-4 and PFS-4 increased CEFA by 238.4% and 246.2% compared with NO, and PB-2/PFS-2 and PB-3/PFS-3 had CEFA values that were 265.4% and 376.9% greater than NO across both years.

Postveraison estimated crop loss and sugar accumulation. Greater estimated amounts of crop loss due to botrytis bunch rot were observed in 2017 relative to 2018, even though slightly more rainfall was observed in 2018 (Fig. 1). Treatment effect on estimated crop loss due to bunch rot varied

over the postveraison period (Fig. 2A and B). In 2017, the estimated crop loss due to rot was greater in NO compared with PFS-4 and PFS-6 on 29 June compared with PFS-4, PFS-6, and PB-6 on 18 July and compared with PFS-6 on 21 Aug. In 2018, estimated crop loss was variable, leading to no significant differences in treatments across all dates. In both years, the estimated amount of crop lost to rot over the final month of maturation was greatest in NO. While lower soluble solids were observed in 2017 than in 2018, the rate of soluble solids accumulation was similar across treatments (Fig. 2C and D). However, NO had significantly lower soluble solids compared with PB-4, PB-6, PFS-6, PB-2/PFS22, and PB-3/PFS-3 at harvest in 2017 and compared with all other treatments at harvest in 2018. Soluble solids increased by ≈ 4 to 5 °Brix in the final month of maturation, during which time a considerable amount of crop was lost due to rot, primarily in NO. Consequently, commercially acceptable maturity may be more consistently attained without crop loss when fruit zones are managed to one to two leaf layers. Fruit zone leaf removal may aid in reducing rot when delayed harvest is desired.

Bunch rot incidence and severity at harvest. Rot incidence and severity at harvest was reduced by the leaf removal treatments compared NO, although results were inconsistent across seasons (Table 2). In 2017, botrytis bunch rot severity was 48% to 77% greater in NO relative to all leaf removal treatments except PB-6. Treatments did not affect sour rot incidence or severity in 2017. In 2018, botrytis bunch rot incidence was reduced by PFS-4 (50%), PB-2/PFS-2 (50%), PB-4 (59%), PB-6 (71%), PB-3/PFS-3 (76%), and PFS-6 (80%), whereas botrytis bunch rot severity was only reduced by PFS-6 (94%) compared with NO. In 2018, sour rot incidence was reduced by PFS-6 (63%) and PB-3/PFS-3 (49%) compared with NO, whereas all leaf removal treatments reduced sour rot severity by a range of 68% to 92% compared with NO (Table 2). LLN was positively and linearly related to crop loss due to botrytis bunch rot and sour rot (Figs. 3 and 4) and to the incidence and severity. These relationships were stronger in 2018 than in 2017 and stronger for botrytis than for sour rot (Fig. 4). Although "year" was not factor accounted for in statistical analysis, these results suggest that leaf removal may improve

Table 1. Prebloom and post-fruit set leaf removal effect on average fruit zone leaf layer number (LLN) and cluster exposure flux availability (CEFA) in 'Chardonnay' at veraison and dormant pruning weight in 2017 and 2018.

Treatment ^z	LLN	CEFA	Pruning wt (kg/m row)
2017			
NO	3.0 a	0.07 d	0.86
PB-4	1.2 b	0.43 c	0.84
PB-6	0.1 d	0.72 a	0.74
PFS-4	0.8 c	0.46 c	0.85
PFS-6	0.1 d	0.69 a	0.80
PB-2/PFS-2	0.8 c	0.49 bc	0.81
PB-3/PFS-3	0.1 d	0.61 ab	0.83
Significance ^y	<0.0001	<0.0001	NS
2018			
NO	2.8 a	0.19 c	0.67
PB-4	1.2 b	0.44 b	0.60
PB-6	0.5 cd	0.64 a	0.54
PFS-4	1.1 bc	0.44 b	0.55
PFS-6	0.2 d	0.63 a	0.51
PB-2/PFS-2	1.1 bc	0.46 b	0.54
PB-3/PFS-3	0.3 d	0.63 a	0.59
Significance	<0.0001	<0.0001	NS

^zNO = no leaf removal; PB-4 and PB-6 = prebloom leaf removal four and six leaves, respectively; PFS-4 and PFS-6 = post-fruit set removal of four and six leaves, respectively. PB-2/PFS-2 and PB-3/PFS-3 = prebloom leaf removal of two leaves with post-fruit set removal of two leaves and prebloom leaf removal of three leaves with post-fruit set removal of three leaves, respectively.

^ySignificance of treatment effects ($P > F$; NS = not significant at 0.05 level). Means in the same treatment group (columns) not sharing a letter are significantly different and means in the same column without letters are not significantly different at the 0.05 level based on adjusted P values using Tukey's honestly significant difference.

Table 2. Prebloom and post-fruit set leaf removal effect on the incidence and severity of botrytis bunch rot and sour rot in 'Chardonnay' at harvest in 2017 and 2018.

Treatment ^z	Botrytis bunch rot		Sour rot	
	Incidence	Severity	Incidence	Severity
2017				
NO	68.0	8.97 a	56.8	6.86
PB-4	60.8	4.70 b	56.8	4.26
PB-6	61.6	5.06 ab	61.6	3.89
PFS-4	61.6	4.70 b	60.0	3.41
PFS-6	51.2	2.02 b	48.8	2.20
PB-2/PFS-2	58.4	3.90 b	58.4	2.09
PB-3/PFS-3	62.4	3.70 b	56.8	3.16
Significance ^y	NS	0.0015	NS	NS
2018				
NO	63.2 a	9.60 a	73.6 a	11.3 a
PB-4	25.6 bc	1.74 ab	47.2 ab	2.12 b
PB-6	18.4 bc	1.05 ab	48.0 ab	2.67 b
PFS-4	32.0 b	2.49 ab	48.0 ab	2.47 b
PFS-6	12.8 c	0.58 b	27.2 b	0.95 b
PB-2/PFS-2	32.0 b	3.11 ab	47.2 ab	3.66 b
PB-3/PFS-3	15.2 bc	1.63 ab	36.0 b	2.34 b
Significance	<0.0001	0.0454	0.0007	0.0009

^zNO = no leaf removal; PB-4 and PB-6 = prebloom leaf removal four and six leaves, respectively; PFS-4 and PFS-6 = post-fruit set removal of four and six leaves, respectively. PB-2/PFS-2 and PB-3/PFS-3 = prebloom leaf removal of two leaves with post-fruit set removal of two leaves and prebloom leaf removal of three leaves with post-fruit set removal of three leaves, respectively.

^ySignificance of treatment effects ($P > F$; NS = not significant at 0.05 level). Means in the same treatment group (columns) not sharing a letter are significantly different and means in the same column without letters are not significantly different at the 0.05 level based on adjusted P values using Tukey's honestly significant difference.

rot management in wetter (2018) over drier (2017) years and that leaf removal may control botrytis bunch rot better than sour rot. However, due to the limitations of a field study and subsequent inability to control several factors, the differences in treatment effects across vintages may also have been due to differences in timing of rainfall events or a change in spray schedules or specific pesticide usage. For example, powdery mildew was observed on many clusters in 2017 but not in 2018; this was

anecdotal and not quantified. However, because powdery mildew can result in latent berry infections that exacerbate late season bunch rots, this may be why leaf removal treatments had a lesser impact on rot management in 2017 than in 2018.

Our results suggest that leaf removal aids in bunch rot management in Georgia and that leaf removal to relatively greater extents can improve rot management. Previous work across variable climates has reported that

bunch rot is reduced with fruit zone leaf removal (English et al., 1989; Hed et al., 2015; Hickey and Wolf, 2018; Smith and Centinari, 2019; Wolf et al., 1986). A study on 'Cabernet franc' in North Carolina demonstrated that rot is reduced by removal of six basal shoot leaves compared with no leaf removal (Hickey et al., 2018b). Rot reduction is consistently attributed to a less dense canopy and an open fruit zone (Hed and Centinari, 2018) as well as decreased cluster compactness due to decreased fruit set and/or berry size (Hed et al., 2015; Hickey and Wolf, 2018; Palliotti et al., 2012). A study in Pennsylvania showed that leaf removal at different timings in 'Grüner Veltliner' can improve rot management, especially during wet years (Smith and Centinari, 2019). Our findings corroborate those of Smith and Centinari (2019), who found that fruit zone leaf removal may improve rot control over fully foliated fruit zones in wetter than in drier years. Rot was still prevalent under the experimental conditions of our study, confirming that Chardonnay can be a challenging cultivar to grow in a humid, subtropical climate.

Components of crop yield. Timing and extent of leaf removal differentially affected crop yield components consistently across seasons (Table 3). Crop yield was reduced by PB-6 compared with PFS-4 in 2017 and PFS-4 and PB-2/PFS-2 in 2018. PB-6 reduced crop yield via a reduction in berry number per cluster and thus average cluster weight. In 2017, PB-6 reduced berry number per cluster by a range of 21.7% to 39.9% compared with PFS-4, PFS-6, PB-2/PFS-2, and PB-3/PFS-3; in 2018, PB-6 reduced berry number per cluster by a range of 34.5% to 36.7% compared with PFS-4 and PFS-6. PB-4 did not reduce berry number per cluster, cluster weight, nor crop yield, whereas PB-6 reduced each of those responses. Therefore, prebloom removal of six basal leaves may be an approximate threshold at which fruit set and crop yield are statistically reduced in 'Chardonnay', at least under conditions like those of this field experiment. Bivariate, linear fits between the number of leaves removed before bloom and the percent change in crop yield components revealed a negative, linear relationship between the number of leaves removed before bloom and percent reduction in berry number per cluster, cluster weight, and crop yield in 2017 and 2018 (Fig. 5). When averaged over both seasons, it was estimated that removal of each additional basal leaf would reduce crop yield by 5.89%, cluster weight by 4.49%, and berry number per cluster by 4.64%.

Our results indicate that prebloom leaf removal reduces crop yield (Diago et al., 2012), which has been documented to be a function of decreased fruit set (Poni et al., 2006), berry number per cluster, and cluster weight (Hickey and Wolf, 2018; Poni et al., 2006). Fruit composition can be improved with leaf removal at earlier phenological stages, which may be a desirable trade-off to a crop reduction in ample-yielding

Fig. 2. Prebloom and post-fruit set leaf removal relationship with estimated crop loss due to botrytis bunch rot in 2017 (A) and 2018 (B) and soluble solids development over time in 2017 (C) and 2018 (D). Treatments reflect timing and level of leaf removal: no leaf removal (NO), prebloom leaf removal of four leaves (PB-4) and six leaves (PB-6), post-fruit set removal of four leaves (PFS-4) and six leaves (PFS-6), prebloom leaf removal of two leaves with post-fruit set removal of two leaves (PB-2/PFS-2) and prebloom leaf removal of three leaves with post-fruit set removal of three leaves (PB-3/PFS-3). Means within the same date not sharing the same letter were significantly different ($\alpha = 0.05$) using Tukey's honestly significant difference. Error bars indicate standard error; $n = 5$. Note: due to the large number of trend lines, letter separators are ordered by treatment as they appear in legend.

Fig. 3. The relationship between leaf layer number (LLN) and total estimated crop loss due to botrytis bunch rot (A) and sour rot (B) at harvest 2017 and 2018. Note: data points represent averages within experimental units; $n = 5$.

cultivars such as Tempranillo, Sangiovese, and Trebbiano (Diago et al., 2012; Poni et al., 2006). With 'Chardonnay', a rot-prone cultivar, a decrease in berries per cluster loosens the cluster, resulting in a high-quality crop due to improved sunlight, radiation, and pesticide penetration (Hed and Centinari, 2018).

Grapevines subjected to post-fruit set leaf removal in Georgia experience similar benefits of open canopies (Tables 2 and 4) compared with those subjected to prebloom leaf removal. Post-fruit set leaf removal can maintain, or increase, crop yield relative to grapevines with unmanaged fruit zones or

subjected to prebloom leaf removal, by way of reducing the amount of crop lost to fewer berries per cluster (Table 3) and rot (Figs. 3 and 4).

Primary juice composition at harvest. Leaf removal treatments tended to increase juice soluble solids and decrease juice total

Fig. 4. Relationship between leaf layer number (LLN) and botrytis bunch rot severity (A) and incidence (C) and sour rot severity (B) and incidence (D) at harvest 2017 and 2018. Note data points represent averages within experimental units; n = 5.

Table 3. Prebloom and post-fruit set leaf removal effect on components of crop yield in 'Chardonnay' at harvest in 2017 and 2018.

Treatment ^a	Crop wt (kg/vine)	Cluster no.	Cluster wt (g)	Berry no./cluster	Berry wt (g)
2017					
NO	4.36 ab	23.8	184.7 bc	94.5 bc	1.95
PB-4	4.19 ab	21.3	198.1 bc	96.1 bc	2.06
PB-6	3.62 b	21.1	169.9 c	84.3 c	2.02
PFS-4	5.53 a	22.8	241.2 a	117.9 a	2.04
PFS-6	4.65 ab	21.3	220.9 ab	115.2 a	1.92
PB-2/PFS-2	4.70 ab	21.4	221.8 ab	110.3 ab	2.01
PB-3/PFS-3	4.60 ab	22.8	202.3 bc	102.6 ab	1.97
Significance ^b	0.0087	NS	<0.0001	<0.0001	NS
2018					
NO	5.28 ab	34.5	152.7 ab	87.8 ab	1.76 a
PB-4	5.34 ab	36.7	145.6 ab	84.1 ab	1.73 ab
PB-6	3.87 b	33.1	116.3 b	69.9 b	1.66 ab
PFS-4	6.91 a	39.7	172.4 a	106.7 a	1.62 ab
PFS-6	6.08 ab	35.4	173.4 a	110.4 a	1.58 b
PB-2/PFS-2	6.29 a	38.5	163.9 ab	100.2 ab	1.63 ab
PB-3/PFS-3	4.72 ab	36.1	129.4 ab	82.1 ab	1.58 b
Significance	0.0078	NS	0.0088	0.0056	0.0069

^aNO = no leaf removal; PB-4 and PB-6 = prebloom leaf removal four and six leaves, respectively; PFS-4 and PFS-6 = post-fruit set removal of four and six leaves, respectively. PB-2/PFS-2 and PB-3/PFS-3 = prebloom leaf removal of two leaves with post-fruit set removal of two leaves and prebloom leaf removal of three leaves with post-fruit set removal of three leaves, respectively.

^bSignificance of treatment effects ($P > F$; NS = not significant at 0.05 level). Means in the same treatment group (columns) not sharing a letter are significantly different and means in the same column without letters are not significantly different at the 0.05 level based on adjusted P values using Tukey's honestly significant difference.

TA compared with NO (Table 4). With the exception of PFS-4, all leaf removal treatments consistently increased soluble solids by a range of 3.9% to 6.2% compared with NO in 2017, and by a range of 3.9% to 5.4% compared with NO in 2018 (Table 4). In 2017, several leaf

removal treatments reduced juice TA by a range of 8% to 18% compared with NO. Juice TA was less affected by treatments in 2018, which had greater postveraison rainfall than 2017, but was reduced by PFS-6 (9%), PB-2/PFS-2 (9%), and PB-3/PFS-3 (12%) compared

with NO. Juice pH was inconsistently affected by treatment, with NO having the lowest recorded pH values in both years. The soluble solids-to-TA ratio was consistently greater in all leaf removal treatments relative to NO. When fruit is shaded, it is not exposed to the radiant heat

Fig. 5. The relationship between the number of basal shoot leaves removed before bloom and the relative change in crop yield (A), cluster weight (B), and berry number per cluster (C) at harvest in 2017 and 2018. Note: percent changes were in reference to the average components of yield from all treatments in which prebloom leaf removal was not conducted: NO (no leaf removal), PFS-4 (post-fruit set removal of four leaves), and PFS-6 (post-fruit set removal of six leaves); data points represent averages within experimental units; $n = 5$.

Table 4. Leaf removal effect on mean soluble solids, titratable acidity (TA), pH, and soluble solids (SS)-to-TA ratio in 'Chardonnay' at harvest in 2017 and 2018.

Treatment ^a	Soluble solids (°Brix)	TA (g/L)	pH	SS-to-TA ratio
2017				
NO	17.8 b	10.1 a	3.27 b	1.77 c
PB-4	18.5 a	9.30 b	3.30 ab	2.00 b
PB-6	18.9 a	8.91 bc	3.33 ab	2.13 ab
PFS-4	18.4 ab	9.02 bc	3.31 ab	2.05 b
PFS-6	18.7 a	8.50 c	3.33 ab	2.21 ab
PB-2/PFS-2	18.6 a	8.77 bc	3.31 ab	2.13 ab
PB-3/PFS-3	18.8 a	8.26 c	3.35 a	2.28 a
Significance ^y	0.0006	<0.0001	0.0096	<0.0001
2018				
NO	20.4 b	8.98 a	3.36 b	2.28 b
PB-4	21.4 a	8.38 ab	3.42 ab	2.57 a
PB-6	21.3 a	8.26 ab	3.44 a	2.59 a
PFS-4	21.2 a	8.33 ab	3.41 ab	2.55 a
PFS-6	21.3 a	8.19 b	3.42 ab	2.60 a
PB-2/PFS-2	21.5 a	8.14 b	3.41 ab	2.65 a
PB-3/PFS-3	21.4 a	7.86 b	3.45 a	2.73 a
Significance	0.0016	0.0042	0.0094	0.0007

^aNO = no leaf removal; PB-4 and PB-6 = prebloom leaf removal four and six leaves, respectively; PFS-4 and PFS-6 = post-fruit set removal of four and six leaves, respectively. PB-2/PFS-2 and PB-3/PFS-3 = prebloom leaf removal of two leaves with post-fruit set removal of two leaves and prebloom leaf removal of three leaves with post-fruit set removal of three leaves, respectively.

^ySignificance of treatment effects ($P > F$; NS = not significant at 0.05 level). Means in the same treatment group (columns) not sharing a letter are significantly different and means in the same column without letters are not significantly different at the 0.05 level based on adjusted P values using Tukey's honestly significant difference.

and will have reduced soluble solids while retaining high TA levels (Smart et al., 1991). Thus, fruit produced in canopies with few fruit zone leaf layers can increase wine quality potential (Smart and Robinson, 1991) but not

in all climates (Spayd et al., 2002; Tarara et al., 2008). A greater soluble solids-to-TA ratio, as registered in fruit sampled from several leaf removal treatment plots, may enable an earlier harvest without having undesirable, high wine

astringency due to excessive acidity (Reynolds et al., 2006). An earlier harvest date may be desirable for commercial producers because the heightened disease pressure experienced toward the end of summer in the eastern United

States may result in depressed crop yield (Fig. 2). Harvesting relatively early may preclude varietal character from fully developing, but the decreased risk for crop loss due to rot may be desirable in some commercial situations. Measuring secondary metabolites was beyond the scope of our experiment, but exposed grapes have been shown to increase favorable wine sensory impact compounds in white-berried grape cultivars (Allegro et al., 2019; Reynolds et al., 2007).

Conclusion

Fruit zone leaf removal can produce a greater sugar-to-acid ratio in grape juice, decreased incidence and severity of bunch rots, and, if practiced after fruit set or to lesser magnitudes before bloom, crop yield maintenance. Leaf removal practices should be regionally tailored because while vineyards located in humid, subtropical climates can benefit from having less than one fruit zone leaf layer, vineyards located in arid climates might require cluster shading to preserve color and acidity under consistently high radiant heating. The goal of fruit zone management is to create a microclimate that is more conducive to optimizing fruit quality and disease management than would otherwise be attained under the macroclimate of the region. Our results illustrate that post-fruit set leaf removal to approximately one leaf layer or less can increase juice soluble solids-to-TA ratio and reduce disease relative to prebloom or no leaf removal; these results may especially apply to rot-susceptible cultivars that are grown in humid, subtropical climates.

Literature Cited

- Allegro, G., C. Pastore, G. Valentini, and I. Filippetti. 2019. Effects of sunlight exposure on flavonol content and wine sensory of the white winegrape Grechetto gentile. *Amer. J. Enol. Viticult.* 70:277–285.
- Bavaresco, L., M. Gatti, S. Pezzutto, M. Fregoni, and F. Mattivi. 2008. Effect of leaf removal on grape yield, berry composition, and stilbene concentration. *Amer. J. Enol. Viticult.* 59:292–298.
- Bubola, M., P. Sivilotti, D. Janjanin, and S. Poni. 2017. Early leaf removal has larger effect than cluster thinning on grape phenolic composition in cv. Teran. *Amer. J. Enol. Viticult.* 68:234–242.
- Crupi, P., A. Coletta, and A. Antonacci. 2010. Analysis of carotenoids in grapes to predict norisoprenoid varietal aroma of wines from Apulia. *J. Agr. Food Chem.* 8:9647–9656.
- Diago, M.P., B. Ayestaran, Z. Guadalupe, S. Poni, and J. Tardaguila. 2012. Impact of prebloom and fruit set basal leaf removal on the flavonol and anthocyanin composition of Tempranillo grapes. *Amer. J. Enol. Viticult.* 63:367–376.
- Dry, P. and B. Coombe (eds.). 2004. Revised version of grapevine growth stages—The modified E-L system. In *Viticulture 1—Resources*. 2nd ed. Winetitles, Adelaide, Australia.
- English, J.T., C.S. Thomas, J.J. Marois, and W.D. Gubler. 1989. Microclimates of grapevine canopies associated with leaf removal and control of Botrytis bunch rot. *Phytopathology* 79:395–401.
- Giese, W.G., T.K. Wolf, C. Velasco-Cruz, L. Roberts, and J. Heitman. 2015. Cover crop and root pruning impacts on vegetative growth, crop yield components, and grape composition of Cabernet Sauvignon. *Amer. J. Enol. Viticult.* 66:212–226.
- Hatch, T.A., C.C. Hickey, and T.K. Wolf. 2011. Cover crop, rootstock, and root restriction regulate vegetative growth of Cabernet Sauvignon in a humid environment. *Amer. J. Enol. Viticult.* 62:298–311.
- Hed, B., H. Ngugi, and T. James. 2009. Relationship between cluster compactness and bunch rot in Vignoles grapes. *Plant Dis.* 93:1195–1201.
- Hed, B., H.K. Ngugi, and J.W. Travis. 2015. Short- and long-term effects of leaf removal and gibberellin on Chardonnay grapes in the Lake Erie region of Pennsylvania. *Amer. J. Enol. Viticult.* 66:22–29.
- Hed, B. and M. Centinari. 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. *HortTechnology* 28:296–303.
- Hickey, C.C., T.A. Hatch, J. Stallings, and T.K. Wolf. 2016. Under-trellis cover crop and rootstock affect growth, yield components, and fruit composition of cabernet sauvignon. *Amer. J. Enol. Viticult.* 67:281–295.
- Hickey, C.C., M.T. Kwasniewski, and T.K. Wolf. 2018a. Extent and timing of leaf removal effects in Cabernet franc and Petit Verdot. II. Grape berry temperature, carotenoids, phenolics and wine sensory analysis. *Amer. J. Enol. Viticult.* 69:231–246.
- Hickey, C.C., R.S. White, and P.M. Brannen. 2018b. The effect of leaf removal timing on Botrytis bunch rot in North Carolina-grown Cabernet franc clones 214 and 327, 2017. *Plant Dis. Mgt. Rpt.* 12:PF015.
- Hickey, C.C. and T.K. Wolf. 2018. Cabernet Sauvignon responses to prebloom and post-fruit set leaf removal in Virginia. *Catalyst* 2:24–34.
- Hickey, C.C. and T.K. Wolf. 2019. Zero fruit zone leaf layers increase *Vitis vinifera* L. ‘Cabernet Sauvignon’ berry temperature and berry phenolics without adversely affecting berry anthocyanins in Virginia. *HortScience* 54:1181–1189.
- Hunter, J.J., O.T. de Villiers, and J.E. Watts. 1991. The effect of partial defoliation on quality characteristics of *Vitis vinifera* L. cv. Cabernet Sauvignon grapes II. Skin colour, skin sugar and wine quality. *Amer. J. Enol. Viticult.* 42:13–18.
- Jackson, D.I. and P.B. Lombard. 1993. Environmental and management practices affecting grape composition and wine quality—a review. *Amer. J. Enol. Viticult.* 44:409–430.
- Lakso, A. and M. Kiewer. 1975. The influence of temperature on malic acid metabolism in grape berries. *Plant Physiol.* 56:370–372.
- Lee, J., R.W. Durst, and R.E. Wrolstad. 2005. Determination of total monomeric anthocyanin pigments content of fruit juices, beverages, natural colorants, and wines by the pH differential method: Collaborative study. *J. AOAC Intl.* 88:1269–1278.
- Liggieri, S., T.K. Wolf, and M.K. Kwasniewski. 2018. Optimized cluster exposure to improve grape composition and health. *American Society of Enology and Viticulture—Eastern Section*, 11 July 2018, King of Prussia, PA.
- Meyers, J.M. and J.E. Vanden Heuvel. 2008. Enhancing the precision and spatial acuity of point quadrat analysis via calibrated exposure mapping. *Amer. J. Enol. Viticult.* 59:425–431.
- Natural Resources Conservation Service, U.S. Department of Agriculture (NRCS, USDA). Web Soil Survey. Dawson, Lumpkin, and White Counties, Georgia (GA362). Aug. 2020. <https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx>.
- Pallioti, A., T. Gardi, J.G. Berrios, S. Civardi, and S. Poni. 2012. Early source limitation as a tool for yield control and wine quality improvement in a high-yielding red *Vitis vinifera* L. cultivar. *Scientia Hort.* 145:10–16.
- Poni, S., L. Casalini, F. Bernizzoni, S. Civardi, and C. Intrieri. 2006. Effects of early defoliation on shoot photosynthesis, yield components, and grape composition. *Amer. J. Enol. Viticult.* 57:397–407.
- Poni, S., F. Bernizzoni, S. Civardi, and N. Libelli. 2009. Effects of pre-bloom leaf removal on growth of berry tissues and must composition in two red *Vitis vinifera* L. cultivars. *Aust. J. Grape Wine Res.* 15:185–193.
- Reynolds, A.G., J.N. Roller, A. Forgione, and C. De Savigny. 2006. Gibberellic acid and basal leaf removal: Implications for fruit maturity, vestigial seed development, and sensory attributes of sovereign coronation table grapes. *Amer. J. Enol. Viticult.* 57:41–53.
- Reynolds, A.G., J. Schlosser, R. Power, R. Roberts, J. Willwerth, and C. De Savigny. 2007. Magnitude and interaction of viticultural and enological effects. I. Impact of canopy management and yeast strain on sensory and chemical composition of Chardonnay Musqué. *Amer. J. Enol. Viticult.* 58:12–24.
- Reynolds, A. and T.K. Wolf. 2008. Grapevine Canopy Management, p. 124–134. In: T.K. Wolf (ed.). *Wine grape production guide for eastern North America*. Natural Resource, Agriculture, and Engineering Service (NRAES) Cooperative Extension, Ithaca, NY.
- Ryona, I., B.S. Pan, D.S. Intrigliolo, A.N. Lakso, and G.L. Sacks. 2008. Effects of cluster light exposure on 3-isobutyl-2-methoxypyrazine accumulation and degradation patterns in red wine grapes (*Vitis vinifera* L. cv. Cabernet Franc). *J. Agr. Food Chem.* 56:10838–10846.
- Sabbatini, P. and G. Howell. 2010. Effects of early defoliation on yield, fruit composition, and harvest season cluster rot complex of grapevines. *HortScience* 45:1804–1808.
- Smart, R., J. Dick, I. Gravett, and B. Fisher. 1991. Canopy management to improve yield and quality: Principles and practices. *S. Afr. J. Enol. Viticult.* 11:3–17.
- Smart, R. and M. Robinson. 1991. *Sunlight into wine: A handbook for winegrape canopy management*. Winetitles, Adelaide, Australia.
- Smith, M.S. and M. Centinari. 2019. Impacts of early leaf removal and cluster thinning on Grüner Veltliner production, fruit composition, and vine health. *Amer. J. Enol. Viticult.* 70:308–317.
- Spayd, S., J.M. Tarara, D.L. Mee, and J.C. Ferguson. 2002. Separation of sunlight and temperature effects on the composition of *Vitis vinifera* cv. Merlot berries. *Amer. J. Enol. Viticult.* 53:171–182.
- Tarara, J., J.M. Lee, S.E. Spayd, and C.F. Scagel. 2008. Berry temperature and solar radiation alter acylation, proportion and concentration of anthocyanins in Merlot grapes. *Amer. J. Enol. Viticult.* 59:235–247.
- VanderWeide, J., I.G. Medina-Meza, T. Frioni, P. Sivilotti, R. Falchi, and P. Sabbatini. 2018. Enhancement of fruit technological maturity and alteration of the flavonoid metabolomic profile in Merlot (*Vitis vinifera* L.) by early mechanical leaf removal. *J. Agr. Food Chem.* 66:9839–9849.
- Wolf, T.K., R.M. Pool, and L.R. Mattick. 1986. Responses of young Chardonnay grapevines to shoot tipping, ethephon, and basal leaf removal. *Amer. J. Enol. Viticult.* 37:263–268.