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Is vigour-based length adjustment during permanent cordon establishment a beneficial practice?

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Summary

Low vigour canes selected for the establishment of permanent cordon arms may lack the sufficient vigour required for uniform budburst and growth of new shoots following cordon training. This may lead to stunted or missing spur positions, particularly in the middle of new cordon arms where the effect is most pronounced due to the prioritisation tendencies of the vine including apical dominance and acrotony. A trial was performed to investigate the benefits of adjusting the length of newly trained canes intended as permanent cordon arms during their establishment to limit their bud number and guide new growth. This length adjustment was based on an assessment of the apparent vigour of selected canes and was performed at the start of the first season of cordon growth, with cordons then extended to their final length. The trial did not yield results indicating a long-term beneficial response to this practice, with physiological measurements including pruning weight showing no difference between length adjusted and control vines in the later seasons of the trial. There was also a lower plant area index (PAI), and higher canopy porosity (Φ) observed in length adjusted vines compared to control vines at several points. There was no difference observed in circumference measures of the distal portion of arms which had undergone a length adjustment, suggesting that the exercise did not have an adverse impact on their capacity for transport and reserve storage. Harvest yield components did not vary with treatment; however, a significantly lower pH was observed in length adjusted vines compared to control vines in the trials final season. Further research could help to provide more insight into the benefits of this practice, as some results from the trial, including a significantly higher pruning weight, cane number, and cane weight observed in the intermediate sections of cordon arms during the first season of growth suggest that it may have been of some aid to the cordons on which it was implemented.

Keywords

grapevine, cordon establishment, cordon longevity, training method, vigour

Introduction

The management of grapevine vegetative growth is a key component of modern viticulture and the concept of vegetative 'vigour' is now well understood by most growers. Loosely recognised as the quality or condition inherent in the expression of rapid growth of vegetation biomass (Winkler *et al.*, 1974), it can be measured in terms of both the speed and quantity of said growth. There are many factors which may influence vine vigour including soil profile (Hubbard *et al.*, 2021), nutrient availability (Balachandra *et al.*, 2009), ground cover (Muscas *et al.*, 2017), water availability and/or irrigation regime (Dry and Loveys, 1998), temperature and sunlight exposure (Hugalde *et al.*, 2020), and pruning technique (Wang *et al.*, 2019). It is a crucial element in maintaining vineyard balance, i.e. the sought-after equilibrium between desired vegetative and reproductive seasonal growth. While in this context it is important in the ongoing management of long-established vineyards, its control is arguably even more important in the early stages of vineyard establishment. Many practitioners believe that thin and short shoots do not make a very good framework for newly trained vines as their growth is likely to be weak and lacking in uniformity (Simonit, 2019). On the other hand, overtly long and excessively thick internodes may not be a better alternative as they can impede the selection and formation of evenly spaced spur positions and general cordon architecture. Careful selection of canes is paramount during the establishment process as those which are retained will grow to become the permanent structures of the vine including the trunk and cordon arms. Logically, cane health is an important consideration in this regard as the utilisation of unhealthy canes may compromise productivity and the health and longevity of perennial wood (Boehm and Coombe, 1992). Node location and directionality is another important factor driving this decision making (Simonit and Sirch, 2009). A 'v-zone' may be formed at the head region of bilaterally trained permanent cordons by originating the cordon arms from a node position located at a desirable distance below the cordon wire. This may help to alleviate foliar disease pressure in the area, especially in high vigour situations where the canopy may be particularly dense. As such,

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canes intended as permanent cordon arms are often selected on the basis of their proximity to the cordon wire and their direction of growth. During the establishment process, it is common to trim back the growth of one or two canes selected as suitable candidates to develop the trunk to just below cordon wire height after the first season of growth (Simonit and Sirch, 2009). There is a risk however with this method of obtaining shoots with very long internodes, and it may be advisable to allow several shoots to develop from the top of the new trunk to limit vigour and internode length (Castaldi, 2016). Another common strategy, as the grower may prefer, is to trim all growth right back to ground level, retaining as little as two nodes, with the goal of increasing uniformity across vines during the next growing season.

The desire for between vine uniformity extends to the establishment of cordon arms. Whether using a unilateral or bilateral training system, after canes have been selected as new arms, they must be trained and secured to the cordon wire. In some heavily mechanised regions, this training may involve wrapping the cordon tightly around the cordon wire to increase stability or for expense reduction (Caravia *et al.*, 2015). The length of cordon arms is typically based on intra-row vine spacing, as any gaps without productive cordon equate to loss in potential yield and profit (Van Zoeren *et al.*, 2020). When securing new arms to the cordon wire, technicians will often cut canes to a length of approximately half of the distance between trunks in the case of bilaterally trained cordons and close to the whole distance between trunks in the case of unilaterally trained cordons. This leaves the distal end of each cordon in close proximity to the cordon of the next vine in the hedgerow sequence, avoiding costly gaps with no productive cordon. The advantage of this method is that it gets the entirety of the desired length of the new cordon into place immediately, and in the case of healthy vines, normally requires minimal oversight after this initial training. An issue that may arise with this method however is that if canes selected as permanent cordon arms are weak and small in diameter, they may lack the vigour needed to support uniform budburst and growth of new shoots (Klodd and Clark, 2020; O'Brien *et al.*, 2021). The impact of this is especially evident in the node positions in the centre of low vigour arms as grapevine shoots display apical dominance (Fournioux, 1998), as well as having an acrotonic tendency to prioritise branching in the shoot distal zone (Torregrosa *et al.*, 2021). Sometimes less than ideal canes may be selected for establishment by necessity due to a lack of more suitable alternatives. In this case, due to a lack of sufficient vigour, some buds may fail to burst at all, even if the process of blinding is undertaken (removing buds at undesirable node positions to guide new growth). On a weaker cane, internodes can appear shorter, and as such additional nodes may need to be de-budded to ensure evenly, well-spaced spur positions. An early shoot thinning is one strategy which can help to improve uniformity in the length and diameter of new shoots along cordons suffering from low vigour in this scenario (Simonit *et al.*, 2012), as the rate of shoot growth tends to increase as the number of shoots per plant decreases (Keller *et al.*, 2015).

A technique promoted by some practitioners entails adjusting the length of low vigour canes during their establishment as permanent cordon arms, by cutting them back to a shorter length and thereby limiting retained node number (Klodd and Clark, 2020; O'Brien *et al.*, 2021). The decision of whether this length adjustment is warranted is based on visual assessment, taking into account cane length and diameter, as well as node number. Low vigour canes are then cut back in length, with the number of nodes retained based on the apparent vigour of the cane. In this case, canes deemed to have sufficient vigour to support uniform growth are cut to full length (i.e. ending in close proximity to the next cordon). The hope is that by adjusting the length of canes intended as new arms and limiting the number of nodes retained, successful budburst may be encouraged as well as the growth and the development of shoots that are of greater diameter and are better suited for selection as permanent spur positions (Castaldi, 2016). Canes that receive a length adjustment may then be brought to full length during the course of the growing season, by selecting an ideally downward facing shoot from the distal portion of the cane, near the cutting point, and training it horizontally along the cordon wire. This selection and extension could also take place during winter pruning. While this method may require some attention to secure the extension as it grows to full length, the desired outcome is a healthier, more productive cordon (O'Brien *et al.*, 2021). This study aimed to quantify the impact of such a length adjustment on cordon arms in the seasons immediately following establishment.

Material and Methods

Experimental site

The trial was set up at a newly planted (3-year-old) vineyard site in Williamstown, South Australia (34°40'21.4"S 138°53'27.0"E) in the spring of 2018. The cultivar was Cabernet Sauvignon (WA Cape Selection), grafted onto 1103 Paulsen, and planted at 3 m × 2 m inter-row and intra-row spacing with a north–south row orientation. Each row had a single foliage wire located 12 cm above the cordon wire, for the use of a sprawl canopy system. The total amount of irrigation discharged was ~1.0 ML/ha during each growing season of the trial (2018-2022). The climatic conditions for the site were sourced from the nearest Australian Bureau of Meteorology (http://www.bom.gov.au/, accessed on 28 May 2022) weather stations located in Williamstown (station number 023752) and Mount Crawford (station number 023878).

Experimental design

The trial consisted of 78 randomly selected vines which were low-to-medium vigour across six adjacent rows (approximately 13 vines per row), with treatments randomly assigned to each row. Thirty-nine of these vines, located across three non-adjacent rows, received a length adjustment (LA), where the vigour of canes selected as permanent cordon arms was assessed and then the lengths of these canes were adjusted based on their apparent vigour. Thirty-nine control vines (C), also located across three non-adjacent rows, received no length adjustment. The canes of control vines were left as long as possible, training them to full length immediately at the time of their initial training if their existing length and health allowed for it (Fig. 1). The assessment of how many nodes to retain during the adjustment of LA vines was based on a visual assessment of apparent vigour. The criteria for this approximation of vigour was cane length, diameter and node number. Where possible, for canes which received a length adjustment, one of the shoots from the most distal portion of the developing arm was selected and trained along the cordon wire horizontally during the growing season to extend arms to their final length.

Full length cordons comprised approximately 10 spur positions on each arm, pruned to typical 2-node spurs over the following seasons. The final step of the cordon extension process for length adjusted vines took place at pruning, when selected canes were cut to final length and secured to their training system. In the case of vines which received a length adjustment on a single arm (as in Fig. 1), only the arm which had been adjusted was considered for analysis. Shoot thinning was performed in the spring of 2018-2020 when newly burst shoots were 5-10 cm, but was not performed in 2021. During this process, shoots originating from the base of spurs, multiple shoots originating from the same node, and shoots originating from non-spur positions including the v-zone or trunk were cleanly removed.

Vegetative growth

Images were taken with the front camera of an iPhone (Apple, Cupertino, CA) twice during the 2018-2019 growing season and three times during each following growing season for the purpose of measuring canopy architecture using the VitiCanopy App (De Bei *et al.*, 2016). One image was taken of each cordon arm from about 80 cm below the vine cordon for the algorithmic assessment of plant area index (PAI).

Arms were split into three sections, proximal (P°), intermediate (I°) and distal (D°) (Fig. 4.1), and pruning weights were measured for each individual arm section. Cordons that were not full length were composed solely of P° sections, composed of both P° and I° sections, or composed of all three sections depending on their length. Section boundaries were determined according to expected total arm length, rather than existing arm length, and comprised 3-4 spur positions each. Cordon circumference was measured at three points (P°, I°, D°) along the arms of each vine using a flexible measuring tape at the time of pruning.

Harvest maturity/yield components

Vines were hand harvested each year and bunch number and total yield per vine were recorded. Total yield was measured with a digital scale. Cordon length was measured at the time of harvest so that yield and its components could be determined on a per metre basis. From yield and bunch number, the average bunch weight was calculated. Five bunches were collected from each vine and were stored at 4 °C for further lab analysis in the days immediately following harvest. 50 berries were randomly collected from these bunch samples and weighed for determination of average berry weight. Bunch samples were then hand crushed in plastic bags with the juice then being collected in 50 mL tubes and centrifuged at 5000 rpm for 5 min (Hettich Universal, Tuttlingen, Germany) before total soluble solids (TSS), pH and titratable acidity (TA) were measured according to (Iland *et al.*, 2004), using an automatic titrator (G20S Compact Titrator, Mettler Toledo, Thebarton, Australia) and a digital refractometer (BRX-242 Erma Inc. Tokyo, Japan).

Physiological

One-year-old cane samples were collected from distal cordon arm sections during pruning for analysis of carbohydrate concentration. Samples consisting of nodes three and four and their interjoining internode were collected from canes originating from the first node of each 2-node spur from the previous growing season. All samples were stored at 4 °C until further processing. Sections approximately 1 cm long were cut from the centre of each internode sample using secateurs and then combined and powderised using a mechanical grinder (A11 basic, IKA, Germany). A commercial enzyme

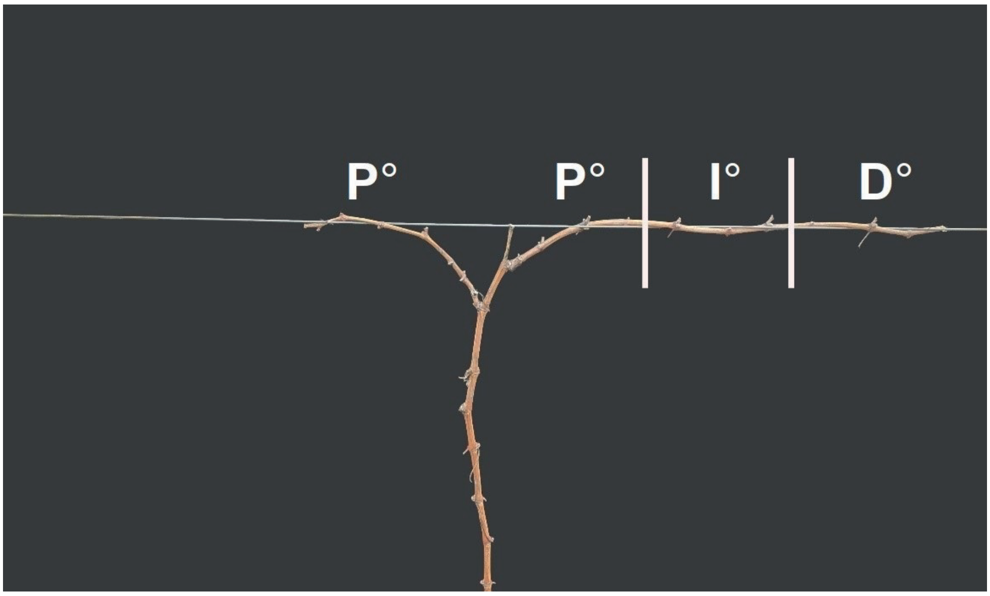

Fig. 1: An example of a newly trained vine which received a length adjustment. The cane on the left was deemed to be of insufficient vigour to support uniform growth and was cut back to a more limited retained node number. The cane on the right was deemed to be of sufficient vigour, and was cut to full length. The delineation between arms sections Proximal (P°), Intermediate (I°), and Distal (D°) are indicated on the right arm. The length adjusted arm in this example, due to its length, consists of only the P° arm section.

assay kit (Total starch assay kit, Megazyme, Ireland) was used to analyse starch levels following the method described in Edwards *et al.* (2010) based on colorimetric assay. Using a spectrophotometer (Multiskan Spectrum, model 00300011, Thermo Electron Corporation, Vantaa, Finland) absorbances were read at 505 nm and starch content was determined using a glucose standard curve. For the analysis of sugar concentration, an anthrone assay was performed with absorbances then read at 600 nm and concentration determined using a fructose standard curve.

Reproductive

Cane samples were collected during winter dormancy in 2020 and 2021 for the purpose of microscopically dissecting buds for examination of bud fertility and the incidence of primary bud necrosis (PBN). Samples were collected from the proximal and distal portions of cordon arms and consisted of nodes 1-4 of canes originating from node two of a 2-node spur. 18 samples were considered per treatment. A razor blade was used to slice buds transversally using the methods described by (Rawnsley and Collins, 2005). A light microscope at 25x magnification (Model EZ4W, Leica, Heerbrugg, Switzerland) was used during this process to assess the number of inflorescence primordia (IP) in the primary bud of each compound bud. If the primary bud was necrotic, the largest secondary bud was assessed in its place based on the assumption that it would grow in compensation for its loss.

Statistical Analysis

ANOVA was performed using XLSTAT Version 2022.3.2 (Addinsoft SARL, Paris, France). Means were separated using Fisher's LSD test at a significance level of $p \leq 0.05$ for all data.

Results

The average November monthly temperature of 2020 was hotter than the other growing seasons, followed by an average December monthly temperature that was cooler than the other growing seasons (Fig. 2). 2021 was the wettest year of the trial, with July in particular being a very wet month having 167.2 mm of rain.

No difference was observed in plant area index (PAI) between length adjusted and control vines in the 2018-2019 growing season (Fig. 3). Length adjusted cordons had significantly lower PAI values than control cordons on two imaging dates in the 2019-2020 growing season, one date in the 2020-2021 season, and two dates in the 2021-2022 season.

Near the end of the first growing season, canopy porosity was found to be significantly lower in vines that had been length adjusted than those that had not (Fig. 4). In the second year, no difference was observed in porosity on any imaging date. In the third year, canopy porosity was higher in vines that had been length adjusted at both veraison and harvest, but not at the start of the growing season. In the fourth year, porosity was higher in length adjusted vines at veraison only.

No significant difference was observed between the circumferences of the proximal, intermediate, or distal arm sections of cordons which received a length adjustment and control cordons in any year (Fig. 5).

In 2019, the intermediate arm section of cordons which had undergone the length adjustment had significantly higher pruning weights than control cordons when considered on a per metre basis (Table 1). No difference was observed between the pruning weights of the intermediate arm sections in any following year. No difference was observed between the pruning weights of the proximal or distal arm sections in any year. No difference was observed in pruning weights in any year on a whole vine basis.

No difference was observed in the number or weight of canes for the proximal arm section in any year (Table 2). In 2019, the intermediate arm sections of cordons which had received a length adjustment had significantly more canes per metre than control cordons. The average weight of these canes was also higher than that of the control. No difference was observed in the number or weight of the canes of the intermediate arm section in any following year. In 2020, the distal sections of control cordons had significantly more canes per metre than length adjusted cordons. No difference was observed in the number of distal canes in any following year, or in cane weight in any year. On a whole vine basis, length adjusted vines had significantly ($p = 0.040$) more canes per metre compared to control vines in 2019; 14.0 and 12.0 respectively. No difference was observed in the number of canes per metre on a whole vine basis in any following season. No difference was observed in cane weight considered on a whole vine basis in any season.

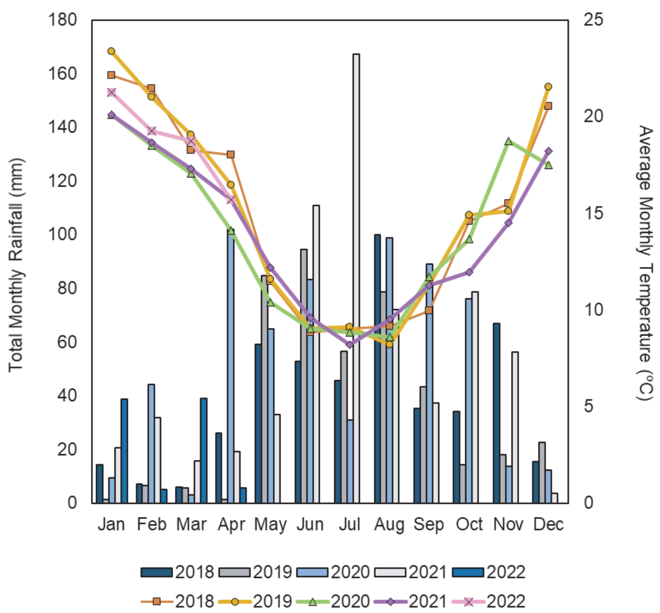

Fig. 2: Average monthly temperature and rainfall calculated from 2018–2022 at the trial site. Climate data were sourced from the nearest Australian Bureau of Meteorology (http://www.bom.gov.au/accessed on 11/07/2022) weather stations located in Williamstown (station number 023752) and Mount Crawford (station number 023878). Lines indicate average temperature and bars indicate total rainfall and a monthly basis.

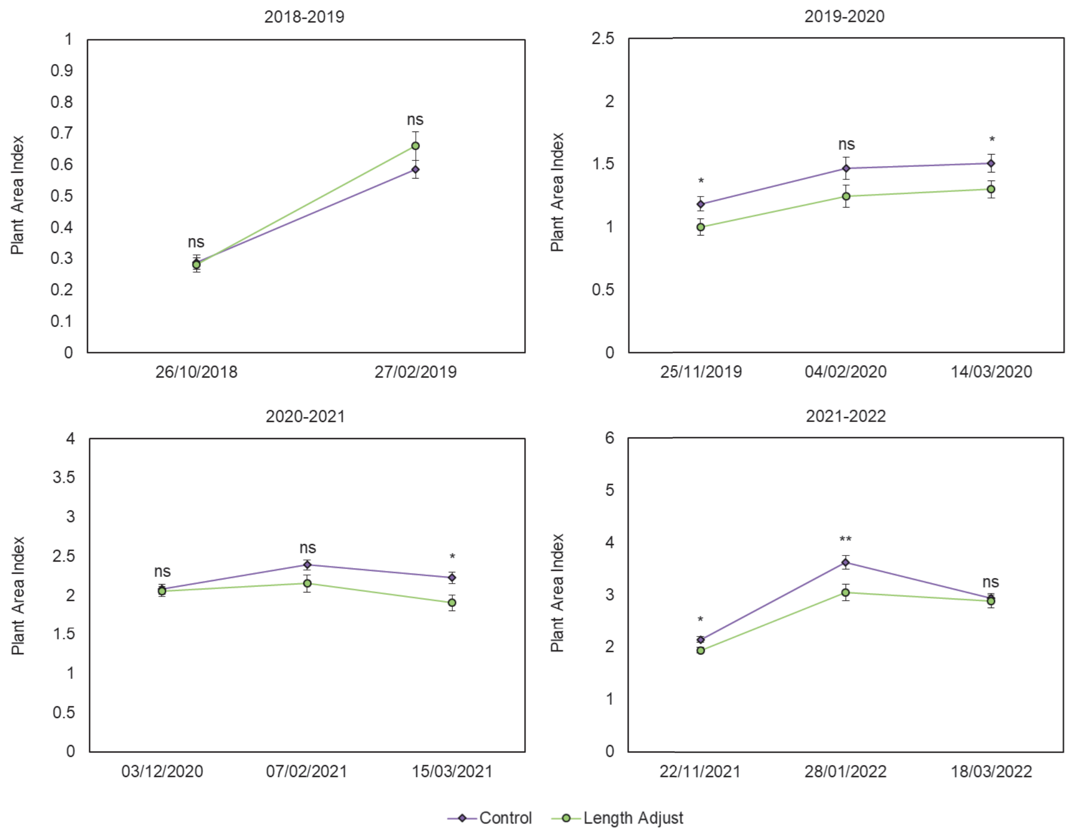

Fig. 3: Plant area index (PAI) measured periodically throughout the growing seasons from 2018-2022 using the VitiCanopy app. Means were assessed using ANOVA. *, ** indicate significant differences at p ≤ 0.05 and 0.01. ns = not significant.

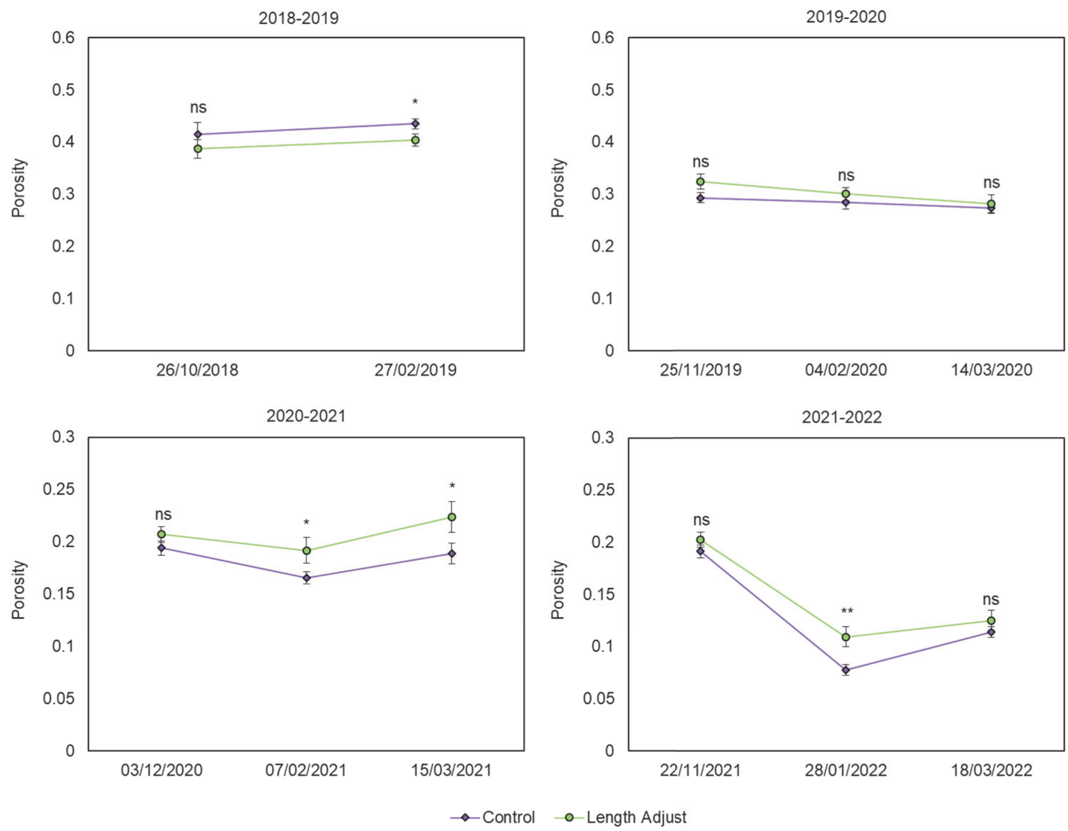

Fig. 4: Canopy porosity (Φ) measured throughout the growing seasons from 2018-2022 using the VitiCanopy app. Means were assessed using ANOVA. *, ** indicate significant differences at p ≤ 0.05 and 0.01. ns = not significant.

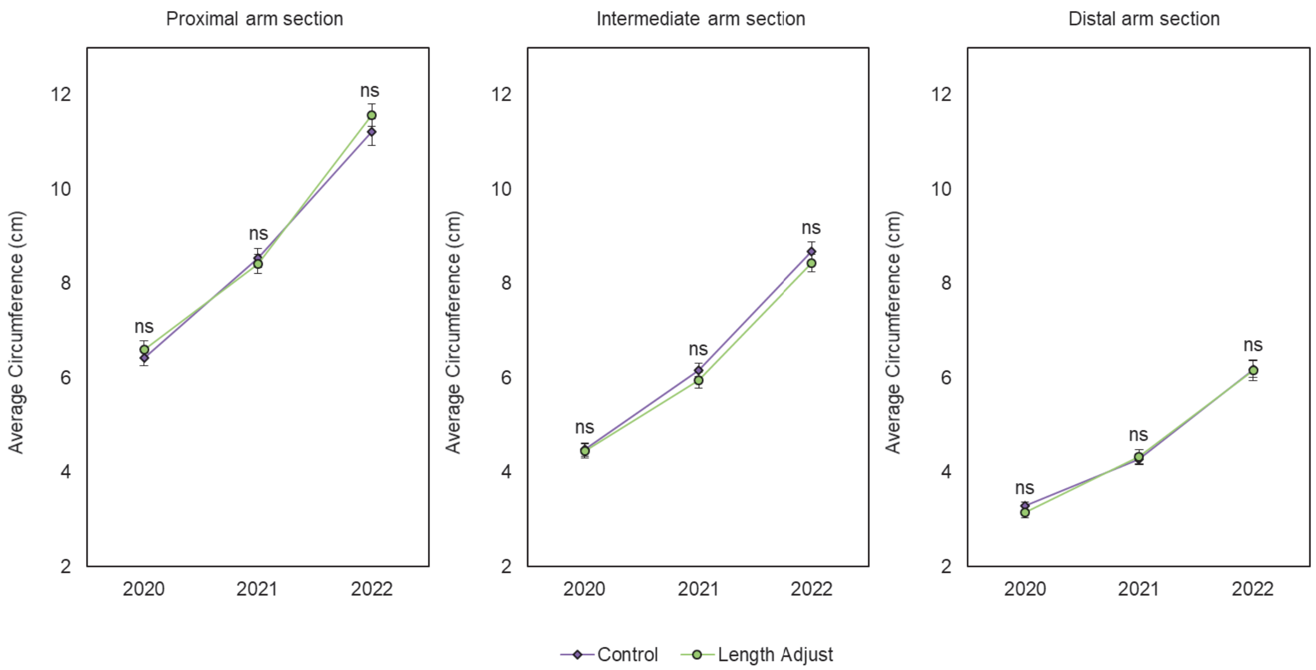

Fig. 5: Average circumference measurements of proximal, intermediate, and distal arm sections from 2020-2022. Means were assessed using ANOVA (p ≤ 0.05). ns = not significant.

Table 1: Average pruning weight from each individual arm section and from total vines (mean ± std).

Year	Treatment	Proximal Pruning Weight (kg · m^{-1})	Intermediate Pruning Weight (kg · m^{-1})	Distal Pruning Weight (kg · m^{-1})	Total Pruning Weight (kg · m^{-1})
2019	Control	0.20 ± 0.10	0.15 ± 0.08	0.31 ± 0.27	0.26 ± 0.16
	Length Adjust	0.20 ± 0.08	0.38 ± 0.16		0.38 ± 0.16
	p value	ns	<0.0001		ns
2020	Control	0.84 ± 0.30	0.45 ± 0.24	0.56 ± 0.25	0.63 ± 0.21
	Length Adjust	0.69 ± 0.31	0.47 ± 0.20	0.55 ± 0.25	0.57 ± 0.17
	p value	ns	ns	ns	ns
2021	Control	1.07 ± 0.42	1.01 ± 0.49	1.28 ± 0.54	1.12 ± 0.37
	Length Adjust	0.97 ± 0.33	0.83 ± 0.23	1.17 ± 0.40	0.99 ± 0.20
	p value	ns	ns	ns	ns
2022	Control	2.09 ± 1.20	1.70 ± 0.82	2.51 ± 1.38	2.11 ± 1.00
	Length Adjust	1.84 ± 1.31	1.58 ± 1.04	2.17 ± 1.58	1.88 ± 1.19
	p value	ns	ns	ns	ns

Means were separated by ANOVA ($p \leq 0.05$). ns = not significant.

The concentration of sugar in cane samples collected from the distal portion of cordons which received a length adjustment was lower than control vines in 2021, but not in 2020 (Fig. 6). No difference was observed in the amount of starch or total non-structural carbohydrates in any year of the study.

No difference was observed in the number of inflorescence primordia in compound buds collected from both the proximal and distal sections of cordon arms in either 2020 or 2021 (Figure 7). No difference was observed in the number of buds with primary bud necrosis (PBN).

Yield and yield components did not vary significantly between control vines and length adjusted vines in any year (Table 3).

No difference was observed in total soluble solids or TA between treatments in any year (Fig. 8). pH was significantly lower in grapes harvested from length adjusted cordons in 2022.

Discussion

Physiological measures of vegetative growth were used as a means of assessing the impact of the length adjustment

Table 2: Average number of canes and cane weights from each individual arm section (mean ± std).

Year	Treatment	Proximal		Intermediate		Distal	
		Cane no. (no./m)	Cane Weight (g)	Cane no. (no./m)	Cane Weight (g)	Cane no. (no./m)	Cane Weight (g)
2019	Control	10.5 ± 2.8	20.9 ± 12.6	10.8 ± 3.6	16.4 ± 11.8	12.4 ± 3.5	24.2 ± 16.5
	Length Adjust	10.8 ± 3.8	22.6 ± 17.1	13.9 ± 3.2	27.7 ± 10.6		
	p value	ns	ns	0.027	0.014		
2020	Control	16.3 ± 2.6	51.7 ± 16.0	12.4 ± 3.7	35.1 ± 10.6	14.4 ± 2.9	37.9 ± 14.7
	Length Adjust	15.9 ± 3.6	42.3 ± 15.3	13.5 ± 3.8	34.6 ± 10.6	11.0 ± 2.9	49.1 ± 16.7
	p value	ns	ns	ns	ns	0.004	ns
2021	Control	18.3 ± 4.3	58.3 ± 15.4	20.0 ± 3.9	49.6 ± 19.1	22.0 ± 4.3	56.9 ± 19.1
	Length Adjust	18.0 ± 3.2	54.2 ± 17.6	20.5 ± 4.2	40.8 ± 9.8	21.9 ± 2.9	53.0 ± 16.5
	p value	ns	ns	ns	ns	ns	ns
2022	Control	26.3 ± 8.5	84.2 ± 55.8	23.3 ± 4.7	74.4 ± 36.4	30.4 ± 5.4	83.3 ± 46.5
	Length Adjust	23.7 ± 6.5	77.8 ± 57.7	24.8 ± 6.3	64.4 ± 41.7	28.9 ± 4.9	71.0 ± 44.0
	p value	ns	ns	ns	ns	ns	ns

Means were separated by ANOVA ($p \leq 0.05$). ns = not significant.

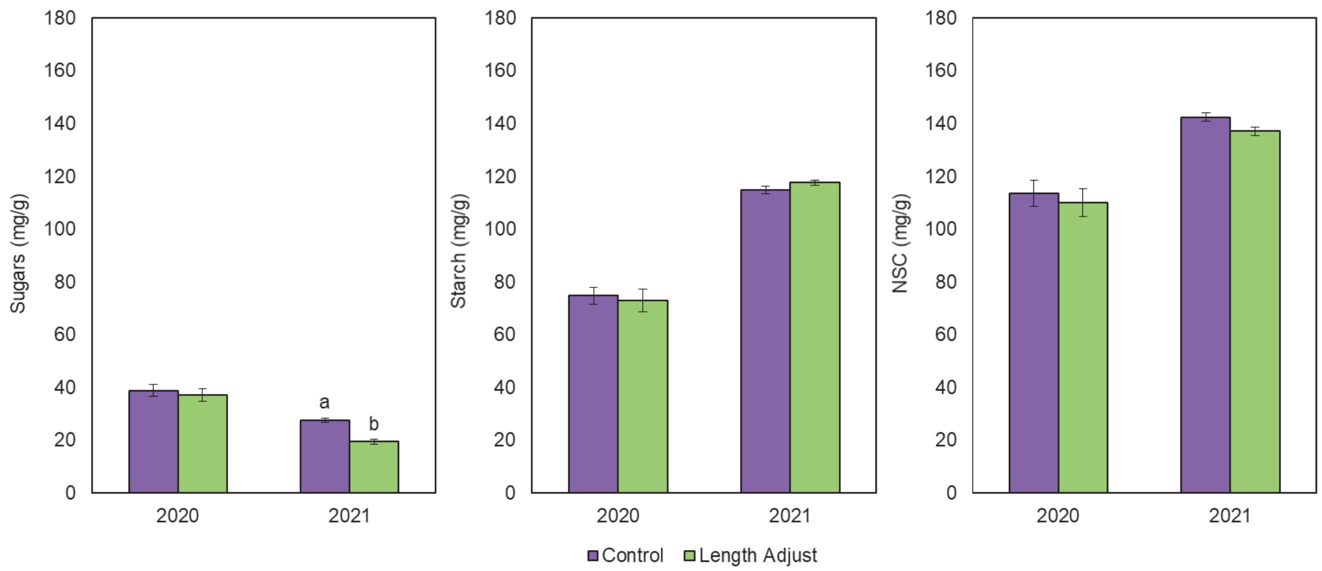

Fig. 6: Average concentration of sugars, starch, and total non-structural carbohydrates (NSC) in cane samples collected from the distal portion of new cordon arms. Means were separated by ANOVA (p ≤ 0.05), and different letters indicate significant differences between concentrations within each season of assessment.

treatment on the health and productivity of new cordon arms. Plant area index (PAI), describing the total one-sided area of plant tissue per unit ground surface area (De Bei *et al.*, 2016), was significantly lower for length adjusted vines than control vines on five out of 11 imaging dates over the course of the 4-year study. While this suggests that length adjusted vines may have suffered from a reduction in vegetative growth rate compared to control vines, other measures indicated that this may have not been the case. The PAI of length adjusted vines was no lower than control vines on either of the imaging dates during the first season of growth, a crucial period of the cordon establishment process (O'Brien *et al.*, 2021). Canopy porosity (Φ) was also lower in length adjusted vines than control vines when imaged near the end of the first season. No difference was observed in average circumference measurements of the proximal, intermediate, or distal arm sections in any year. This includes the winter of 2020, where one might have reasonably expected the distal arm sections of adjusted cordons to be of smaller circumference than control cordons (Torregrosa *et al.*, 2021), as they were comprised strictly of 2-year-old wood rather than 3-year-old wood as was the case with medium vigour control cordons which were trained to full length immediately.

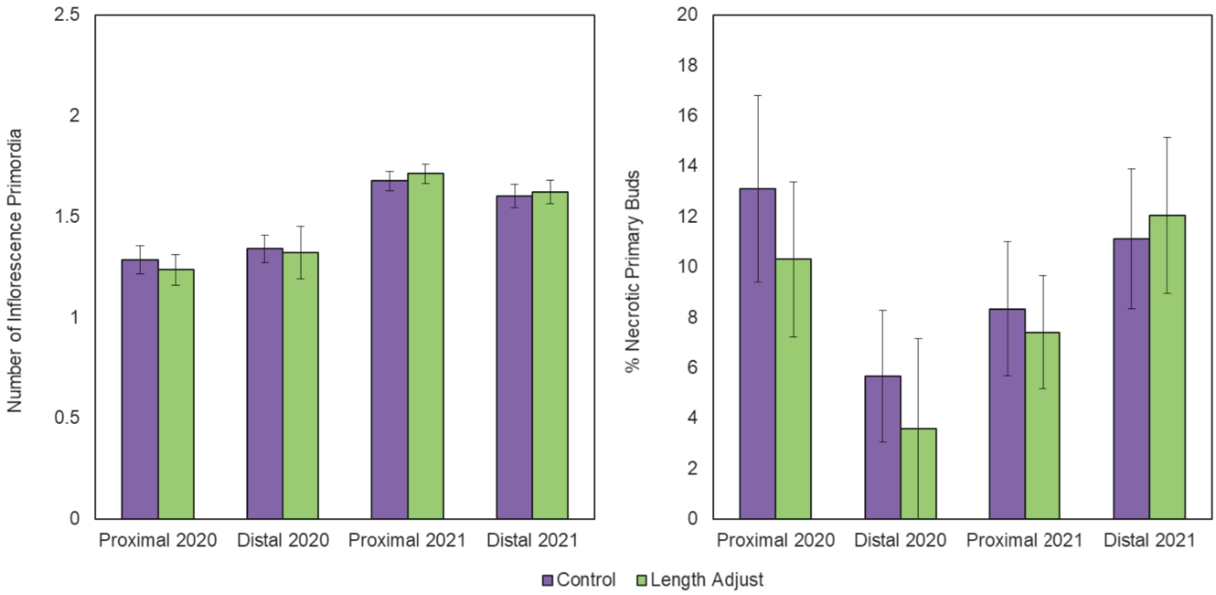

Fig. 7: Average number of inflorescence primordia within the compound bud and % of compound buds with a necrotic primary bud. Means were separated by ANOVA (p ≤ 0.05) and differences were found to be non-significant.

Table 3: Effect of length adjustment on yield and yield components (mean ± std).

Year	Treatment	Yield (kg · m^{-1})	Bunch no. (no./m)	Bunch Weight (g)	Berry Weight (g)
2020	Control	1.4 ± 0.4	23 ± 7.8	65.1 ± 28.8	0.65 ± 0.07
	Length Adjust	1.4 ± 0.4	21 ± 6.3	70.1 ± 26.6	0.70 ± 0.19
	p value	ns	ns	ns	ns
2021	Control	3.7 ± 0.8	39 ± 7.1	95.0 ± 16.1	0.80 ± 0.08
	Length Adjust	3.4 ± 0.9	37 ± 7.6	94.6 ± 16.4	0.89 ± 0.27
	p value	ns	ns	ns	ns
2022	Control	3.9 ± 1.5	47 ± 13.7	81.7 ± 14.2	0.95 ± 0.06
	Length Adjust	3.5 ± 1.0	46 ± 10.3	76.2 ± 22.3	0.97 ± 0.22
	p value	ns	ns	ns	ns

Means were separated by ANOVA (p ≤ 0.05). ns = not significant.

After one growing season, there was a significantly higher number of canes observed originating from the intermediate portion of arms which had undergone a length adjustment (13.9 canes · m^{-1}) compared to those which had not undergone a length adjustment (10.8 canes · m^{-1}). The increased number of intermediate canes observed as a result of the length adjustment is an indicator of the success of the treatment in providing many suitable candidate canes for selection for the use of extending the cordons to their final length. It also shows that many of the intermediate nodes burst and grew successfully during the first growing season, likely as a consequence of the reduced count node of adjusted arms (Keller *et al.*, 2015). Canes originating from this arm section were also found to be heavier on average in cordons which had received a length adjustment (27.7 g) compared to control cordons (16.4 g) after the first season. This resulted in an average pruning weight of intermediate arms sections which was 153.3% higher for length adjusted (0.38 kg · m^{-1}) than control (0.15 kg · m^{-1}) cordons. This increase in the pruning weight of length adjusted vines correlated with the lower porosity observed in length adjusted vines at the end of the first growing season, and suggests that the treatment was successful in encouraging vegetative growth in the early stages of development. No other differences were observed in pruning weights on an individual arm section or whole vine basis in any year of the study.

After the second growing season, significantly less canes were observed in the distal portion of length adjusted canes (11.0 canes/m) compared to control canes (14.4 canes · m^{-1}). This is logical when one considers that the distal portion of newly extended arms did not yet have fully formed spur positions. In this case, fruit bearing canes originated directly from the nodes of the extended cordon rather than spurs and therefore typically had one cane per spur position rather than two canes. Many of the medium vigour control vines had the

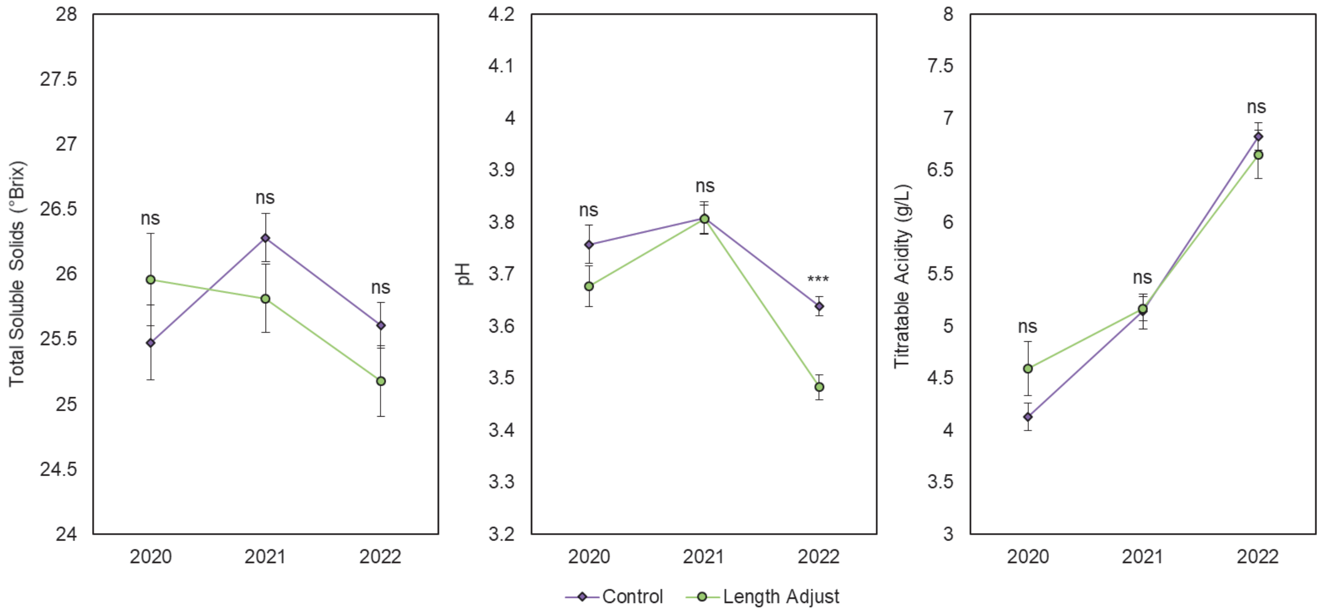

Fig. 8: Harvest measurements including total soluble solids (TSS), pH, and titratable acidity (TA). Means were assessed using ANOVA. *** indicates significance at $p \leq 0.0001$. ns = not significant.

entirety of the length of their arms in place during the initial training and as such had distal 2-node spurs at the time of this measure. Lower vigour control vines, while left as long as possible during the initial training, required an extension themselves to be brought to full length, albeit an extension of less node length than had they undergone the length adjustment treatment. Despite LA cordons having less distal shoots, there was no difference observed in the pruning weights of the distal arm sections at the end of the second year. By the end of the third year, 2-node spurs were present in the distal section of all cordons and no difference was observed in the number of distal canes in 2021 or 2022. There was also no difference observed in the number of canes, or the weight of canes originating from proximal or intermediate arm sections in 2021 or 2022. This correlated with pruning weight, where no difference was observed from 2020-2022 for any arm section or for whole vines. On a whole vine basis, length adjusted vines had significantly more canes per metre compared to control vines in 2019 but not in the following seasons. This was driven by the large number of intermediate canes observed in length adjusted vines. In the case of low vigour cordons, it is the intermediate (middle) arm section where one would expect to see the greatest detrimental effects including missing or stunted growth (Fournioux, 1998; Torregrosa *et al.*, 2021). As such, it makes sense that the pruning weight of the intermediate arm sections (0.15 kg · m^{-1}) of control cordons was lighter than proximal (0.20 kg/m) and distal arm sections (0.31 kg · m^{-1}) in 2019.

Yield and yield components did not vary between control vines and length adjusted vines in any year of the trial, suggesting that the treatment did not have a noticeably positive or negative effect on vine productivity. Bunch number and bunch weight varied between years, with no apparent pattern observed between length adjusted and control vines. Bearer number was similar between length adjusted and control cordons, as there was no difference in cane numbers from 2020-2022. The differences observed in PAI and Φ between LA and C cordons on several imaging dates could have had implications on canopy shading and the light environment of the fruit zone, an important parameter for fruit ripening (Kliewer and Smart, 1989; Jackson and Lombard, 1993; Sun *et al.*, 2017). However, no difference was observed in TSS in any year of the study. This suggests that although length adjusted vines had apparently lower PAI and higher Φ values during the ripening periods of 2021 and 2022, this did not have an impact on grape sugar accumulation. In addition to affecting the light environment of the fruit zone, leaf area also determines the capacity of the vine for photosynthesis (Poni *et al.*, 2006). The implication of this is that differences in PAI may indicate differences in source/sink balance both in terms of carbon available for the accumulation of grape sugar and competitory vegetative growth (Ollat and Gaudillere, 1998; Kliewer and Dokoozlian, 2005). While no difference was observed in TA in any season, pH was much lower in grapes from length adjusted vines compared to control vines in 2022, but not in previous years.

Very minimal differences were observed in the reserve status of cane samples collected from the distal portion of cordon arms. There was lower sugar found in samples from length adjusted cordons in 2021, but when considered with starch, no difference in the amount of total non-structural carbohydrates (NSC). In 2020, there was no difference observed in the levels of sugars, starch, or NSC in distal canes. Cordon volume may come into play here, as the volume of the cordon, along with the other perennial structures of the vine including the trunk and roots, impact the capacity of the vine for overwintering reserve storage (Bates *et al.*, 2002). The lack of difference observed between circumference measurements taken from the proximal, intermediate, and distal arm sections indicates that length adjusted cordons had a comparable volume to non-adjusted cordons and also a similar capacity for reserve storage. In terms of bud fertility, neither the proximal nor distal portions of cordon arms displayed differences in the number of inflorescence primordia or % of necrotic primary buds. This is despite the differences observed in PAI and Φ, suggesting the possibility of differences in leaf area and light conditions at the renewal zone. Canopy shading (Perez and Kliewer, 1990) and pruning level (Collins and Rawnsley, 2004) have previously been implicated in the occurrence of PBN. The lack of differences observed in distal cane internode carbohydrate levels in this trial may have had an impact here as reductions in bud carbohydrate levels are also associated with the occurrence of PBN (Vasudevan *et al.*, 1998).

Conclusion

While the results of this trial do not indicate a long-term beneficial response as a consequence of adjusting the length of new cordon arms during their establishment via an assessment of cane vigour, this does not mean that the vines which received such an adjustment did not benefit from the practice. During the first growing season, the treatment was seemingly successful in encouraging vegetative growth, with length adjusted vines having more shoots and a lower canopy porosity than control vines. This effect was especially pronounced in the intermediate sections of new cordon arms, which had a greater pruning weight, cane number, and average cane weight. This is critical, as in situations where there is insufficient vigour for unhindered bud burst and shoot development, the effect would usually be most pronounced in this arm section. While the length adjustment did seem to encourage the growth of canes in the middle of the cordon that were both bigger and more numerous, the benefits of this may have been limited to the first growing season. There was an immediate beneficial impact of a higher number of canes to utilise for extending LA arms to their final length, but the low vigour C vines were not lacking in options for their own extensions if required. The supposed benefit of the length adjustment method is that by encouraging growth at struggling node positions, particularly those in the centre of cordon arms, the end result may be fewer missing spur positions. This did not seem to be the case in this trial, as no difference was observed in the number of canes of length adjusted or control vines in any of the three years succeeding the first growing season, including when shoot thinning was (2019-2020 and 2020-2021 seasons) and was not (2021-2022 season) performed. This was true both when considering the entire vine as well as individual arm sections, including the intermediate arm section. Reduced PAI and increased Φ observed in length adjusted cordons during these seasons further supported that there was no benefit in terms of vegetative growth after the first season, and perhaps even a penalty. The perennial structure of the cordon itself did not seem to suffer from the treatment however, with similar circumferences observed between length adjusted and control vines for all arm sections. It is possible that this treatment could have a stronger beneficial response in other cultivars, particularly those in low vigour environments which struggle with apical dominance. Further research focusing on such an environment where the control vines are more likely to suffer severe detrimental effects arising from a high retained node number could better illustrate the comparative beneficial response of the treatment over a longer term.

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Conflicts of interest

The authors declare that they do not have any conflicts of interest.

References

Balachandra, L., Edis, R., White, R.E., Chen, D., 2009: The relationship between grapevine vigour and N-mineralization of soil from selected cool climate vineyards in Victoria, Australia. Journal of Wine Research 20 (3), 183-198. DOI: 10.1080/09571260903471977.

Bates, T.R., Dunst, R.M., Joy, P., 2002: Seasonal dry matter, starch, and nutrient distribution in 'Concord' grapevine roots. HortScience 37 (2), 313-316, DOI: 10.21273/HORTSCI.37.2.313.

Boehm, E.W., Coombe, B.G., 1992: Vineyard Establishment. In: Coombe, B.G., Dry, P.R. (Eds.): Viticulture, vol. 2, Practices, 23-41. Winetitles, Adelaide, Australia.

Caravia, L., Collins, C., Shepherd, J., Tyerman, S., 2015: Wrapping arms for cordon establishment: Is it a stressful practice for grapevines? Wine & Viticulture Journal 30, 48-50.

Castaldi, R., 2016: Vite: Mantenere funzionale il cordone permanente. Informatore Agrario 2, 81-84.

Collins, C., Rawnsley, B., 2004: Factors influencing primary bud necrosis (PBN) in Australian vineyards. VII International Symposium on Grapevine Physiology and Biotechnology, Davis, California, USA.

De Bei, R., Fuentes, S., Gilliham, M., Tyerman, S., Edwards, E., Bianchini, N., Smith, J., Collins, C., 2016: VitiCanopy: A free computer app to estimate canopy vigor and porosity for grapevine. Sensors 16, e585. DOI: 10.3390/s16040585.

Dry, P.R., Loveys, B.R., 1998: Factors influencing grapevine vigour and the potential for control with partial rootzone drying. Australian Journal of Grape and Wine Research 4, 140-148, DOI: 10.1111/j.1755-0238.1998.tb00143.x.

Edwards, E.J., Downie, A.F., Clingeleffer, P.R., 2010: A simple microplate assay to quantify nonstructural carbohydrates of grapevine tissues. American Journal of Enology and Viticulture 62, 133-137. DOI: 10.5344/ajev.2010.10051.

Fournioux, J.C., 1998: Influences foliaires dans le contrôle du développement des « bourgeons anticipés » chez *Vitis vinifera*. Canadian Journal of Botany 76, 1385-1403. DOI: 10.1139/b98-051.

Hubbard, S.S., Schmutz, M., Balde, A., Falco, N., Peruzzo, L., Dafflon, B., Léger, E., Wu, Y., 2021: Estimation of soil classes and their relationship to grapevine vigor in a Bordeaux vineyard: advancing the practical joint use of electromagnetic induction (EMI) and NDVI datasets for precision viticulture. Precision Agriculture 22, 1353-1376. DOI: 10.1007/s11119-021-09788-w.

Hugalde, I.P., Aguero, C.B., Barrios-Masias, F.H., Romero, N., Viet Nguyen, A., Riaz, S., Piccoli, P., McElrone, A.J., Walker, M.A., Vila, H.F., 2020: Modeling vegetative vigour in grapevine: unraveling underlying mechanisms. Heliyon 6, e05708. DOI: 10.1016/j.heliyon.2020.e05708.

Iland, P., Bruer, N., Edwards, G., Weeks, S., Wilkes, E., 2004: Chemical Analysis of Grapes and Wine: Techniques and Concepts. Winetitles, Broadview, Australia.

Jackson, D.I., Lombard, P.B., 1993: Environmental and management practices affecting grape composition and wine quality: A review. American Journal of Enology and Viticulture 44, 409-430.

Keller, M., Deyermond, L.S., Bondada, B.R., 2015: Plant hydraulic conductance adapts to shoot number but limits shoot vigour in grapevines. Functional Plant Biology 42, 366-375. DOI: 10.1071/FP14206.

Kliewer, W., Smart, R., 1989: Canopy manipulation for optimizing vine microclimate, crop yield and composition of grapes. In: Wright, C.J. (Ed.): Manipulation of fruiting, 275-291. Butterworth & Co, Nottingham, UK. DOI: 10.1016/B978-0-408-02608-6.50023-0.

Kliewer, W.M., Dokoozlian, N.K., 2005: Leaf area/crop weight ratios of grapevines: Influence on fruit composition and wine quality. American Journal of Enology and Viticulture 56, 170-181.

Klodd, A., Clark, M., 2020: Building new grapevine cordons: Only strong wood allowed. University of Minnesota Extension: Fruit and Vegetable News. (https://blog-fruit-vegetable-ipm.extension.umn.edu/2020/11/building-new-grapevine-cordons-only.html. Access: 11/09/2022).

Muscas, E., Cocco, A., Mercenaro, L., Cabras, M., Lentini, A., Porqueddu, C., Nieddu, G., 2017: Effects of vineyard floor cover crops on grapevine vigor, yield, and fruit quality, and the development of the vine mealybug under a Mediterranean climate. Agriculture, Ecosystems & Environment 237, 203-212. DOI: 10.1016/j.agee.2016.12.035.

O'Brien, P., De Bei, R., Sosnowski, M., Collins, C., 2021: A Review of factors to consider for permanent cordon establishment and maintenance. Agronomy 11, 1811. DOI: 10.3390/agronomy11091811.

Ollat, N., Gaudillere, J.P., 1998: The effect of limiting leaf area during stage I of berry growth on development and composition of berries of *Vitis vinifera* L. cv. Cabernet Sauvignon. American Journal of Enology and Viticulture 49, 251-258.

Perez, J., Kliewer, W.M., 1990: Effect of shading on bud necrosis and bud fruitfulness of Thompson Seedless grapevines. American Journal of Enology and Viticulture 41, 168-175.

Poni, S., Casalini, L., Bernizzoni, F., Civardi, S., Intrieri, C., 2006: Effects of early defoliation on shoot photosynthesis, yield components, and grape composition. American Journal of Enology and Viticulture 57, 397-407.

Rawnsley, B., Collins, C., 2005: Improving vineyard productivity through assessment of bud fruitfulness and bud necrosis. Final report to the Grape and Wine Research and Development Corporation – SAR 02/05, Adelaide, Australia. (https://www.wineaustralia.com/getmedia/1b8f407d-6891-4971-bb57-4c7bc2c532ef/SAR-02-05).

Simonit, M., 2019: Simonit & Sirch's Guyot Methodology: The Vine Pruning Manual to Limit Trunk Diseases. Verona, Edizioni L'Informatore Agrario s.r.l.

Simonit, M., Deledda, F., Giudici, M., Manfreda, L., Ostan, M., Turata, R., Zanutta, A., 2012: Vite: Potatura «virtuosa» applicazione e vantaggi. Informatore Agrario 37, 36-46.

Simonit, M., Sirch, P., 2009: Potatura secca della vite, tagliare solo legno giovane. Informatore Agrario 36, 48-54.

Sun, R.Z., Cheng, G., Li, Q., He, Y.N., Wang, Y., Lan, Y.B., Li, S.Y., Zhu, Y.R., Song, W.F., Zhang, X., Cui, X.D., Chen, W., Wang, J., 2017: Light-induced variation in phenolic compounds in Cabernet Sauvignon grapes (*Vitis vinifera* L.) involves extensive transcriptome reprogramming of biosynthetic enzymes, transcription factors, and phytohormonal regulators. Frontiers in Plant Science 8, 547, DOI: 10.3389/fpls.2017.00547.

Torregrosa, L., Carbonneau, A., Kelner, J.J., 2021: The shoot system architecture of *Vitis vinifera* ssp. *sativa*. Scientia Horticulturae 288, 110404. DOI: 10.1016/j.scienta.2021.110404.

Van Zoeren, J., Martinson, T.E., Caldwels, D., Walter-Peterson, H., 2020: Missing parts: The cost of missing cordons, canes and vines. Appellation Cornell: Grapes 101, (https://grapesandwine.cals.cornell.edu/newsletters/appellation-cornell/2020-newsletters/issue-40-march-2020/grapes-101/).

Vasudevan, L., Wolf, T.K., Welbaum, G.G., Wisniewski, M.E., 1998: Reductions in bud carbohydrates are associated with grapevine bud necrosis. Vitis 3, 189-190. DOI: https://doi.org.10.5073/vitis.1998.37.189-190.

Wang, X., De Bei, R., Fuentes, S., Collins, C., 2019: Influence of canopy management practices on canopy architecture and reproductive performance of Semillon and Shiraz grapevines in a hot climate. American Journal of Enology and Viticulture 70, 360-372. DOI: 10.5344/ajev.2019.19007.

Winkler, A.J., Cook, J.A., Kliewer, W.M., Lider, L.A., 1974: General Viticulture. University of California Press, Berkeley, USA.