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Modifying Shoot Tip Management to Reduce Cluster Compactness and Lateral Emergence in ‘Cabernet franc’ Grapevines

Anne K. Logan and Justin A. France
School of Integrative Plant Science, Cornell University, 134A Plant Sciences Building, Ithaca, NY 14853

James M. Meyers
Eastern New York Commercial Horticulture program, Cornell Cooperative Extension, Hudson Falls, NY 12839

Justine E. Vanden Heuvel
School of Integrative Plant Science, Cornell University, Ithaca, NY 14853

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***Abstract*. To manage excessive vine vigor, *Vitis vinifera* L. ‘Cabernet franc’ grapevines were subjected to shoot wrap, shoot tuck, and hedge (control) techniques at one of two growth stages (shoot tips at 30 cm or at 90 cm above the top catch wire) in the Finger Lakes region of New York from 2016 to 2019. Shoot tuck and shoot wrap both reduced fruit zone lateral counts, with reductions up to 33% and 56% compared with the control, respectively. Shoot wrap reduced fruit zone lateral lengths by up to 50% and cluster compactness by up to 2.4 fewer berries per centimeter rachis. Although shoot wrap improved spray penetration to the clusters by up to 28% in one year of the study, enhanced point quadrat analysis indicated that occlusion layer number was not affected by the treatments. Shoot tip management treatments did not affect yield or fruit composition consistently. Phenological timing of shoot tip management had little impact on vine growth. Although the impacts of these modified shoot tip management practices on lateral emergence and cluster morphology were generally positive, the required hand labor to apply the treatments on a large scale may discourage the use of these management practices.**

Excessive vine vigor often leads to issues such as poor canopy ventilation, inconsistent fruit ripening, and a high incidence of cluster rot. Hedging, or shoot tipping, is one common approach to managing vigorous vegetative growth in vertical shoot-positioned grapevines (Smart and Robinson, 1991; Wolf, 2008). A short-term solution, top hedging of positioned shoots, reduces canopy density only temporarily in the fruit zone if the shoots are hanging downward over the top wire. In addition, hedging ultimately results in more vigorous vegetative growth through newly emerged lateral shoots following the loss of apical dominance from shoot tip removal (Mason et al., 2014; Reynolds and Wardle, 1989). Clusters can also be affected by hedging. When shoot tips were removed early in the season, translocation of assimilates to the cluster improved the fruit set, leading to greater cluster compactness (Molitor et al., 2015; Vasconcelos and Castagnoli, 2000).

Emerging lateral shoots and compact clusters tend to exacerbate fungal disease incidence such as botrytis bunch rot caused by *Botrytis cinerea* and resulting from fruit zone shading, limited air circulation, and reduced fungicide penetration into clusters (Hed et al., 2009; Molitor et al., 2015). Symptoms of botrytis bunch rot include gray–brown mold sporulating growth covering grape berries that then shrink, shrivel, and change color to brown (white grapes) or red (purple grapes) when mature. Dull-green or reddish brown spots cover leaves, and brown spots cover pedicels and rachises, killing them and causing portions of the cluster to shrivel and drop.

Preliminary findings of one study showed that spray penetration into the clusters decreased linearly when cluster compactness increased (Hed et al., 2009). In addition, fruit zone leaf removal at trace bloom reduced cluster compactness by up to 26% and bunch rot by up to 83% (Hed et al., 2009).

There are few published studies on the impact of hedging as a canopy management tool. The timing of shoot tip manipulation can impact cluster and canopy growth. Early-season hedging at bloom or postbloom led to greater total leaf area and canopy density in the fruiting zone (Koblet, 1987; Molitor et al., 2015; Reynolds and Wardle, 1989). Delaying hedging to full canopy reduced total leaf area per shoot and per vine quantified about 1 month before veraison, possibly limiting the growth of the photosynthesizing leaf area of ‘DeChaunac’ vines trained on a high wire cordon (Reynolds and Wardle, 1989). Delaying hedging can also help reduce cluster compactness (berry number per centimeter rachis length). Vines topped 4 weeks after the end of flowering had the lowest cluster compactness in vertical shoot-positioned trained ‘Pinot gris’ in 1 year of a 2-year study in Luxembourg (Molitor et al., 2015). However, there is new interest in the wine grape industry regarding the use of shoot wrapping or shoot tucking as possible alternatives to hedging (France et al., 2018). This technique of wrapping shoots along the top catch wire or tucking shoots into the catch wires is known in the wine grape industry as palissage or tressage, respectively.

Molitor et al. (2015) found that shoot wrap (when used as a control to quantify total shoot growth in a season) reduced cluster compactness in ‘Pinot gris’ compared with hedging 1 week before and at bloom. France et al. (2018) evaluated the shoot wrap and shoot tuck techniques preliminarily in New York, noting six fewer lateral shoots per vine with the shoot wrap technique, and longer rachises by 1.4 cm in vines with the shoot tuck technique, compared with vines in the hedged treatment. In their study, cluster compactness was not reduced consistently by either technique compared with hedging in ‘Riesling’ wine grapes. A long-term study comparing the shoot tuck, shoot wrap, and hedge techniques is lacking in the literature.

The objective of our 4-year study was to investigate effects of shoot tip management and timing of application on vine growth, fruit composition, cluster morphology, and disease severity/incidence in ‘Cabernet franc’ wine grapes. We hypothesized that implementing either shoot wrap or shoot tuck early during the season would reduce lateral emergence and cluster compactness in ‘Cabernet franc’ vines compared with hedging.

Materials and Methods

Experimental setup. From 2016 to 2019, this study was conducted on *Vitis vinifera* ‘Cabernet franc’ cl. 1 grafted onto 3309C rootstock, located in a 0.25-ha research vineyard (elevation, 124 m) in Lansing, NY (lat. 42°34′15″N, long. 76°35′39″W). Following establishment of the experiment, it was determined that one of the nine rows of the experiment was ‘Cabernet franc’ cl. 4 (rather than cl. 1). The cl. 4 row did not differ visually from the cl. 1 row. To account for this difference in clones, the row was included as a random effect in the statistical model.

Vines were planted in 2008 on a Hudson-Cayuga silt loam soil on a 5% to 8% west-facing slope, with a vine-by-row spacing of 1.8 × 2.8 m. Each row contained 24 vines in six panels, with each panel consisting of four vines. Each row contained two experimental units, with each consisting of three panels of four vines per panel, for a total of 12 vines per experimental unit. The interior two panels of each experimental unit (eight vines) were designated as treatment data collection panels. The treatments were replicated three times. Row middles were originally planted with fescue species, but by the start of the experiment were filled with a range of grass and broadleaf species. Row middles were maintained with period mowing;

under-vine herbicide strips were maintained with glyphosate applications twice per season.

During dormancy, vines were cane-pruned to 40 nodes per vine and shoot-thinned to 30 shoots per vine in 2017 and 2018, and 28 shoots per vine in 2016 and 2019. Vines were trained to a two-tier flat-bow system in which canes were laid down bilaterally on two fruiting wires, with four canes per vine and shoot subjected to vertical shoot positioning (VSP). Three shoot tip management methods (shoot wrap, shoot tuck, and hedge) were evaluated in a randomized complete block design in a factorial, with treatment application at two timings: early (shoots reach 30 cm above the top wire) and late (shoots reach 90 cm above the top wire). Diagrams of the shoot tip management methods can be found in France et al. (2018). The early treatments were applied on 30 June 2016, 19 June 2017, 27 June 2018, and 2 July 2019. The late treatments were applied were on 15 July 2016, 6 July 2017, 12 July 2018, and 13 July 2019. The treatment combinations were as following for early applications of techniques: control (CE), shoot tuck (STE), shoot wrap (SWE); and for late applications of techniques: control (CL), shoot tuck (STL), shoot wrap (SWL).

Climate data were obtained from the Cornell University Network for Environment and Weather Applications (NEWA) Lansing station except for Sept. and Oct. 2019. Data for these 2 months were not available at the Lansing station, so data were obtained from the Romulus station (lat. 42°42′00.0″N, long. 76°45′00.0″W) because the region is similar climatically to the Lansing station (newa.cornell.edu). Historic data from 2004 to 2015 were also obtained for the Lansing station except for June 2010, which were obtained from another climatically similar region at the Ovid station (lat. 42°41′24.0″N, long. 76°45′00.0″W) because no data were available for either the Lansing or Romulus stations. July to Sept. 2010 data were also missing from all three NEWA stations. Rainfall and growing degree days (GDDs) (base threshold of 10 °C) were calculated from precipitation and temperature data obtained from 1 Apr. to 31 Oct. for all years except for the missing months in 2010.

Shoot quantification and lateral emergence. Bud survival was quantified on 12 May 2017, 21 May 2018, and 30 May 2019 by recording the number of live and dead buds per vine and calculating the proportion of nodes that developed on primary shoots. Four randomly selected primary shoots were tagged per vine (totaling 32 shoots per experimental unit) and were measured throughout the growing season every 2 to 4 weeks from near-bloom until veraison using electronic calipers (model ME1002; Hangzhou Maxwell Tools, Zhejiang, China) to determine the effects of shoot tip management techniques on shoot diameter.

Before harvest, lateral shoots were counted on each of the eight data vines in the interior panels on 21 Sept. 2016, 1 Sept. 2017, and 18 Sept. 2019, and after harvest on 17 Oct. 2018. As a part of the counting process, the vine canopy was divided vertically into three main sections: the fruit zone (0 cm from the fruiting wire to 30 cm above fruiting wire), the middle canopy (30–60 cm above the fruiting wire), and the upper canopy (60–90 cm above the fruiting wire) (France et al., 2018). In 2018, only laterals in the fruit zone were counted. Lateral lengths were also measured in each zone on 24 lateral shoots per experimental unit on 21 Sept. 2017, 30 Oct. 2018, and 17 Sept. 2019.

Canopy structure. Vine canopy structure was analyzed on each data vine using enhanced point quadrat analysis (EPQA) and photosynthetically active radiation at 50% veraison [Eichhorn-Lorenz (E-L 36)] on 14 Aug. 2017, 23 Aug. 2018, and 10 Aug. 2019 as described by Meyers and Vanden Heuvel (2008). Leaf layer number (LLN), percent interior clusters (PIC), percent interior leaves (PIL), occlusion layer number (OLN), cluster exposure layers (CEL), leaf exposure flux availability (LEFA), and cluster exposure flux availability (CEFA) were determined using Canopy Exposure Mapping Tools (version 1.7; available from jmm533@cornell.edu).

To characterize canopy surface and leaf area, measurements of vine height, width, and length were taken on a per-vine basis on 21 Aug. 2019. Leaf area was obtained at 50% to 75% veraison (E-L 36–37) on 3 Sept. 2019. One shoot per vine, or eight shoots per experimental unit, were harvested and the clusters removed; primary and lateral leaves were counted separately. Leaf area for each set was quantified using a LI-COR 3100 leaf area meter (LI-COR, Lincoln, NE).

Leaf blade nutrient status. Twenty leaf blades per experimental unit were collected from the fifth node up from the base, from techniques applied at early timing only at veraison (E-L 36–37) on 28 Aug. 2019. Composite samples were washed with mild soap, then rinsed with deionized water and sent to the Cornell Nutrient Analysis Laboratory to determine total C and N using combustion, and macro- and micronutrients (Al, B, Ca, Cu, Fe, K, Mg, Mo, Mn, Na, P, and Zn) using a dry ash extraction method as described by Campbell and Plank (1998).

Disease incidence. Spray penetration to clusters was analyzed on 10 Aug. 2017, 13 Aug. 2018, and 22 Aug. 2019, close to veraison (when vines were most susceptible to cluster rot), using spray penetration cards (Salyani and Fox, 1999). Four 5.1- × 7.6-cm water-sensitive spray cards (TeeJet; Gempler's, Janesville, WI) per experimental unit were fastened with zip ties and placed in front of clusters located in the fruit zone. Vines were sprayed with water, stimulating the same settings used in a standard spray program for cluster rot. To analyze the spray cards, percent surface area of the card covered by spray was calculated by counting the number of squares that were at least 50% blue, in response to exposure to water spray, using a 1-cm grid sheet.

Incidence and severity of *Plasmopara viticola*, commonly known as grapevine downy mildew, were evaluated in a 1- × 1.5-m section in the middle of each data collection panel. All leaves in the section were removed near harvest on 24 Sept. 2018 and 12 Sept. 2019, and were rated both for incidence (percentage of leaves having any sign of downy mildew vs. percentage of leaves not having any sign) and for severity (1, 0% to 25%; 2, 26% to 50%; 3, 51% to 75%; 4, 76% to 100% of leaf area infected). Downy mildew was identified by yellow lesions on the upper leaves and burnt edges, as well as brown spots on the underside (Wolf, 2008).

Yield parameters and cluster morphology. Grapes from each experimental unit were harvested on 5 Oct. 2016, 14–16 Oct. 2017, 15 Oct. 2018, and 15 Oct. 2019, and were weighed for yield in kilograms per vine using a hanging scale (SA3N340; Salter Brecknell, Fairmont, MN). Vines were harvested on a per-vine basis in all years except for 2019, when they were harvested on a per-panel basis. In all years, and particularly in 2019, there were significant crop losses resulting from bird feeding despite protective netting. After pruning, pruning weight was quantified using the hanging scale on 26 Mar. 2017, 10 and 11 Mar. 2018, and 12 Mar. 2019, and the Ravaz index (crop load/pruning weight) was calculated. In 2019, pruning weights were collected after harvest.

Fruit composition. Clusters were scored at ≈50% veraison, or at E-L stage 36, for the proportion of berries that changed color from green to red (1, 0% to 25%; 2, 25% to 50%; 3, 50% to 75%; 4, 75% to 100%), to evaluate whether shoot tip modification techniques applied early or late impacted the rate of berry softening and color change during veraison (Coombe, 1995).

Berry data were collected after harvest on 20 randomly selected clusters from each experimental unit by measuring the main rachis length and by counting total berry number

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A.K.L. is a PhD Student.
J.A.F. is a Former MS Student.
J.M.M. is a Viticulture Extension Specialist.
J.E.V.H. is a Professor.
J.E.V.H. is the corresponding author. E-mail: justine@cornell.edu.

per cluster; cluster compactness was determined based on the number of berries per centimeter of the main rachis (France et al., 2018). After harvest data collection, and after removing fruit with more than 30% rot, the fruit were transported to the New York State Wine Analytical Laboratory at Cornell AgriTech (Geneva, NY). Soluble solids (Brix) were quantified on juice samples using a digital refractometer with temperature compensation (model PA203X; Misco, Solon, OH); pH was measured with a calibrated pH meter (Accument Basic AB15; Fisher Scientific, Pittsburgh, PA). Titratable acidity was measured by autotitrating 5 mL of juice with 0.10 M NaOH to a pH endpoint of 8.2 using a pH meter (848 Titrino Plus; Metrohm, Riverview, FL). Juice samples were also tested for yeast assimilable N (YAN) by enzymatic analysis for primary amino N and NH_3 (model RS-232; Randox Monaco RX, Kearneysville, WV). To quantify anthocyanins on juice samples, the Admeo Anthocyanin Enzyme Kit (Admeo Inc., Angwin, CA) and a spectrophotometer (model 384 plus; VWR International Spectramax, San Jose, CA) were used; samples were read at 520 nm.

Statistical analysis. Two-way analysis of variance, with technique and timing as the two factors, was used with treatments as a fixed variable and experimental units as a response variable. Significance was determined at $\alpha = 0.05$. Random effects including replicate, row, climate, and spatial variability were accounted for. For post hoc mean separation testing, Tukey's honestly significant difference method was used. Models were run with replicate and replicate nested in half row as random effects because one half row consisted of an experimental unit.

Results

Weather and precipitation. The greatest number of GDDs occurred in 2018 (1762 °C) compared with 2019, which had the lowest GDDs (at 1513 °C, as shown in Table 1). Total precipitation from 1 Apr. to 31 Oct. was 45.8 cm in 2016, which is in the class III drought classification (Table 1). Total precipitation for the 2017 growing season, the wettest season in this study, was almost double that of 2016—at 81.1 cm (Table 1). In particular, the months of July and October had the greatest amount of precipitation for 2017. Total precipitation was 66.5 cm and 68 cm for 1 Apr. to 31 Oct. in 2018 and 2019, respectively.

Bud survival. Vines subjected to late timing application had a 2% greater bud survival than those subjected to early timing application at the start of the 2019 growing season only ($P = 0.0015$, data not shown). This small increase was statistically significant but is unlikely biologically significant.

Lateral emergence and length. Shoot tip modification technique affected the number of laterals in the fruit zone significantly. SWE reduced fruit zone lateral counts by 41%, 23%, and 56% compared with CE in 2017, 2018, and 2019, respectively. SWL reduced laterals by almost 50% compared with CL in 2017 and by almost 30% in 2018 (Table 2). STL reduced fruit zone lateral counts by 15% compared with CL in 2018. Lateral counts in the middle and upper canopy varied by technique. The interaction was not significant in 2017 or 2018. Compared with CE, SWE reduced middle canopy counts by 51% in 2017 and upper canopy counts by 43% and 31% in 2017 and 2019, respectively (Table 2). SWL reduced upper canopy in 2017 by 26% only compared with CL. STE reduced fruit zone lateral counts by 33% compared with CE in 2019 (Table 2).

The greatest reductions in lateral length in the fruit zone compared with CE and CL were in the SWE and SWL treatments. SWE reduced fruit zone lateral lengths by 43%, 50%, and 41% in 2017, 2018, and 2019, respectively (Table 2). Lateral length in the middle canopy was affected mostly by technique in 2017 and 2018 in the upper canopy, whereas lateral length was affected by both technique and timing of technique application in 2017, 2018, and 2019 (Table 2). In general, SW at both timings also reduced lateral lengths in the middle and upper canopies (Table 2).

Vegetative growth. Treatments did not consistently impact EPQA parameters, which quantified canopy architecture and light exposure. OLN, LLN, PIC, and PIL did not differ significantly between techniques or timings (data not shown). The SWE treatment improved CEFA and LEFA by 0.08, compared with the CE treatment in 2017 (Table 3). In 2018, SWE improved CEFA and LEFA by 0.09 and 0.07, respectively, compared with CE whereas SWL improved LEFA by 0.05 compared with CL. In 2019, the SWE treatment improved LEFA by 0.09 compared with CE.

In 2019, ST technique increased leaf number by six leaves more than C ($P = 0.0012$), increasing leaf area per shoot to 1588 cm^2 compared with 1164 cm^2 in C ($P = 0.0326$) (data not shown). Number of lateral leaves per shoot and lateral leaf area did not differ significantly among techniques or timing of application (data not shown).

Leaf blades of SWE vines in 2019 had a greater P concentration (912.5 mg/kg) compared with vines from the CE treatment (834.7 mg/kg) and STE treatment (812.1 mg/kg) at $P = 0.0340$ (data not shown). Other than P, macro- and micronutrient leaf blade concentrations did not differ among treatments.

Spray penetration and downy mildew. In 2017, there was no significant difference between techniques or timing of technique application because all cards turned blue, possibly a result of humid canopies at the time of spray card data collection. In 2018, SW technique, regardless of timing, increased spray penetration to the clusters by 28% ($P = 0.0306$), as shown by the color change of the cards after spray exposure, compared with the C technique (Fig. 1A). Technique application timing and interactions did not differ. Mean percentage spray coverage was not significantly different among treatments in 2019 (Fig. 1B).

At least 86% and 95% of vines in all treatments had downy mildew lesions in 2017 and 2019, respectively, likely resulting from high rainfall amounts early in the growing season. In 2018, CE vines had the lowest incidence of downy mildew lesions at 60%, whereas STE had the greatest incidence at 69% ($P = 0.0454$ for technique, data not shown). Anecdotally, the greatest incidence of downy mildew occurred in the upper portions of the canopy, where the

Table 1. Growing degree day (GDD) accumulation calculated from daily minimum and maximum temperatures from 1 Apr. to 31 Oct., and precipitation for the experimental site from 2016 to 2019.[z]

Variable by mo.	2016	2017	2018	2019	Historic[y]
GDD (base, 10 °C)					
April	29	92	14	44	43
May	161	150	252	139	169
June	299	297	288	271	281
July	421	371	412	424	373
August	428	331	408	333	338
September	287	265	292	234	232
October	111	171	96	69	86
Total	1,735	1,676	1,762	1,513	1,522
Precipitation (cm)					
April	4.6	9.5	5.3	6.7	6.5
May	4.5	11.8	5.0	1.2	5.6
June	2.1	12.2	5.7	9.9	7.5
July	4.1	22.7	14.9	9.2	12.7
August	9.6	3.5	11.0	9.7	8.5
September	4.0	5.8	12.5	5.1	6.9
October	16.9	15.6	12.1	15.4	15.0
Total	45.8	81.1	66.5	68.0	65.4

[z]Data for GDDs and precipitation were obtained from the NEWA station at Lansing, NY, except for Sept. and Oct. 2019; those data were obtained from the NEWA at Romulus (Thirsty Owl) station.

[y]Historic GDD and precipitation data were the averages from 2004 to 2019 from the Network for Environment and Weather Applications (NEWA) station at Lansing, NY, except for June 2010 (obtained from the Ovid station), July to Sept. 2010 (missing data range), and Sept. to Oct. 2019 [obtained from the NEWA at Romulus (Thirsty Owl) station].

Table 2. Elongation and number of emerged lateral shoots per 'Cabernet franc' vine in the fruit zone (fruiting wire to 30 cm above the fruiting wire), middle canopy (30–60 cm above the fruiting wire), and upper canopy (60–90 cm from the fruiting wire), subjected to techniques applied early and late in 2017–19 in Lansing, NY. Values are estimated mean ± SE.

Timing	Technique	Lateral counts per vine, fruit zone	Lateral counts per vine, middle canopy	Lateral counts per vine, upper canopy	Average lateral length per lateral shoot, fruit zone (cm)	Average lateral length per lateral shoot, middle canopy (cm)	Average lateral length per lateral shoot, upper canopy (cm)
2017[z]							
Early	Control	37 ± 4.5 b[y]	57 ± 7.3 b	51 ± 6.0 b	10.7 ± 1.7 b	28.0 ± 2.6 b	66.3 ± 3.1 b
	Shoot tuck	25 ± 4.5 ab	52 ± 7.3 b	43 ± 6.0 ab	7.4 ± 1.2 ab	21.6 ± 2.6 ab	62.7 ± 3.1 b
	Shoot wrap	22 ± 4.5 a	28 ± 7.3 a	29 ± 6.0 a	6.1 ± 1.0 a	16.3 ± 2.6 a	49.6 ± 3.1 a
Late	Control	29 ± 4.5 B	54 ± 7.3 A	46 ± 6.0 B	10.6 ± 1.7 A	26.8 ± 2.6 A	62.1 ± 3.1 B
	Shoot tuck	23 ± 4.5 AB	48 ± 7.3 A	55 ± 6.0 AB	8.1 ± 1.3 A	22.9 ± 2.6 A	53.4 ± 3.1 B
	Shoot wrap	15 ± 4.5 A	45 ± 7.3 A	34 ± 6.0 A	6.9 ± 1.1 A	20.3 ± 2.6 A	40.4 ± 3.1 A
	P value, technique	0.0248	0.0277	0.0150	0.0045	0.0093	<0.0002
	P value, timing	0.1479	0.4929	0.4311	0.5714	0.5264	0.0133
	P value, timing:technique	0.7639	0.1720	0.3442	0.7870	0.3555	0.7241
2018							
Early	Control	39 ± 1.5 b	—	—	8.2 ± 0.9 b	11.6 ± 1.3 b	42.0 ± 2.7 b
	Shoot Tuck	36 ± 1.4 b	—	—	6.3 ± 0.9 ab	12.3 ± 1.3 b	43.7 ± 2.7 b
	Shoot Wrap	30 ± 1.5 a	—	—	4.1 ± 0.9 a	7.9 ± 1.3 a	27.8 ± 2.7 a
Late	Control	41 ± 1.6 C	—	—	7.3 ± 0.9 B	10.0 ± 1.3 AB	32.2 ± 2.7 B
	Shoot Tuck	35 ± 1.5 B	—	—	5.7 ± 0.9 AB	11.3 ± 1.3 B	27.5 ± 2.7 B
	Shoot Wrap	29 ± 1.5 A	—	—	4.2 ± 0.9 A	7.4 ± 1.3 A	15.8 ± 2.8 A
	P value, technique	0.0001	—	—	0.0017	<0.0001	<0.0001
	P value, timing	0.9903	—	—	0.9293	0.3584	<0.0001
	P value, timing:technique	0.4254	—	—	0.9277	0.5720	0.5046
2019							
Early	Control	45 ± 2.5 b	31 ± 2.4	39 ± 2.6 b	7.5 ± 0.7 b	9.2 ± 0.6 ab	25.6 ± 2.1 b
	Shoot Tuck	30 ± 2.6 a	32 ± 2.5	34 ± 2.6 ab	6.0 ± 0.7 b	9.6 ± 0.7 b	22.8 ± 2.1 b
	Shoot Wrap	20 ± 2.6 a	26 ± 2.5	27 ± 2.6 a	4.4 ± 0.7 a	7.7 ± 0.6 a	13.4 ± 2.1 a
Late	Control	35 ± 2.6 A	29 ± 2.5	36 ± 2.6 A	6.6 ± 0.7 A	8.8 ± 0.7 A	16.3 ± 2.1 A
	Shoot Tuck	28 ± 2.6 A	29 ± 2.5	37 ± 2.6 A	6.4 ± 0.7 A	8.5 ± 0.7 A	13.0 ± 2.2 A
	Shoot Wrap	27 ± 2.6 A	26 ± 2.5	37 ± 2.6 A	5.8 ± 0.7 A	9.5 ± 0.6 A	13.7 ± 2.1 A
	P value, technique	0.0001	0.0794	0.0989	0.0020	0.6054	0.0074
	P value, timing	0.4074	0.3914	0.1222	0.5112	0.8276	0.0021
	P value, timing:technique	0.0248	0.6935	0.0486	0.1107	0.0415	0.0375

[z]Control was hedged twice in early timing in 2017 and 2019 because some shoots did not reach 30 cm above the top catch wire at first hedging.

[y]Lowercase letters indicate a separation of treatments within timing for early, and uppercase letters indicate a separation of treatments within timing for late, by Tukey's honestly significant difference test at a 5% significance level. For the columns in which there are no upper- and lowercase letters, there are no differences between these values.

shoots were wrapped around the wire in the SW treatment or were bent in the ST treatment.

Cluster compactness. Clusters from SW vines had 15 fewer berries per cluster than clusters from C vines in 2016 (Fig. 2A). The 2017 season was a very heavy crop year, with more berries per cluster than in other years. SW had 14 fewer berries per cluster than C vines in 2017 (Fig. 2B). In 2018 and 2019, there were no significant differences in berry number per cluster. In 2016, SW technique had the longest rachis length per cluster—1.7 cm longer than C vines (Fig. 2E). There was a significant interaction between timing and technique for cluster compactness in 2016 only. SWE treatment reduced cluster compactness by 2.4 berries per cm of rachis in vines compared with the CE treatments ($P = 0.0131$, data not shown). There was no significant interaction between application timing and technique in the other years for cluster compactness metrics. Timing of application also did not affect cluster compactness metrics consistently. SW technique generally reduced cluster compactness in 3 of the 4 years of the study (Fig. 2I–L). In 2017, SW had lower cluster compactness with 1.6 fewer berries per cm of rachis, than C (Fig. 2J). In 2018, SW had 1.0 fewer berries per cm of rachis than C, at 6.5 berries per cm rachis (Fig. 2K).

Yield components. Since crop losses to birds and disease were significant, data presented here may not accurately reflect treatment impacts on yield components. Nonetheless, technique and application timing inconsistently impacted yield per vine with 4.6 to 6.5, 8.5 to 10.5, 4.8 to 6.1, and 2.9 to 4.1 kg per vine, in 2016, 2017, 2018, and 2019, respectively (data not shown). In 2017, there was a significant interaction between technique and timing: SWE vines had lower yield per vine by 1.6 kg/vine compared with CE likely due to reduced berry number (Fig. 2F). In 2018, SWL had 1.0 and 1.3 kg lower yield per vine than CL and STL, respectively. Technique and timing of application inconsistently impacted cluster number per vine which varied by year with 56 to 69, 63 to 69, 54 to 64, and 39 to 53 clusters per vine in 2016, 2017, 2018, and 2019, respectively. In 2019, SWE vines had 14 fewer clusters per vine than CE. Technique and timing affected average cluster weight per cluster and berry weight per berry inconsistently (data not shown). In 2017, SW technique reduced cluster weight in vines by 21 g per cluster compared with the C technique. In 2019, vines subjected to early technique applications had lower berry weight by 0.09 g per berry than vines subjected to late technique application.

Pruning weight did not differ among technique or timing of application for all years, with 0.68 to 0.92, 0.71 to 1.00, 0.43 to 0.60, and 1.08 to 1.29 kg per vine of pruned growth, in 2016, 2017, 2018, and 2019, respectively (data not shown). Given the repeated removal of plant material from the hedging treatments only, pruning weight is unlikely to be a good indicator of vine size in this experiment.

Fruit composition. The shoot tip management technique affected fruit composition inconsistently. The technique affected progression through veraison in only 2 of the 4 years studied, and the impacts were slight. In 2016, vines that underwent the ST and SW techniques, regardless of application timing, were 15% more advanced in veraison progression than vines in the C techniques (Table 4). Veraison rating did not differ among techniques or timing in 2017 (data not shown). A trend similar to that of 2016 was observed for 2018, with an 18% increase in veraison progression in both the ST and SW treatment vines compared to C vines, regardless of application timing. In 2018 only, there was a significant interaction between technique and timing for titratable

Table 3. Enhanced point quadrat metrics in ‘Cabernet franc’ vines subjected to techniques applied early and late from 2017 to 2019, collected at 50% veraison in Lansing, NY. Values are estimated means ± SE.

Timing	Technique	CEL	LEL	CEFA	LEFA
2017					
Early	Control	1.3 ± 0.06 ab[z]	0.7 ± 0.05	0.11 ± 0.01 a	0.26 ± 0.01 a
	Shoot tuck	1.4 ± 0.06 b	0.6 ± 0.05	0.12 ± 0.01 a	0.30 ± 0.01 ab
	Shoot wrap	1.1 ± 0.06 a	0.5 ± 0.05	0.19 ± 0.01 b	0.34 ± 0.01 b
Late	Control	1.1 ± 0.06 A	0.6 ± 0.05	0.18 ± 0.01 A	0.32 ± 0.01 A
	Shoot tuck	1.1 ± 0.06 A	0.6 ± 0.05	0.16 ± 0.01 A	0.32 ± 0.01 A
	Shoot wrap	1.2 ± 0.06 A	0.5 ± 0.05	0.16 ± 0.01 A	0.34 ± 0.01 A
	P value, technique	0.1078	0.2387	0.0097	0.0059
	P value, timing	0.0645	0.4909	0.0262	0.0192
	P value, timing:technique	0.0159	0.5238	0.0008	0.0679
2018					
Early	Control	1.1 ± 0.08	0.6 ± 0.03 a	0.13 ± 0.02 a	0.27 ± 0.01 a
	Shoot tuck	1.1 ± 0.07	0.6 ± 0.03 a	0.19 ± 0.02 ab	0.32 ± 0.01 b
	Shoot wrap	0.9 ± 0.07	0.5 ± 0.03 a	0.22 ± 0.02 b	0.34 ± 0.01 b
Late	Control	1.1 ± 0.07	0.7 ± 0.03 B	0.19 ± 0.02 A	0.29 ± 0.01 A
	Shoot tuck	1.0 ± 0.08	0.6 ± 0.03 AB	0.22 ± 0.02 A	0.30 ± 0.01 A
	Shoot wrap	0.9 ± 0.07	0.5 ± 0.03 A	0.23 ± 0.02 A	0.34 ± 0.01 B
	P value, technique	0.0618	0.0008	0.0389	0.0006
	P value, timing	0.6226	0.1423	0.1083	0.9072
	P value, timing:technique	0.7273	0.2529	0.5465	0.3292
2019					
Early	Control	0.9 ± 0.1	0.5 ± 0.03	0.19 ± 0.03 a	0.30 ± 0.01 a
	Shoot tuck	0.9 ± 0.1	0.5 ± 0.03	0.24 ± 0.03 ab	0.36 ± 0.01 b
	Shoot wrap	0.8 ± 0.1	0.4 ± 0.03	0.30 ± 0.03 b	0.39 ± 0.01 b
Late	Control	0.8 ± 0.1	0.5 ± 0.03	0.26 ± 0.03	0.37 ± 0.01 A
	Shoot tuck	0.7 ± 0.1	0.4 ± 0.03	0.29 ± 0.03	0.38 ± 0.01 A
	Shoot wrap	0.7 ± 0.1	0.4 ± 0.03	0.29 ± 0.03	0.37 ± 0.01 A
	P value, technique	0.4972	0.1374	0.0827	0.0020
	P value, timing	0.2353	0.1051	0.1683	0.0427
	P value, timing:technique	0.7497	0.3511	0.3391	0.0020

[z]Lowercase letters indicate a separation of treatments within timing for early, upper case letters indicate a separation of treatments within timing for late, by Tukey’s honest significant difference test at a 5% significance level. For the columns where there are no upper and lowercase letters, there are no differences among these values.

[y]CEL = cluster exposure layer, LEL = leaf exposure layer (cluster or leaf exposure layer is the number of shading leaf between cluster or leaf, respectively, and the boundary of the canopy, CEFA = cluster exposure flux availability, LEFA = leaf exposure flux availability (Cluster or leaf exposure flux availability is the percentage expressed as a decimal of the above canopy photon flux that reaches a cluster or leaf, respectively) (Meyers and Vanden Heuvel, 2008).

acidity. SWE vines had 0.9 g/L more titratable acidity than CE vines (data not shown). Neither technique nor timing affected pH significantly in all years, except in 2016, in which SW technique increased pH by 0.19 U more than the ST technique (Table 4). However, the SW technique, regardless of timing, increased YAN in the fruit by 23 mg/L more than the ST technique in 2018 only (Table 4).

Cost comparison. A cost comparison was undertaken to assess the potential costs of applying either the SW or ST technique, as well as other canopy management practices that could be avoided. Assumptions of labor and equipment costs are detailed in Table 5. If either technique could be completed in 30 s per vine for a vineyard with a standard 1.8- × 2.7-m vine-by-row spacing, then the cost would be comparable to that of two mechanical hedge passes, which is common in the northeastern United States (Wolf, 2008). These mechanical techniques could potentially be replaced due to the reduced emergence and length (Table 2).

Discussion

Two vine parameters, lateral emergence and cluster compactness, were affected consistently over at least 3 of the 4 years of our study. Both SW and ST techniques generally reduced lateral emergence in the fruit zone, with more profound effects noted with the SW technique. The observed reduction in lateral shoot emergence in all canopy zones of SW vines in this study were similar to a previous study on shoot wrap and tuck techniques (France et al., 2018). Vines in the C treatments likely compensated for the loss of leaf area in response to hedging, with new growth deriving from lateral shoot emergence (Reynolds and Wardle, 1989). Hormone interactions and carbohydrate availability were found to regulate lateral emergence together in grapevines, possibly explaining the lower numbers of lateral shoots that emerged in 2016 and in the SW treatments (Eltom et al., 2013; Mason et al., 2014).

Bending shoots can also promote lateral bud outgrowth along the bent portions of primary shoots. In pear trees, shoot bending was found to accelerate flower development and to change endogenous hormone levels, suggesting that the ability of lateral buds to compete for assimilates was increased (Ito et al., 1999). This mechanism may explain the lack of differences in our study in lateral length in the ST compared with the C treatments observed in the middle and upper canopies, as well as in the 135° and 180° angling treatments in a small study (A.K. Logan, unpublished data).

Cluster compactness was also greatly reduced in both SW and ST techniques from 2016 to 2018. This can be attributed to fewer berries per cluster throughout this entire time frame, as well as rachis elongation in 2016 only. The first study to evaluate both the SW and ST techniques (France et al., 2018) did not report a change in cluster compactness among treatments, but did find that the ST treatment increased rachis length by 1.4 cm compared with the C treatment. Rachis internode length, as determined by internode cell expansion before antithesis, was identified as a major determinant of inflorescence openness (Shavrukov et al., 2004).

Flower number and fruit set rate could also affect cluster morphology (Carmona et al., 2008; Tello and Forneck, 2018). When leaves were removed early in the season, fruit set was reduced, leading to fewer berries per cluster and looser clusters (Poni et al., 2006). Reduced assimilate availability shortly after flowering could have reduced fruit set and berry number per cluster, reducing cluster compactness in the SW treatment as vines abandoned weaker flowers and smaller berries (Caspari et al., 1998; Poni et al., 2006).

Timing of treatment application had inconsistent results in lateral shoot and cluster compactness metrics. In contrast, delaying hedging to 4 weeks after flowering

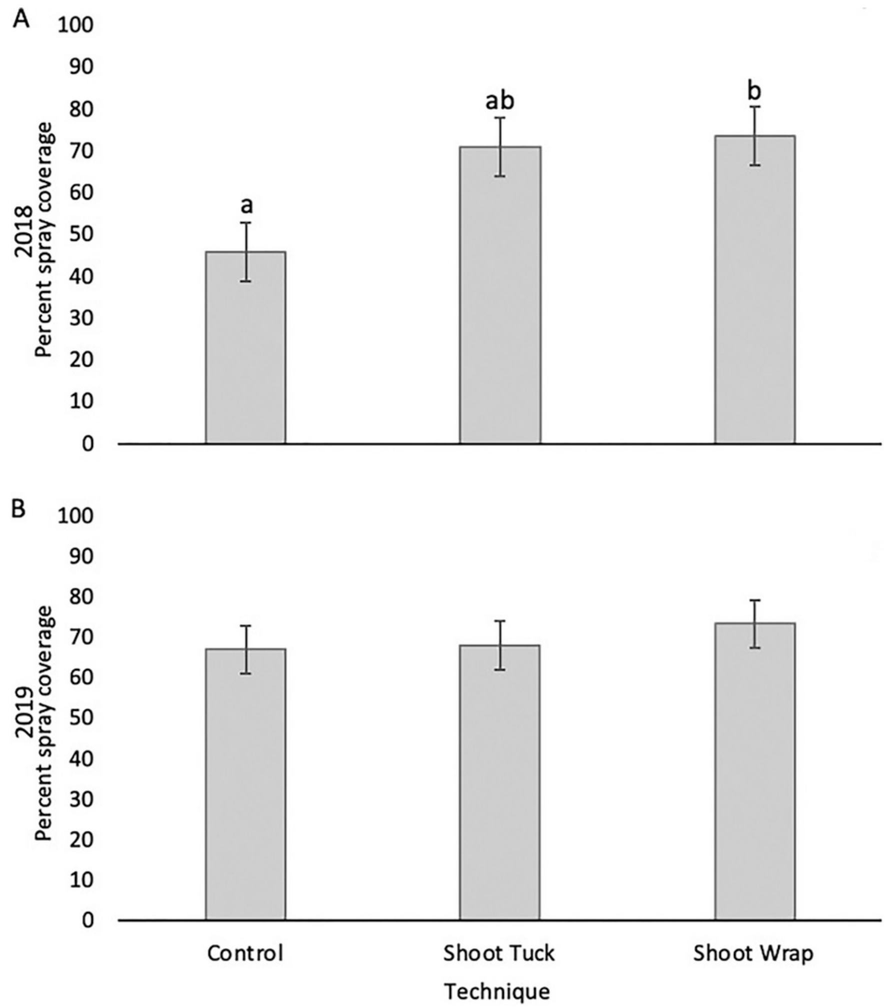

Fig. 1. Percent spray coverage of spray cards placed in the fruit zone of 'Cabernet franc' vines subject to shoot management techniques collected at Lansing, NY, on (**A**) 13 Aug. 2018 and (**B**) 22 Aug. 2019. Bars with different letters indicate significant differences in estimated mean ± SE of techniques at $P < 0.05$ by Tukey's honestly significant different test.

was found to loosen grape clusters and reduce lateral shoot length consistently, especially in the upper canopy, at nodes 8 to 10 in a hedging study (Molitor et al., 2015). The longer laterals observed in the CE treatment across all zones were similar to the observed increased average lateral length in vines subjected to earlier shoot toppings (Molitor et al., 2015).

The sizeable but nonsignificant increase in YAN observed in 2018 in the SW treatments was in agreement with a previous study that reported large but nonsignificant increases in YAN in the SW and ST treatments compared with the C treatment (France et al., 2018). The increased canopy surface area per vine and the number of leaves per shoot in the wrapped vines may have contributed to the increased YAN. Leaf blade sampling in 2019 also showed high levels of N across all treatments applied early, suggesting greater N uptake. The increase in titratable acidity observed in the SWE treatment in our study was similar to that observed in a small study that compared the hedging and SW techniques (Vanden Heuvel, 2015). France et al. (2018) reported that SW and ST techniques increased titratable acidity by 0.3 and 0.7 g/L, in one year only.

The reductions in lateral emergence and lateral lengths especially in the fruit zone may eliminate the need for leaf removal, which is commonly practiced in VSP-trained systems (Smart and Robinson, 1991). The cost comparison indicated that if either technique (SW or ST) could be completed in 60 s or less per vine, the production cost per hectare would be similar to prior to adoption due to the elimination of the costs of both hedging and mechanical leaf removal. If application of SW or ST requires more than 60 s per vine, the cost of production would increase substantially.

Table 4. Rating of veraison progression at Eichhorn-Lorenz stage 36 (0 = most green and hardest, 5 = most color and softest) and fruit composition metrics in clusters at harvest of 'Cabernet franc' subjected to shoot management techniques applied early or late at Lansing, NY. Values are estimated means ± SE.

Technique	Veraison rating[z]	Soluble solids (Brix)	Titratable acidity (g/L)	pH	Total anthocyanins (mg/L)[y]	YAN (mg/L)
2016						
Control	3.3 ± 0.17 a[x]	17.5 ± 0.4	7.6 ± 1.4	3.46 ± 0.07 ab	—	—
Shoot tuck	3.6 ± 0.17 b	17.8 ± 0.4	9.5 ± 1.4	3.32 ± 0.07 a	—	—
Shoot wrap	3.6 ± 0.17 b	18.1 ± 0.4	7.0 ± 1.4	3.51 ± 0.07 b	—	—
P value	0.0058	0.2468	0.2125	0.0483	—	—
2018						
Control	2.3 ± 0.16 a	20.2 ± 0.2	5.4 ± 0.2	3.48 ± 0.03	23.3 ± 3.0	78 ± 5.3 ab
Shoot tuck	2.8 ± 0.16 b	20.4 ± 0.2	5.2 ± 0.2	3.47 ± 0.03	28.9 ± 3.0	70 ± 5.3 a
Shoot wrap	2.8 ± 0.16 b	19.8 ± 0.2	5.8 ± 0.2	3.50 ± 0.03	27.9 ± 3.0	93 ± 5.3 b
P value	0.0121	0.1434	0.0572	0.8151	0.4099	0.0362
2019[w]						
Control	2.2 ± 0.18	—	8.7 ± 0.5	3.09 ± 0.01	20.0 ± 2.1	47 ± 3.5
Shoot tuck	1.9 ± 0.18	—	9.4 ± 0.5	3.08 ± 0.01	14.2 ± 2.1	44 ± 3.5
Shoot wrap	1.6 ± 0.18	—	9.1 ± 0.5	3.06 ± 0.01	15.1 ± 2.1	42 ± 3.5
P value	0.0628	—	0.1316	0.3879	0.1428	0.4641

[z]Samples were misplaced so no data were available in 2017.

[y]Anthocyanin and YAN data were not obtained from the 2016 samples.

[x]Lowercase letters indicate a separation of techniques regardless of timing by Tukey's honestly significant difference test at a 5% significance level. Timing and interactions were not significant, so only the main effects are reported.

[w]Insufficient leaf area resulted in very low soluble solids and poor ripening in 2019.

YAN = yeast assimilable N.

Table 5. Economic comparison for the ‘Cabernet franc’ shoot tip modification techniques against standard viticultural canopy management practices: assumed costs of labor and equipment for different viticultural practices and predicted costs of time spent wrapping or tucking shoots.

Modification technique	Cost	Assumption	Source
Viticultural practice			
Hedging 2×	$272/ha	$23/h, skilled	Davis et al. (2020)
Hedging 2× + leaf removal	$558/ha	$23/h, skilled; $17.50/h, unskilled	Davis et al. (2020)
Time spent wrapping or tucking per vine			
30 s	$291/ha	$17.50/h, unskilled	Davis et al. (2020)
60 s	$582/ha	$17.50/h, unskilled	Davis et al. (2020)
90 s	$873/ha	$17.50/h, unskilled	Davis et al. (2020)

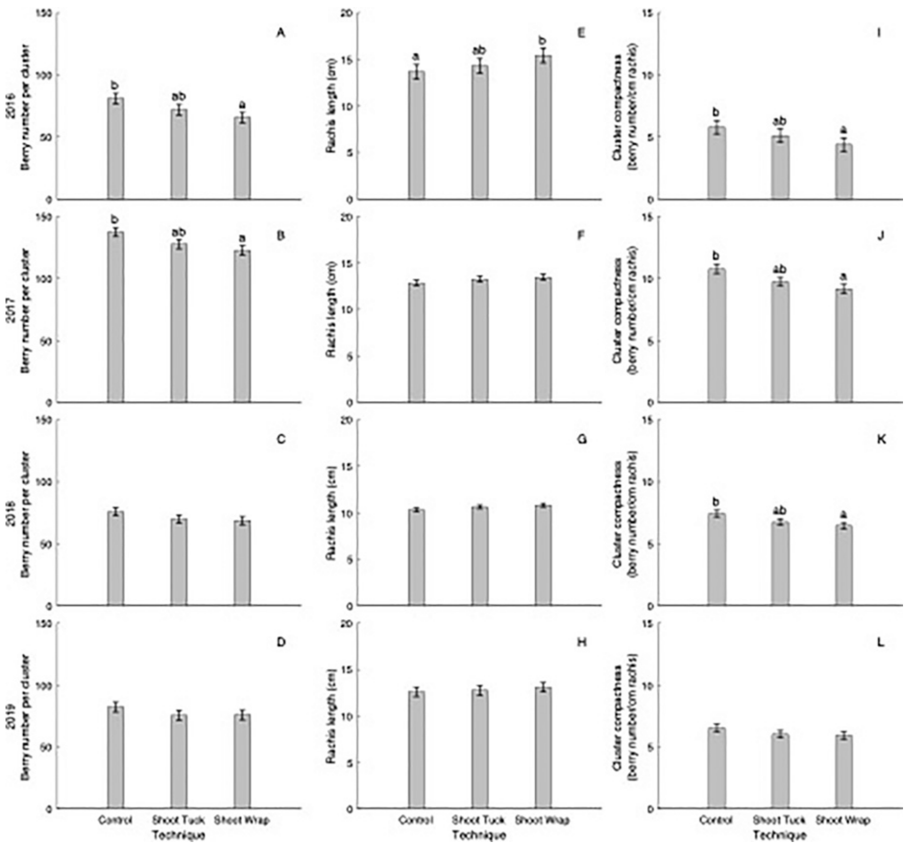

Fig. 2. (**A–D**) Berry number per cluster for 2016–19, respectively; (**E–H**) Rachis length for 2016–19, respectively; and (**I–L**) cluster compactness for 2016–19, respectively; in ‘Cabernet franc’ vines subjected to shoot management techniques regardless of timing application in Lansing, NY. Data were collected at harvest on 5 Oct. 2016, 14–16 Oct. 2017, 15 Oct. 2018, and 15 Oct. 2019. Values are estimated mean ± SE. Bars with different letters indicate significant differences among the main effect of technique by Tukey’s honestly significant difference test at a 5% significance level.

Conclusion

This study was initiated to evaluate the application of shoot tip modification techniques at two growth stages. Although the shoot wrap and shoot tuck treatments reduced lateral emergence in the fruit zone and cluster compactness consistently, the timing of treatment application did not affect these metrics consistently.

Wrapping or tucking shoots may be a viable alternative to hedging to reduce vegetative growth through reductions in lateral emergence and cluster compactness. As a function of reduced lateral emergence and length, these treatments also have the potential to eliminate leaf removal and may replace hedging without affecting production costs negatively. To our knowledge, this is the first study investigating long-term impacts of shoot tip modification technique applications on the vegetative and reproductive parameters of grapevines.

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