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ORIGINAL RESEARCH ARTICLE

Changes in total soluble solids concentration, fruit acidity, and yeast assimilable nitrogen in response to altered leaf area to fruit weight ratio in Pinot noir

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ABSTRACT

The increasing consumer demand for lower alcohol wine and the need to mitigate against a warming climate presents new challenges for winegrowers and the desire to produce grapes with lower total soluble solids (sugar) or earlier harvesting, while preserving other wine compounds and attributes, particularly for varieties intended for red wine production. We investigated how reducing vine leaf area through shoot trimming and leaf removal, applied at different severities and timings to modify the leaf area to fruit weight (LA) ratio, affects fruit composition for producing lower alcohol quality Pinot noir wine. Shoot trimming treatments (half canopy, H in 2015/16 and 2016/17, and quarter canopy, Q in 2016/17 by alternately removing leaves after trimming shoots to half) were applied shortly before veraison (V-, E-L 34), during veraison (V, E-L 35) and post-veraison (V+, E-L 36) in three different vineyard locations (Marlborough, Canterbury and Central Otago, New Zealand). Untrimmed vines served as the control. Lateral shoots were removed during treatment application, and regrowth was removed to maintain a consistent leaf area. Results showed that reducing the LA:FW ratio delayed the accumulation and concentration of total soluble solids (reduction of 1.0 to 2.7 °Brix) at harvest in all trimmed vines over both seasons. Berry weight, malic acid concentration, titratable acidity, and pH at harvest were unaffected by trimming. At target TSS levels of 18 °Brix (10 % ethanol, v/v) in the Marlborough vineyard and 20 °Brix (11 % v/v) in the Central Otago vineyard, V+ vines showed malic acid and titratable acidity levels comparable to the control. At the Canterbury vineyard, these parameters remained similar across all treatments at 16 °Brix (8.9 % v/v). Yeast-assimilable nitrogen concentration increased (188 to 411 mg/L) in early trimmed vines. At Central Otago, roots showed lower carbohydrate reserves across all trimming treatments, likely due to the high yield at the site, while at Canterbury, trimming did not result in significant differences in carbohydrate reserves, likely due to the low yield at the site. At the Marlborough vineyard, vines trimmed early and more severely had less starch in their roots, while HV+ vines maintained similar levels of starch to controls. In conclusion, halving the canopy post-veraison (HV+, LA 0.70 m^2/kg as observed in Marlborough) could be considered a viable viticultural option to lower sugar accumulation, thereby reducing potential alcohol content, without affecting titratable acidity and pH. This practice offers significant potential for adapting to a warming climate and producing lower alcohol Pinot noir wines in a sustainable manner.

KEYWORDS: Pinot noir, shoot trimming, pre-veraison, veraison, post-veraison, LA:FW

INTRODUCTION

The impact of climate change on grapevines, with its associated increases in temperatures and atmospheric carbon dioxide concentrations (Intergovernmental Panel on Climate Change, 2021), has been shown to advance the phenological development and disrupt the usual dynamics of compound accumulation in grape berries (Cameron *et al.*, 2021; Cameron *et al.*, 2022; Chuine *et al.*, 2004; Cook & Wolkovich, 2016; Droulia & Charalampopoulos, 2021; Hannah *et al.*, 2013; Jones, 2006; Parker *et al.*, 2011; Ramos & Martínez de Toda, 2020; Tiffon-Terrade *et al.*, 2023; Webb *et al.*, 2007). Without changes in vine management, this is already resulting in fruit harvest with higher sugar concentration, which would translate into wine with higher alcohol levels. This also leads to changes in other compositional characteristics, such as higher pH and low acidity (Bobeica *et al.*, 2015; Filippetti *et al.*, 2015; Palliotti *et al.*, 2013; Wu *et al.*, 2013).

In addition, the demand for low alcohol wines in the international market is increasing, driven by health considerations, social responsibility concerns (Jordão *et al.*, 2015; Masson *et al.*, 2008; Saliba *et al.*, 2013), and the fiscal impact of increased taxes on alcohol, which increase the final price of the product (Masson *et al.*, 2008). Therefore, there is a pressing need to adapt viticultural practices to the changing climate and address the growing international preference for wines with lower alcohol.

Reducing alcohol in wines can be achieved through technological methods in the winery or by viticulture practices. However, winery practices are often criticised for negatively affecting wine sensory characteristics. For example, alcohol reduction using reverse osmosis in Merlot and Syrah wines caused a decrease in perceived wine balance, aromas, and persistence in the mouth (Meillon *et al.*, 2009).

Canopy manipulation has been presented as a vineyard-based tool to adjust sugar concentrations for adaptation to climate change or low-alcohol wine production. Leaf removal reduces the overall carbohydrate supply to the berries (sinks), which can lead to lower sugar content in the fruit at harvest (Candolfi-Vasconcelos & Koblet, 1991; Parker *et al.*, 2016; Poni & Giachino, 2000), even though increases or no change in sugar levels have been observed in cases where improved microclimate conditions, such as increased light exposure, occurred and leaf area to fruit weight (LA:FW) ratios were unaffected (Bledsoe *et al.*, 1988; Bubola & Peršurić, 2012; Chorti *et al.*, 2010; Hunter *et al.*, 1995; Kliewer & Antcliff, 1970; Pastore *et al.*, 2013; Percival *et al.*, 1994). Leaf area to fruit weight (LA: FW) ratios that range from 0.8 m2/kg to 1.2 m2/kg are considered ideal to harvest ripe fruit with optimal sugar concentrations and colour (Kliewer & Dokoozlian, 2005). However, vines have the capacity to compensate when LA:FW ratios are reduced by increasing photosynthetic efficiency of the remaining leaves (Petrie *et al.*, 2003). Therefore, to significantly impact sugar accumulation rates, relatively large amounts of the canopy need to be removed. Previous studies indicate that significant reductions in LA:FW ratio, particularly introduced during early berry development (E-L 19 to E-L 34), have led to a decrease in total soluble solids (TSS), or berry sugar concentrations (Bubola *et al.*, 2022; Parker *et al.*, 2014; Parker *et al.*, 2015; Pastore *et al.*, 2011; Poni & Giachino, 2000; Stoll *et al.*, 2010; Toda & Balda, 2013).

Changes in titratable acidity (TA) and pH have been inconsistent, with some studies reporting an increase in fruit organic acids when sugar concentration is reduced due to the removal of vine leaf area. (Ollat & Gaudillere, 1998; Pastore *et al.*, 2011; Poni & Giachino, 2000; Wu *et al.*, 2013), and others indicating no change (Bobeica *et al.*, 2015; Parker *et al.*, 2015; Poni *et al.*, 2013; Stoll *et al.*, 2010; Toda & Balda, 2013). Likewise, harvest pH often either decreases (Ollat & Gaudillère, 2000; Pastore *et al.*, 2011; Poni & Giachino, 2000; Toda & Balda, 2013; Wu *et al.*, 2013) or remains the same (Palliotti *et al.*, 2013; Parker *et al.*, 2015; Poni *et al.*, 2013; Stoll *et al.*, 2010). This may be explained by differences in the timing and severity of the LA:FW ratio manipulations, likewise the climate, location, and physical configuration (training system) of the studies. The variability in findings from previous research indicates that further trials that address the timing and severity of LA:FW ratio manipulations are critical to determine consistent trends.

A further compositional component of interest is yeast assimilable nitrogen (YAN). YAN is comprised of primary amino acids and ammonium and is a critical parameter for wine quality, affecting alcoholic fermentation and aroma compound formation (Bell & Henschke, 2005). Reduced LA:FW ratios increased harvest YAN in Chasselas and Pinot Noir berries (Spring *et al.*, 2012), and in Pinot noir when leaf removal was performed shortly after fruit set (Pineau *et al.*, 2017). Stoll *et al.* (2010) also reported increased YAN in Riesling when vines were source limited at E-L 27. However, limited information is available regarding the influence of late-stage LA:FW reduction (veraison onwards) on YAN. Furthermore, because free amino acids are major precursors for important wine quality-related secondary metabolites such as phenolic and aroma compounds (Guan *et al.*, 2017), which are predominantly synthesised late in the growing season, exploring potential late-stage changes in nitrogenous compounds could offer valuable insights.

If leaf removal to lower the LA:FW ratio is used to modify ripening to change berry sugar and, therefore, wine alcohol, then the longer-term consequences of a source reduction (leaf removal) for vine balance and productivity need to be considered. Studies by Bennett (Bennett, 2002), in which only basal leaves were retained (4, 8, and 12 weeks post bloom), and Zufferey *et al.* (2012), who used shoot topping (canopy height maintained 0.75m; LA:FW ratio 0.5 m2/kg) at E-L 26, have shown that reducing photoassimilate production during the growing season might deplete storage reserves, even with compensatory increases in photosynthetic rates of the remaining leaves. Howell (2001) cautions that heightened leaf efficiency may not fully compensate for severely source-limited vines. Therefore, it is crucial to investigate vine performance parameters, including vegetative growth, yield characteristics and reserve replenishment, resulting from altered LA:FW ratios during subsequent growing season(s). This is particularly critical in cool-climate viticultural regions where senescence of the vine leaves can coincide with harvest maturity.

This study aims to investigate the influence of modifying the LA:FW ratio at different times and severities on Pinot noir berry composition (sugar, TA, pH and YAN). Unlike previous studies that separately examined canopy manipulation at pre-veraison, veraison, and post-veraison, or only tested one treatment of leaf removal, our research integrated both timing and severity of leaf removal at different levels throughout the pre-veraison to mid-ripening period to investigate consistency of trends. We also evaluated these manipulations at a targeted sugar composition, a critical comparison to ascertain fruit compositional changes for low-alcohol wine production. The study was also conducted in three distinct wine growing regions, enabling key trends to be determined. Findings from this study can help inform us about the potential of canopy manipulation as an adaptation strategy to climate change or a tool for low alcohol wine production.

MATERIALS AND METHODS

1. Trial vineyards and climate

Experiments were conducted in three vineyards located in different regions of New Zealand, using vertically positioned Pinot noir clone 777 grafted onto 3309 rootstock. The vineyards were situated in Marlborough (-41°38’25”S, 174°06’47”E), Central Otago (-45°04’12”S, 169°11’26”E), and Canterbury (-43°38’60”S, 172°30’0”E). The Marlborough vineyard was planted in 1999, with a vine spacing of 2.4 m by 1.4 m (2,976 vines/ha). In Central Otago, the vines were planted in 2000, spaced 2.5 m by 1.6 m (2,500 vines/ha). Both of these sites featured vines with two cordons and were spur pruned to two and three nodes, respectively. The Canterbury vineyard, also planted in 1999, had a vine spacing of 2.5 m by 1.2 m (3,333 vines/ha) and was pruned to two canes. Canopy height was maintained at 1.2 m across all sites. As the vineyards varied in climate, soil, management practices (e.g., pruning type) and cropping levels, cross-site comparison was not the focus of the study.

In general, the 2015/16 season was drier than the 2016/17 season for all trial sites (Figure 1), with Marlborough and Central Otago receiving less rainfall than the long-term average (LTA). At the Marlborough and Canterbury vineyards, the months of March and April (preharvest) 2017 were remarkably wet, receiving 45 % and 43 % of the total seasonal rainfall (July to April) rainfall, respectively. The cumulative seasonal growing degree days (GDD) (1 October–30 April, Winkler Index) in 2015/16 and 2016/17, with GDDs (base 10 °C) of 1339 and 1307 in Marlborough, 1220 and 1025 in Central Otago, and 1032 and 1037 in Canterbury, further categorise the trial sites as Region-I viticultural regions. These categorise the trial sites as Region-I (i.e. <1390 Celsius degree days, base 10 °C) of cool climate viticultural regions (Amerine & Winkler, 1963).

2. Experimental design

Field experiments followed a randomised block design, with treatments replicated five times (each replicate consisting of one bay of five vines) across two growing seasons, 2015/16 and 2016/17. In 2015/16, a 50 % canopy trimming

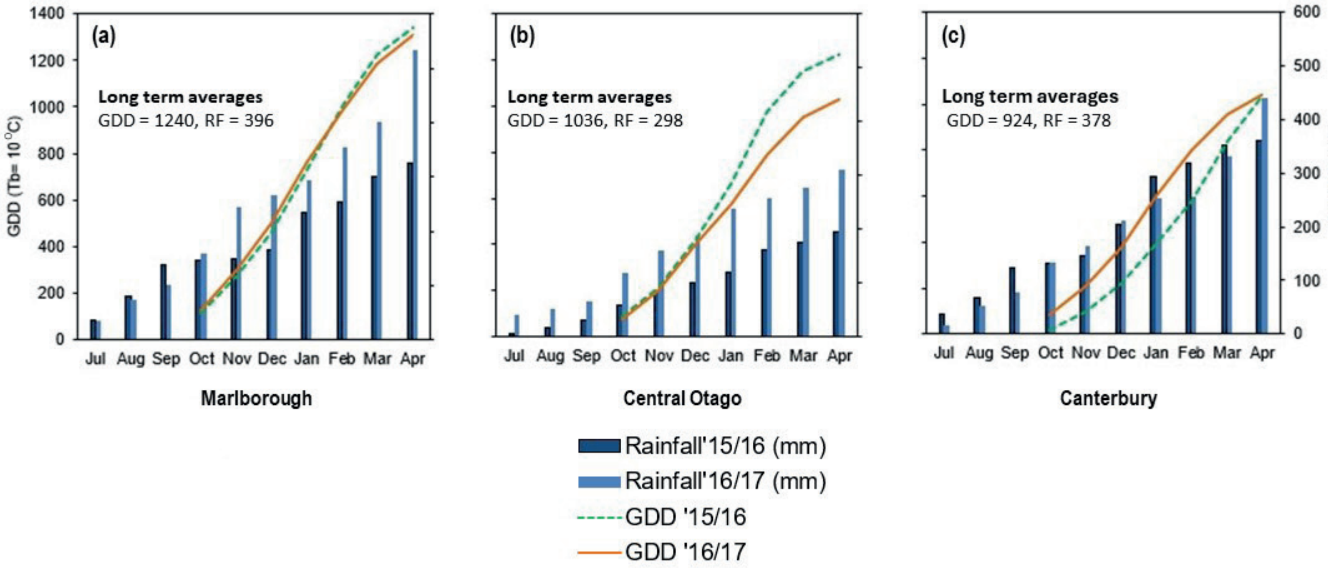

FIGURE 1. Heat summation in growing degree-days (GDD base 10 °C, Winkler Index) and seasonal (2015/16, 2016/17) cumulative rainfall of all trial sites. 2016/17 total GDDs: In 2015/16 and 2016/17, GDD (base 10 °C) of 1339, 1307; 1220, 1025 and 1032, 1037 characterised Marlborough (a), Central Otago (b) and Canterbury (c) vineyards, respectively. Weather data were sourced from nearby stations of the respective locations. Long-term averages (LTA) for GDD and rainfall were 1240, 396; 1036, 298; and 924, 378 for Marlborough, Central Otago (Agnew & Raw, 2016), and Canterbury (G. Creasy, unpublished) respectively.

(H, i.e., trimmed to half the canopy height, where full canopy was 1.2m, and half canopy was 0.6 m) was applied using secateurs at pre-veraison (V- i.e. E-L:34), veraison (V, i.e. E-L:35), and post-veraison (V+, i.e. E-L:36), at all sites (except no V- at Central Otago), resulting in treatments: FV-, FV, FV+, HV-, HV, and HV+ (F = full canopy). Lateral growth removal was manually conducted during treatment installation and periodically when growth was visible, for consistent leaf area. In 2016/17, since a new treatment with 75 % canopy reduction (quarter canopy or Q) was added, new vines were used to prevent carry-over effects from the previous season's treatments, ensuring no residual impacts from prior canopy manipulations. This approach was specifically chosen to isolate the treatment effects, and by conducting the experiment over two seasons, we were able to generalise trends in vine responses across different years. The Q treatment was achieved by alternately removing leaves after trimming shoots to half at V-, V, and V+. For F vines, lateral growth removal was restricted to the V- treatment as observations from 2016 indicated that the timing of lateral growth removal did not significantly affect full canopy vines. As a result, the treatments were categorised as follows: FV-, HV-, HV, HV+, QV-, QV, and QV+. During the installation of the treatments, lateral growth was removed from all vines, including those that were not trimmed, and regrowth was not allowed. Untrimmed vines were used as a control in both seasons.

3. Leaf chlorophyll concentration and stomatal conductance

In all sites and in both years, leaf greenness was used as a proxy for chlorophyll concentration in leaves measured by a portable chlorophyll meter (SPAD-502, Minolta Camera Co. LTD, Osaka, Japan). For each vine in a bay, during seasons 2015/16 and 2016/17, four mature leaves (with an established photosynthetic apparatus) close to the foliage wire were randomly selected and five SPAD readings were recorded from each leaf in its distal part and in a radial pattern, and an average value was calculated for each leaf. Measurements were taken at E-L 37 and E-L 38 (harvest).

Stomatal conductance was recorded in both exposed, intact leaves of three vines per replicate on clear, sunny days using a leaf porometer (SC-1, Decagon Devices Inc., Pullman, WA USA) at E-L 37 when berries were not quite ripe.

4. Cluster exposure, yield components, leaf area and pruning weight

In 2015/16, photosynthetically active radiation (PAR) was measured (two times per replicate, on two separate vines) using a ceptometer (AccuPAR LP80, Decagon Devices Inc., Pullman, WA USA), orienting the probe on a horizontal plane with the light sensors facing the sky to measure ambient PAR above the canopy and inside the canopy within the fruiting zone. Measurements were taken during a clear day between 11:00 AM and 2:00 PM (a time chosen to minimise variability due to stable light conditions) at E-L 37. The ratio of in-canopy to ambient PAR readings was calculated. Point Quadrat measurements were performed to assess canopy density in the cluster zone (Smart & Robinson, 1991) at E-L 37 in 2015/16.

Monitored vines were hand-harvested and the following harvest measurements were taken: clusters per vine, average cluster weight, total yield per vine, and pruning weight per meter of row (weight of one-year-old growth). Vine leaf area (m2 per vine) at harvest was also estimated by collecting and weighing all leaves between the trunks of two designated vines in each replicate bay, then subsampling 10 % of the total fresh leaf weight to measure leaf area using a Li-Cor LI-3100C Area Meter (Lincoln, NE, USA). LA:FW ratio and yield to pruning weight ratio (Ravaz index, Y:P) were computed.

5. Root carbohydrates

In 2016/17, 10 mm root samples were collected freeze-dried, and finely ground using liquid nitrogen for the analysis of carbohydrates according to the methods described by Allen *et al.* (1974) and Rose *et al.* (1991).

6. Berry sample and basic fruit chemistry

A total of 120 berries per replicate were sampled from randomly selected clusters on both the east and west sides of the canopy, with one berry each systematically collected from the top, mid, and bottom of the cluster. These berries were stored in sample bags, transported in an insulated container to the laboratory, and frozen at -20 °C until analysis. For each replicate, 40 frozen berries were sub-sampled, defrosted overnight at 4ºC thawed (Cynkar *et al.*, 2008), bench-thawed at room temperature, manually crushed, and coarsely filtered using a stainless-steel strainer for analysis of TSS, pH, TA, malic acid, and YAN.

Total soluble solids (TSS, °Brix) were determined using a digital refractometer (PAL-1; Atago Inc., USA). Must pH and TA (expressed as equivalents of tartaric acid, g/L) were determined with an automatic titrator (799 GPT Titrino, Metrohm AG, Herisau, Switzerland) with a sampler (788 Sample Processor, Metrohm AG, Herisau, Switzerland) and using 0.1 M sodium hydroxide (NaOH) at an end-point of pH 8.2, at room temperature. Malic acid was determined by RQflex® 10 (2013) using 1mL (1:25 dilution) grape juice.

YAN (mg/L) concentration of the grape juice was determined by measuring ammonia nitrogen (AN) (mg/L) and primary amino acid nitrogen (PAAN) (mg/L). Grape juice stored at -20 °C was thawed on a bench to room temperature, clarified by centrifugation at 8936 g for 5 min and then AN (340 nm) and PAAN (335 nm) determined spectrophotometrically (UV-1800, Shimadzu Corp., Kyoto, Japan) using 1 cm path length methacrylate disposable cuvettes and Vintessential analysis test kits 4A110 and 4A120 (Vintessential Laboratories, Dromana, Australia), respectively.

7. Statistical analysis

Results were analysed by analysis of variance (ANOVA) with treatment means separated by Fisher's unprotected least significant difference (LSD) at $p < 0.05$ (Saville, 2003). In both seasons, exponential three-parameter growth curves

($y = a + br^x$) were fitted for the Marlborough and Central Otago sites, while linear curves were used for the Canterbury vineyard. These curve choices were based on the pattern of the evolution of TSS. The number of days (DOY) needed to reach 18 °Brix (equivalent to producing lower alcohol, approximately 10 % v/v post-fermentation) at Marlborough, 20 °Brix at Central Otago (11 % v/v), and 16 °Brix (8.9 % v/v) at Canterbury were derived from the regressions. Different targets total soluble solids concentrations representing low alcohol targets were chosen depending on the conditions. While the target TSS was set at 18 °Brix at the Marlborough vineyard, at Canterbury vineyard it was set lower at 16 °Brix due to pre-harvest wet and cold weather preventing ripening to 18 °Brix; at Central Otago, the target was 20 °Brix, since TSS was already at 18.8 °Brix when the V+ treatment was applied. The concentrations of malic acid, titratable acidity, and yeast assimilable nitrogen were interpolated at those target TSS concentrations. The statistical software package GenStat 18 (VSN International Ltd, UK) was used to perform all analyses. All Figures were plotted in Microsoft Excel 2016.

RESULTS AND DISCUSSION

1. Vegetative growth, canopy microclimate, and vine performance

F vines had higher leaf area and pruning weights across all sites and both seasons in comparison to the H and Q vines irrespective of time of trim (Tables 1-4). The only exception was at the Canterbury vineyard in 2015/16, where early leaf fall confounded leaf area measurements, with little difference among trim heights (Table 3). The overall lower pruning weights and reduced leaf area in the Central Otago site also indicated less vigorous vines at that site (Tables 2 and 4). Additionally, although the goal was to remove 50 % and 75 % of the canopy, the observed leaf areas were not strictly proportional, as achieving an exact 50 % reduction is inherently challenging during trimming. Furthermore, from a physiological perspective, source-limited vines tend to enlarge their remaining leaves, which accounts for the higher leaf area observed even after half and quarter canopy trimming. The leaf area in Canterbury was also reduced by early senescence.

Irrespective of variations in leaf area, canopy density (Point Quadrat) and PAR transmittance did not differ among treatments at any site (Tables 1-3). Leaf greenness varied with treatments in both years, showing higher levels in early trimmed vines (Figure 2 b, d). In the 2015/16 ripening period (E-L 37), H vines were 6 % greener at the Marlborough site and 5 % greener at the Central Otago site compared to F vines. At harvest (E-L 38), leaf greenness of H vines showed a 21 % increase at the Marlborough site and a 56 % increase at the Central Otago site. As SPAD has been related to chlorophyll concentration and nitrogen content (Porro *et al.*, 2001), the increased leaf greenness indicates greater amounts of both. These findings align with previous findings reported by Hofäcker (1978) for Müller Thurgau and Reisling, Candolfi-Vasconcelos & Koblet (1991) in Riesling and Petrie *et al.* (2000) in Pinot noir. Spring *et al.* (2012) also demonstrated elevated leaf nitrogen content and chlorophyll index in Chasselas and Pinot noir vines following pre-veraison de-lateraling and shoot trimming, indicating that leaf removal improved nitrogen concentration in the remaining leaves. At the Central Otago site, the marked increase in leaf greenness is likely due to the higher crop level (higher sink strength) relative to the reduced vegetative source effect on leaf photosynthetic capability, as also observed by Petrie *et al.* (2000) and Candolfi-Vasconcelos & Koblet (1991) during ripening. The connection between SPAD and stomatal conductance (gs) is relevant, as SPAD reflects chlorophyll content, which correlates with photosynthetic capacity, while gs measures gas exchange and photosynthetic regulation. Higher SPAD values often signal increased chlorophyll, enhancing photosynthetic potential and explaining the higher gs values. At the Canterbury vineyard in 2015/16, an immediate rise in leaf greenness (as well as stomatal conductance, gs, Table 3) following trimming was evident, but it was not sustained until harvest; the absence of differences at harvest could be related to the changes in the environment, such as cool temperatures and low solar radiation that may have initiated leaf senescence (Flore & Lakso, 1989; Körner, 2003; Poorter *et al.*, 2006; Taylor & Whitelaw, 2001). The most apparent reason, however, for early leaf yellowing (chlorophyll degradation) and abscission at the Canterbury vineyard was low yield at the site (Table 3). Low assimilate demand in plants causes sugar accumulation in leaves, leading to feedback inhibition of photosynthesis (Paul & Foyer, 2001) and resulting chlorophyll degradation as a protective measure against oxidative stress (Tränkner *et al.*, 2018). Consequently, the vine may experience an early shutdown and premature leaf fall (Keller *et al.*, 2014), which signals the initiation of senescence/nutrient recycling processes (Thomas, 2013). In the 2016/17 season, a slight increase in yield at the Canterbury vineyard resulted in higher leaf greenness at the E-L 38 stage compared to 2015/16.

2. Yield and vine balance

In both seasons and in all trial sites, number of clusters per vine, cluster weight, berry weight and yield were not statistically affected by trimming (Table 1-4).

The absence of yield differences due to treatments in the Marlborough and Central Otago sites led to higher Ravaz indices in H vines compared to the F control in both seasons (Figure 2 a, b, c). A Ravaz Index in the range from 3 to 6 is indicated as optimal for small-clustered varieties, such as Pinot noir growing in cool climate (Kliewer & Dokoozlian, 2005). The vines in Central Otago consistently exceeded the optimal range, indicating overcropping (Figure 2c). This result is attributed to the retention of three-node spurs, leading to higher yields and an elevated Ravaz index. In 2015/16 at the Canterbury vineyard, the Ravaz index was smaller than this range suggesting undercropping (Figure 2e). Similarly, the lack of differences in yield among treatments led to lower LA:FW ratios for trimmed vines compared to

TABLE 1. Vine parameters as affected by canopy height and trimming time treatments at the Marlborough vineyard, 2016.

	Canopy height, H			Trim time, T				H*T							
Parameter	F	H	*P*-value	V-	V	V+	*P*-value	FV-	FV	FV+	HV-	HV	HV+	*P*-value	LSD (5 %)
Total leaf area/m (m^2)	1.93^{a}	1.24^{b}	<0.001	1.70	1.51	1.55	0.114	2.11^{a}	1.81^{a}	1.87^{a}	1.28^{b}	1.22^{b}	1.23^{b}	0.339	0.26
Clusters/vine	31	29	0.161	31	31	28	0.267	32	33	29	29	30	28	0.789	6
Cluster weight (g)	88	90	0.690	91	92	92	0.057	84	89	92	83	94	92	0.645	11
Berry weight (g)	1.06	1.06	0.458	1.06	1.07	1.05	0.146	1.06	1.07	1.04	1.06	1.07	1.11	0.692	0.11
Yield/m (kg)	1.96	1.85	0.303	1.82	2.05	1.84	0.215	1.95	2.09	1.86	1.70	2.02	1.82	0.740	0.41
Pruning weight/m (kg)	0.82^{a}	0.54^{b}	<0.001	0.66	0.70	0.68	0.655	0.81^{a}	0.83^{ab}	0.83^{abc}	0.50^{c}	0.58^{c}	0.54^{bc}	0.824	0.15
Canopy characteristics															
Percent gap (PG)	12.3	14.0	0.509	13.5	15.0	11.0	0.427	12.0	17.0	8.0	15.0	13.0	14.0	0.262	9.0
Leaf layer number (LLN)	1.3	1.3	0.965	1.2	1.3	1.4	0.224	1.2	1.2	1.5	1.2	1.4	1.2	0.093	0.27
Percent internal leaves (PIL)	8.5	8.1	0.865	6.9	9.4	8.6	0.570	5.6	8.2	11.6	8.2	10.6	5.6	0.144	7.0
Percent internal clusters (PIC)	8.0	9.3	0.823	4.2	12.2	9.5	0.506	5.0	2.8	16.2	3.4	21.6	2.8	0.083	20.2
PAR transmittance (%)	19	22	0.07	19	20	22	0.236	19	20	19	20	21	25	0.282	0.05

F = Full canopy; H = Half canopy; V- = Pre-veraison; V = Veraison; V+ = Post-veraison. Means values separated using Unprotected Fisher's LSD test ($p < 0.05$), and means within rows represented by different superscript letters are significantly different.

TABLE 2. Vine parameters as affected by canopy height and trimming time treatments at the Central Otago vineyard, 2016.

	Canopy height, H			Trim time, T				H*T							
Parameter	F	H	*P*-value	V-	V	V+	*P*-value	FV-	FV	FV+	HV-	HV	HV+	*P*-value	LSD (5 %)
Total leaf area/m (m^2)	1.50	1.11	<0.001	-	1.35	1.26	0.270	-	1.50^{a}	1.50^{a}	-	1.20^{ab}	1.02^{b}	0.278	0.25
Clusters/vine	30	29	0.491	-	28	31	0.181	-	29	31	-	27	31	0.621	6
Cluster weight (g)	120	122	0.649	-	124	118	0.372	-	125	114	-	122	122	0.349	18
Berry weight (g)	1.26	1.29	0.169	-	1.28	1.27	0.710	-	1.25	1.26	-	1.31	1.28	0.447	0.08
Yield/m (kg)	2.11	2.23	0.571	-	2.12	2.23	0.610	-	2.04	2.18	-	2.20	2.27	0.862	0.647
Pruning weight/m (kg)	0.25	0.17	<0.001	-	0.19	0.23	0.080	-	0.23^{ab}	0.27^{a}	-	0.15^{c}	0.18^{bc}	0.803	0.06
Canopy characteristics															
Percent gap (PG)	14.0	10.0	0.384	-	12.0	12.0	0.998	-	16	12	-	8	12	0.384	6.3
Leaf layer number (LLN)	1.5	1.4	0.394	-	1.4	1.5	0.505	-	1.4	1.6	-	1.4	1.3	0.361	0.22
Percent internal leaves (PIL)	12.9	12.5	0.909	-	9.8	15.6	0.090	-	7.6	18.2	-	12.0	13.0	0.151	4.5
Percent internal clusters (PIC)	47.7	23.5	0.108	-	33.7	37.5	0.786	-	48	47.3	-	19.3	27.7	0.750	19.7
PAR transmittance (%)	22	23	0.569	-	23	22	0.544	-	24	20	-	22	24	0.059	0.02

F = Full canopy; H = Half canopy; V- = Pre-veraison; V = Veraison; V+ = Post-veraison. Means values separated using Unprotected Fisher's LSD test ($p < 0.05$), and means within rows represented by different superscript letters are significantly different.

TABLE 3. Vine parameters as affected by canopy height and trimming time treatments at the Canterbury vineyard, 2016.

	Canopy height, H			Trim time, T				H*T							
Parameter	F	H	*P*-value	V-	V	V+	*P*-value	FV-	FV	FV+	HV-	HV	HV+	*P*-value	LSD (5 %)
Total leaf area/m (m^2)	0.47	0.37	0.066	0.41	0.41	0.45	0.758	0.46	0.42	0.53	0.36	0.39	0.36	0.550	0.18
Clusters/vine	26	27	0.651	28	25	25	0.391	28	23	25	28	27	25	0.656	7
Cluster weight (g)	40	39	0.790	39	37	44	0.112	38	35	48	39	38	41	0.357	11
Berry weight (g)	0.88	0.89	0.705	0.93	0.87	0.87	0.314	0.90	0.86	0.89	0.95	0.87	0.86	0.583	0.12
Crop yield/m (kg)	0.83	0.85	0.887	0.91	0.67	0.93	0.163	0.90	0.59	0.99	0.91	0.75	0.87	0.622	0.42
Pruning weight/m (kg)	0.62^{a}	0.42^{b}	<0.001	0.53	0.48	0.55	0.221	0.63^{ab}	0.52^{bc}	0.71^{a}	0.43^{c}	0.44^{c}	0.39^{c}	0.019	0.11
Stomatal conductance (gs)	312	376	0.004	327	349	356	0.460	289	302	346	366	395	366	0.286	69
Canopy characteristics															
Percent gap (PG)	3.0	2.3	0.517	3.5	2.5	2.0	0.480	5.0	3.0	1.0	2.0	2.0	3.0	0.153	3.7
Leaf layer number (LLN)	2.1	2.0	0.108	2.1	2.1	2.1	0.648	2.2	2.1	2.2	1.9	2.2	2.0	0.172	0.24
Percent internal leaves (PIL)	22.2	17.2	0.067	19.1	20.9	19.2	0.816	23.8	19.5	23.3	14.4	22.2	15.1	0.128	9.2
Percent internal clusters (PIC)	52.0	55.0	0.697	42.8	59.8	57.9	0.165	44.0	48.7	63.3	41.7	71.0	52.4	0.207	27.6
PAR transmittance (%)	28	24	0.428	27	0.30	21	0.301	27	35	21	26	25	21	0.672	0.17

F = Full canopy; H = Half canopy; V- = Pre-veraison; V = Veraison; V+ = Post-veraison. Means values separated using Unprotected Fisher's LSD test ($p < 0.05$), and means within rows represented by different superscript letters are significantly different.

TABLE 4. Vine parameters as affected by canopy height and trimming time treatments at the Marlborough, Central Otago and Canterbury vineyards, 2017.

Parameter	FV-	HV-	HV	HV+	QV-	QV	QV+	*p*-value	LSD (5 %)
Marlborough									
Total leaf area/m (m^2)	2.40^{a}	1.24^{b}	1.24^{b}	1.23^{b}	0.66^{c}	0.65^{c}	0.68^{c}	<0.001	0.15
Clusters/vine	30	29	27	28	29	28	29	0.972	7
Cluster weight (g)	81	82	94	88	87	87	89	0.976	28
Berry weight (g)	1.39	1.40	1.39	1.40	1.40	1.39	1.40	0.915	0.04
Crop yield/m (kg)	1.78	1.71	1.81	1.74	1.75	1.72	1.85	0.998	0.54
Pruning weight/m (kg)	0.90^{a}	0.54^{b}	0.57^{b}	0.58^{b}	0.56^{b}	0.54^{b}	0.57^{b}	<0.001	0.09
Central Otago									
Total leaf area/m (m^2)	1.69^{a}	0.99^{b}	1.04^{b}	0.99^{b}	0.64^{c}	0.62^{c}	0.59^{c}	<0.001	0.06
Clusters/vine	32.8	35.2	30.6	33.6	29.8	32.4	33.8	0.755	7.3
Cluster weight (g)	120.2	114.7	138.2	123.9	119.6	113.2	109.5	0.355	25.4
Berry weight (g)	1.22	1.22	1.21	1.25	1.23	1.23	1.24	0.995	0.13
Crop yield/m (kg)	2.46	2.46	2.36	2.57	2.29	2.57	2.27	0.722	0.46
Pruning weight/m (kg)	0.31^{a}	0.18^{b}	0.18^{b}	0.16^{b}	0.17^{b}	0.16^{b}	0.18^{b}	<0.001	0.05
Canterbury									
Total leaf area/m (m^2)	2.30^{a}	1.31^{b}	1.30^{b}	1.30^{b}	0.79^{c}		0.80^{c}	<0.001	0.23
Clusters/vine	33	35	32	30	31		33.6	0.631	7.0
Cluster weight (g)	68.2	59.0	61.1	65.1	59.8		62.4	0.981	27.5
Berry weight (g)	1.38	1.23	1.30	1.32	1.15		1.32	0.410	0.23
Crop yield/m (kg)	1.57	1.41	1.45	1.55	1.36		1.45	0.980	0.66
Pruning weight/m (kg)	0.86^{a}	0.46^{b}	0.46^{b}	0.49^{b}	0.48^{b}		0.45^{b}	<0.001	0.07

F = Full canopy; H = Half canopy; Q = Quarter canopy (i.e. leaves removed after trimming shoots to half); V- = Pre-veraison; V = Veraison; V+ = Post-veraison. Mean values separated using Unprotected Fisher's LSD test ($p < 0.05$) and means within rows represented by different superscript letters are significantly different.

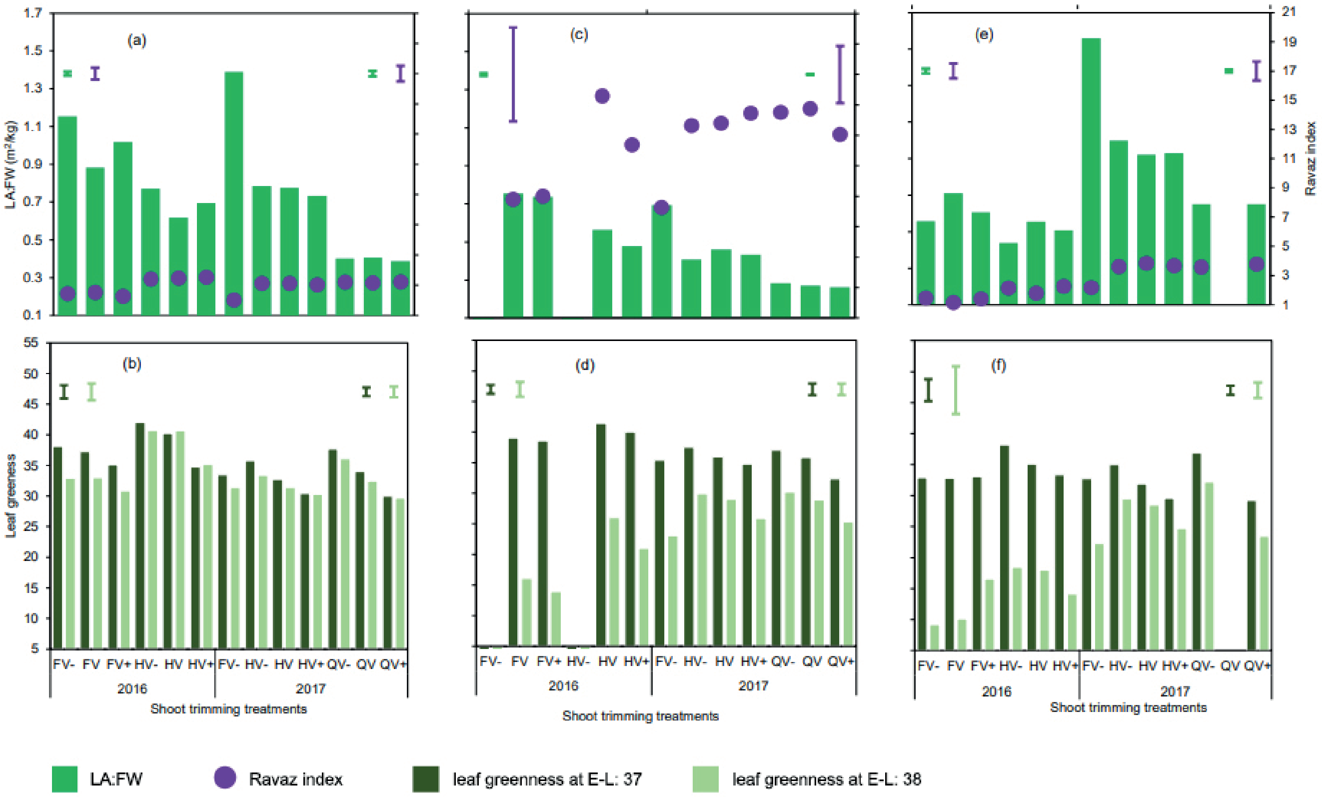

FIGURE 2. Shoot trimming at various berry phenological stages and its effects on vine leaf area to fruit weight ratio (LA:FW), Ravaz index and leaf chlorophyll concentration

LA:FW (green square), Ravaz index (purple circle), leaf greenness at E-L: 37 (dark green square) and leaf greenness at E-L: 38 (light green square) at the Marlborough site (a, b), the Central Otago site (c, d), Canterbury site (e, f). F = Full canopy; H = Half canopy; Q = Quarter canopy (i.e. leaves removed after trimming shoots to half); V- = Pre-veraison, V = Veraison, V+ = Post-veraison. Error bars indicate least significant differences (LSD) for Fisher's unprotected LSD ($p < 0.05$).

their untrimmed counterparts (Figure 2 a, b, c) across all sites and in both years. In 2016 at Canterbury, however, shoot trimming did not alter the LA:FW ratio due to early leaf fall, preventing measurement of the areas that were there earlier in the season. Achieving optimal levels of sugar accumulation, berry weight, and colour in vertically trained vines with a single canopy design typically requires a LA:FW within the range of 0.8 to 1.2 m^2/kg (Kliewer & Dokoozlian, 2005). In this study, irrespective of the timing, shoot trimming practices consistently led to a reduced LA:FW ratio, ranging from 0.52 m^2/kg to 0.69 m^2/kg in 2015/16 (Canterbury data excluded due to early leaf fall) and from 0.27 m^2/kg to 0.95 m^2/kg in 2016/17.

3. Fruit composition

3.1. Total soluble solids (TSS)

In 2015/16 (Table 5) lower LA:FW ratios led to lower TSS at the Marlborough site, with HV- showing a decrease of 2.30 °Brix (-1.4 % v/v post-fermentation ethanol), while HV and HV+ had smaller reductions of 1.98 °Brix (-1.2 % v/v) and 1.02 °Brix (-0.6 % v/v). Likewise, at the Central Otago site, early source-limited berries (HV) had a TSS reduction of 1.48 °Brix (-0.9 % v/v) compared to FV-. Previous studies with around 50 to 60 % source limitation during berry development (E-L 29 to E-L 37) reported TSS reductions ranging from 0.7 °Brix to 2.4 °Brix (Bubola *et al.*, 2022; Caccavello *et al.*, 2017; Filippetti *et al.*, 2015; Pastore *et al.*, 2013; Poni *et al.*, 2013; Valentini *et al.*, 2019); therefore, our findings align with these ranges. At the Canterbury vineyard, shoot trimming had minimal effect on TSS reduction due to low yields driving higher LA:FW ratios.

In 2016/17 at the Marlborough site there was a marked reduction in harvest TSS relative to FV-, ranging from 2.7 °Brix (-1.6 % v/v) in QV- berries to 1.6 °Brix (0.9 % v/v) in HV+ berries (Table 6). HV+ showed a greater reduction in 2016/17 compared with the 2015/16 season (-1.6 °Brix in 2016/17 vs -1.02 °Brix in 2015/16), likely as a result of trimming earlier when berries had attained 16.4 °Brix (compared with the V+ trim at 18.4o Brix in 2015/16). Similarly at the Central Otago site, harvest TSS were reduced by 1.78 °Brix (-1.1 % v/v), 1.40 °Brix (-0.8 % v/v), 1.24 °Brix (-0.7 % v/v), and 1.06 °Brix (-0.6 % v/v) in QV-, QV, HV-, HV, respectively (Table 6).

A substantial delay to achieve 18 °Brix at the Marlborough site was observed, ranging from approximately 6 to 24 days. Likewise at the Central Otago site a 6 to 13 days (with the exception of HV+ and QV+) was observed to reach 20 ºBrix (Table 7). This confirms the 10-day delays in reaching 21 °Brix due to 50 % source limitation previously measured in Pinot Noir vines (Parker *et al.*, 2015). In 2015/16, trimming at the Canterbury vineyard resulted in only a 1.22 °Brix difference (-0.7 % v/v) between the highest (FV-, 22.4o) and the lowest (HV, 21.14o) treatments at harvest (Table 5). In 2016/17, unfavourable wet and cool weather conditions during ripening had considerably slowed sugar accumulation at this site. Only fruit from FV- treated vines had reached 18 °Brix (Table 6). At harvest, TSS of QV, HV and HV berries was reduced by 1.5 °Brix compared to the control (-0.9 % v/v), while HV+ and QV+ berries had similar TSS compared to FV- berries. The time to reach 16 °Brix varied among treatments, with earlier trimmed vines experiencing a delay of up to 8 days (Table 7). The reduction in TSS in H and Q vines, particularly in Marlborough and Central Otago, highlights LA:FW ratio reduction as a tool to delay ripening in the context of climate change or reduce TSS for lower alcohol wine production.

3.2. Malic acid, titratable acidity, and pH

Malic acid concentration and TA at harvest remained unaffected by the severity of trimming and the timing at all sites and in both years.

This demonstrates that where TA, pH and malic were unchanged in response to timing and severity of trimming, there is a de-synchronisation of basic fruit chemistry, as TSS does change. Bobeica *et al.* (2015) strongly assert that organic acids, such as malic acid, are less affected by carbon constraints (LA:FW 0.33 m2/kg in Sangiovese) introduced at E-L 34 than sugar accumulation. This lack of difference in TA and pH and consequent desynchronisation with TSS, appears to occur throughout defoliation treatments from as early as E-L 29, as demonstrated in Parker *et al.* (2015) and Stoll *et al.* (2010). Furthermore, Filippetti *et al.* (2015) and Palliotti *et al.* (2013) reported similar results when Sangiovese vines were source limited by 58 % (LA:FW 0.39 m2/kg) and 36 % reduction in leaf area at E-L 37, respectively. At target TSS levels, malic acid and TA of V+ remained similar to the control (FV-) at the Marlborough and Central Otago sites (Table 7), indicating that trimming post-veraison remains a potential option for producing lower alcohol wines and adapting to climate change.

3.3. Yeast assimilable nitrogen

Early LA:FW ratio reduction increased yeast assimilable nitrogen (YAN) concentrations in all sites and years, except in the undercropped Canterbury site during 2016 (Table 5). The result aligns with previous findings reported by, for example, Spring *et al.* (2012) in Chasselas and Pinot noir (as well as increased N concentration in remaining leaves), Pineau *et al.* (2017) in Pinot noir, and Stoll *et al.* (2010) who observed increased YAN concentrations in response to alterations in LA:FW ratios, accompanied by enhanced nitrogen concentration in remaining leaves. QV- treatments consistently exhibited higher YAN values across all the sites when compared to other treatments at the same target TSS concentrations, suggesting that both early trimming and severity play a role. However, while YAN is essential for fermentation, excessive YAN can have detrimental effects. Elevated YAN can increase the risk of unwanted microbial activity, such as spoilage organisms like Brettanomyces, leading to off-flavours (Bely *et al.*, 1990). Additionally, it may cause overproduction of volatile acidity, impacting wine aroma and taste (Ough & Bell, 1980). High YAN levels are also linked to the formation of ethyl carbamate, a compound associated with potential health risks (Ough & Lee, 1981).

TABLE 5. Fruit composition at harvest in response to shoot trimming at various times in 2016.

	Marlborough					Central Otago					Canterbury				
	Total soluble solids	Malic acid (g/L)	Titratable acidity (g/L)	pH	Yeast assimilable nitrogen (mg/L)	Total soluble solids	Malic acid (g/L)	Titratable acidity (g/L)	pH	Yeast assimilable nitrogen (mg/L)	Total soluble solids	Malic acid (g/L)	Titratable acidity (g/L)	pH	Yeast assimilable nitrogen (mg/L)
Trim height, H															
F	22.9^{a}	4.24	6.29	3.73	242^{b}	22.3^{a}	4.95	7.11	3.68	285^{b}	21.8^{a}	5.11	7.88	3.73	353
H	21.7^{b}	4.32	6.47	3.75	272^{a}	21.1^{b}	5.05	7.35	3.69	317^{a}	21.2^{b}	5.16	7.68	3.73	345
P-value	<.001	0.376	0.164	0.109	0.061	<.001	0.611	0.315	0.509	0.006	0.001	0.485	0.214	0.941	0.675
Trim time, T															
V-	22.4^{a}	4.29	6.39	3.72	276^{a}						21.8^{a}	5.14	7.86	3.70	347
V	21.8^{b}	4.38	6.43	3.75	249^{b}	21.5^{b}	5.03	7.37	3.70	317^{a}	21.4^{b}	5.15	7.78	3.74	356
V+	22.7^{a}	4.18	6.32	3.75	246^{b}	21.9^{a}	4.97	7.09	3.67	285^{b}	21.4^{ab}	5.12	7.70	3.75	344
P-value	0.015	0.192	0.754	0.203	0.047	0.018	0.76	0.245	0.388	0.006	0.106	0.941	0.708	0.084	0.867
H*T															
FV-	23.4^{a}	4.27	6.32	3.68	256^{ab}						22.4^{a}	5.12	8.22	3.68	358
FV	22.3^{ab}	4.30	6.22	3.74	223^{b}	22.2^{a}	4.98	7.04	3.69	279^{b}	21.6^{ab}	5.10	7.84	3.75	355
FV+	23.0^{a}	4.15	6.34	3.75	247^{ab}	22.3^{a}	4.91	7.18	3.66	290^{b}	21.5^{b}	5.10	7.58	3.77	346
HV-	21.5^{b}	4.30	6.46	3.75	295^{a}						21.2^{b}	5.16	7.50	3.72	336
HV	21.2^{b}	4.46	6.64	3.76	276^{a}	20.7^{c}	5.07	7.70	3.71	355^{a}	21.1^{b}	5.19	7.72	3.74	357
HV+	22.4^{ab}	4.20	6.30	3.75	245^{ab}	21.5^{b}	5.02	7.00	3.68	280^{b}	21.4^{b}	5.13	7.82	3.74	342
P-value	0.107	0.813	0.310	0.275	0.093	0.052	0.959	0.245	0.972	<0.001	0.027	0.941	0.061	0.310	0.856
LSD (5 %)	0.90	0.32	0.43	0.06	35.5	0.50	0.59	0.71	0.09	29.8	0.56	0.27	0.56	0.06	66.1

F = Full canopy, H = Half canopy; V- = Pre-veraison, V = Veraison, V+ = Post-veraison. Means values separated using Unprotected Fisher's LSD test ($p < 0.05$), and means within rows represented by different superscript letters are significantly different.

TABLE 6. Fruit composition at harvest in response to shoot trimming at various times, in 2017.

	Marlborough					Central Otago					Canterbury				
Treatments	Total soluble solids	Malic acid (g/L)	Titratable acidity (g/L)	pH	Yeast assimilable nitrogen (mg/L)	Total soluble solids	Malic acid (g/L)	Titratable acidity (g/L)	pH	Yeast assimilable nitrogen (mg/L)	Total soluble solids	Malic acid (g/L)	Titratable acidity (g/L)	pH	Yeast assimilable nitrogen (mg/L)
FV-	21.2^{a}	4.80	7.30	3.30	188^{d}	22.4^{a}	5.52	6.64	3.54	204^{ab}	18.2^{a}	7.51	9.72	3.28	338^{b}
HV-	18.9^{bc}	4.68	7.16	3.30	235^{b}	21.2^{b}	5.36	6.60	3.50	221^{ab}	17.3^{bc}	7.46	9.70	3.27	351a^{b}
HV	19.1^{bc}	4.68	7.00	3.38	194^{d}	21.3^{b}	5.60	6.72	3.58	203^{b}	17.4^{bc}	8.02	9.20	3.29	333^{b}
HV+	19.6^{b}	4.97	7.10	3.45	199^{d}	21.5^{b}	5.62	6.82	3.57	203^{b}	17.7^{ab}	6.86	9.04	3.30	321^{b}
QV-	18.5^{c}	5.04	7.08	3.45	288^{a}	20.6^{b}	5.58	6.70	3.61	234^{a}					
QV	19.2^{bc}	5.06	6.96	3.41	229^{bc}	21.0^{b}	5.46	6.56	3.62	213^{ab}	16.7^{c}	8.06	8.98	3.26	411^{a}
QV+	19.3^{bc}	5.08	7.04	3.40	205^{cd}	21.4^{b}	5.83	6.86	3.58	203^{b}	17.6^{ab}	6.87	9.18	3.30	319^{b}
P-value	<0.001	0.959	0.697	0.982	<0.001	<0.001	0.600	0.811	0.322	0.275	<0.001	0.751	0.173	0.930	0.002
LSD (5 %)	0.610	1.06	0.41	0.10	25.9	0.60	0.49	0.46	0.10	30.4	0.53	2.13	0.73	0.93	20.5

F = Full canopy; H = Half canopy; Q = Quarter canopy (i.e. leaves removed after trimming shoots to half); V- = Pre-veraison; V = Veraison; V+ = Post-veraison. Means values separated using Unprotected Fisher's LSD test ($p < 0.05$), and means within rows represented by different superscript letters are significantly different

TABLE 7. Response of malic acid, titratable acidity and yeast assimilable nitrogen (YAN) to shoot trimming at various Pinot noir developmental stages at 18 °Brix at the Marlborough site, 20 °Brix at the Central Otago site and at 16 °Brix at Canterbury sites, 2017.

Treatments →	FV-	HV-	HV	HV+	QV-	QV	QV+	*p*-value	LSD (5 %)
Marlborough									
DOY at 18 °Brix	66^{f}	85^{ab}	78^{cd}	72^{ef}	90^{a}	81^{bc}	73^{de}	<0.001	7
Malic acid (g/L	7.0^{a}	5.2^{cd}	5.9^{bc}	6.6^{ab}	5.0^{d}	5.5^{cd}	6.7^{a}	<0.001	0.77
Titratable acidity (g/L)	10.1^{a}	7.9^{c}	8.2^{bc}	8.9^{b}	7.5^{c}	7.9^{c}	8.7^{b}	<0.001	0.79
YAN (mg/L)	230^{cd}	252^{b}	223^{d}	236^{cd}	291^{a}	240^{bc}	234^{cd}	<0.001	14.0
Central Otago									
DOY at 20 °Brix	87^{d}	95^{bc}	93^{c}	87^{d}	100^{a}	98^{ab}	88^{d}	<0.001	5
Malic acid (g/L	6.2^{a}	5.5^{b}	5.5^{b}	6.3^{a}	5.4^{b}	5.3^{b}	6.1^{a}	<0.001	0.50
Titratable acidity (g/L)	7.7^{a}	6.9^{cd}	7.2^{bc}	7.6^{a}	6.5^{d}	6.7^{d}	7.5^{ab}	<0.001	0.40
YAN (mg/L)	212^{c}	226^{b}	206^{c}	210^{c}	239^{a}	213^{c}	208^{c}	<0.001	12.5
Canterbury									
DOY at 16 °Brix	89^{d}	94^{b}	93^{bc}	91^{cd}	97^{a}	-	91^{cd}	<0.001	2.4
Malic acid (g/L	9.7	8.8	9.1	8.6	8.5	-	8.6	0.416	1.27
Titratable acidity (g/L)	10.8	10.9	10.6	10.4	10.5	-	10.5	0.675	0.68
YAN (mg/L)	308^{bc}	331^{b}	313^{bc}	296^{c}	386^{a}	-	300^{bc}	<0.001	34

F = Full canopy, H= Half canopy, Q=Quarter canopy; V-= Pre-veraison, V= Veraison, V+= Post-veraison. Mean values separated using Unprotected Fisher's LSD test ($p < 0.05$) and means within rows represented by different superscript letters are significantly different.

TABLE 8. Root carbohydrates as affected by canopy height and trimming time treatments at Marlborough, Central Otago and Canterbury sites, 2017.

Parameter	FV-	HV-	HV	HV+	QV-	QV	QV+	*p*-value	LSD (5 %)
Marlborough									
Soluble sugars (% dw)	3.4	3.3	3.4	3.3	3.1	3.3	3.3	0.779	0.42
Starch (% dw)	11.9^{a}	10.7^{c}	10.4^{c}	11.5^{ab}	10.6^{c}	10.4^{c}	10.9^{bc}	<0.001	0.76
Total CHO	15.4^{a}	14.0^{c}	13.8^{c}	14.8^{ab}	13.7^{c}	13.7^{c}	14.2^{bc}	<0.001	0.75
Central Otago									
Soluble sugars (% dw)	3.1^{ab}	2.9^{bc}	2.8^{c}	3.3^{a}	2.8^{c}	2.9^{c}	3.2^{a}	<0.001	0.25
Starch (% dw)	10.5^{a}	8.0^{b}	7.6^{bc}	8.4^{b}	5.5^{d}	6.6^{cd}	8.1^{b}	<0.001	1.29
Total CHO	13.6^{a}	10.9^{bc}	10.4^{cd}	11.8^{b}	8.2^{e}	9.5^{de}	11.3^{bc}	<0.001	1.30
Canterbury									
Soluble sugars (% dw)	3.3	3.2	3.1	3.2	3.1		3.1	0.685	0.30
Starch (% dw)	13.9^{ab}	14.3^{ab}	14.1^{ab}	14.7^{a}	13.7^{b}		13.9^{b}	0.108	0.73
Total CHO	17.2^{ab}	17.5^{ab}	17.3^{ab}	17.8^{a}	16.7^{b}		16.9^{b}	0.088	0.77

F = Full canopy; H = Half canopy; Q = Quarter canopy; V- = Pre-veraison; V = Veraison, V+ = Post-veraison. Mean values separated using Unprotected Fisher's LSD test ($p < 0.05$) and means within rows represented by different superscript letters are significantly different.

Furthermore, too much YAN can lead to imbalanced flavour profiles and higher alcohol content, which may not be desirable in lighter wines (Dukes & Butzke, 1998). Despite these concerns, the YAN concentrations observed here are sufficient and unlikely to cause fermentation issues, such as yeast releasing hydrogen sulfide, as none of the values fell below the recommended minimum range of 130 to 150 N mg/L mg/L (Agenbach, 1977; Bely *et al.*, 1990; Camila, 2016; Dukes & Butzke, 1998; Keller, 2020). Moreover, nitrogen-containing compounds, such as amino acids, contribute to flavour, aroma, and mouthfeel (Moukarzel *et al.*, 2023; Ough & Bell, 1980; Ough & Lee, 1981; Webster *et al.*, 1993; Yuan *et al.*, 2018), suggesting that changes in YAN, as observed in this study, could potentially influence wine style, offering a positive role in producing quality lighter wines and adapting to climate change.

4. Root carbohydrates

At the Marlborough site, more severe, and/or early trimmed vines had reduced starch carbohydrate reserves, while post-veraison half canopy vines (HV+: LA:FW 0.70 m2/kg, Figure 2) maintained similar concentration of root starch as FV- (Table 8). This finding aligns with those of Palliotti et al.(2013) and Herrera *et al.* (2015), where approximately half-canopy Merlot and Sangiovese vines were able to maintain their carbohydrate reserve after source limitation was induced at E-L 36 and E-L 37, respectively. In agreement, Bennett *et al.* (2005) reported a reduction in reserve carbohydrate in Chardonnay following 75 % leaf removal at 4, 8, and 12 weeks post bloom. At the Central Otago site, late trimming did not affect concentrations of reserve soluble sugar, but did reduce concentrations of starch (Table 8). This change could be attributed to the higher yield/sink strength

(Table 4), which might make the reserves less of a priority and lead to the draining of reserve replenishment. In contrast, at the Canterbury vineyard, under-cropping seemed to mitigate treatment differences in root carbohydrates even when vines were trimmed; only quarter canopy vines had reduced starch concentrations in the roots, at both treatment times (Table 8). It is important to note that a reduction in carbohydrate reserves might hinder the sustainable production of the desired wine style (low alcohol wine, in this case). Continual trimming season after season could affect vine carbohydrate status, leading to weaker vine growth and reduced cropping in subsequent seasons.

CONCLUSION

Shoot trimming, regardless of timing, effectively reduces the concentration of total soluble solids (TSS) without affecting malic acid, titratable acidity, and pH at harvest. At target TSS concentrations of 18 °Brix (Marlborough) and 20 °Brix (Ferris-II), HV+ and QV+ had a similar concentration of malic acid and titratable acidity at harvest compared to the control. At 16 °Brix, Canterbury -based vines did not show differences in the concentrations of malic acid and titratable acidity due to treatment.

Yeast assimilable nitrogen (YAN) concentration increased in early trimmed vines at all sites. However, the YAN concentration was deemed sufficient, regardless of trimming treatments, indicating that YAN is unlikely to limit the production of lower alcohol Pinot noir wine under these conditions. Furthermore, even though not tested in the current study, the increase in YAN (which includes amino acids) in trimmed vines could potentially impact the flavour, aroma, and mouthfeel of low-alcohol wines, both positively and negatively.

In addition, early trimmed vines tended to have greener leaves (high SPAD readings), as supported by the increased stomatal conductance (gs) measurements in the Canterbury vineyard, potentially signalling a compensatory increase in photosynthesis. Importantly, the reduction in leaf area did not negatively impact yield in either growing season, but this may have consequences for the vine's ability to recharge storage reserves. In 2017, in the Central Otago site, a decline in root carbohydrate reserves was observed across all treatments, attributed to high yield. This reduction in reserve carbohydrates could result in a reduced capacity for vines to sustainably ripen similar quantities of fruit in subsequent seasons. At the Marlborough site, only half-canopy vines trimmed post-veraison (HV+) effectively maintained root carbohydrate reserves. The low crop load in the Canterbury vineyard meant only slight differences among treatments were found for this parameter. Note that different vines were used in each of the two seasons of this study.

In conclusion, the post-veraison trimming of vines to half-canopy (HV+), aiming for a moderate LA: FW ratio of approximately 0.70 m²/kg (as observed in Marlborough), can help maintain carbohydrate reserves. This practice offers potential benefits in adapting to the warming climate and the production of low-alcohol wines, with six days delay in ripening to reach 18 °Brix and 1.6 °Brix reduction at harvest, translating to a potential alcohol reduction of 0.96 % v/v.

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