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Asynchronous accumulation of sugar and phenolics in grapevines following post-veraison leaf removal

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ABSTRACT

Climate change necessitates the re-evaluation of viticultural practices to manage increasing grape sugar concentrations and meet consumer demand for lower-alcohol wines. This study aimed to evaluate whether modifying the leaf area to fruit weight (LA:FW) ratio through shoot trimming could reduce sugar accumulation while maintaining phenolic quality in Pinot noir grapes. We examined both the timing and severity of canopy reduction, implementing shoot trimming treatments (half canopy, H, in 2015–2016 and 2016–2017, and quarter canopy, Q, in 2016–2017) at three stages: pre-veraison (V–, E-L 34), veraison (V, E-L 35), and post-veraison (V+, E-L 36) across three vineyard locations. In each trimmed treatment (H or Q), lateral shoots were removed concurrently with shoot trimming to maintain consistent leaf area. Our results show that reducing the LA:FW ratio through trimming delayed and reduced grape sugar accumulation. Phenolic responses, however, varied by timing: early trimming (V–, V) decreased anthocyanin concentration at harvest of up to 37 % in QV– vines compared to controls, primarily due to reduced accumulation rates. In contrast, late trimming (QV+, HV+) maintained the concentration of anthocyanins at harvest and at target soluble solids and preserved anthocyanin-to-sugar ratios similar to the control. Total phenols, seed and skin tannins were unaffected by trimming, particularly in QV+ and HV+ treatments. Therefore, while these treatments decreased soluble solids, these phenolic components remained unchanged. Our results demonstrated that post-veraison (V+) shoot trimming could be a promising strategy to produce darker-colored berries at lower sugar concentrations. Therefore, trimming post-veraison but early in the maturity phase (~15 °Brix) to half-canopy level (HV+), represents a more sustainable approach for achieving dark-colored grapes while maintaining unaltered phenolic profiles at lower sugar concentrations.

KEYWORDS: climate change, Pinot noir, shoot trimming, post-veraison, low-alcohol wine, phenolics, anthocyanins

INTRODUCTION

Rising temperatures and elevated CO_2 concentrations caused by climate change (IPCC, 2021) accelerate vine phenology, leading to higher berry sugar concentrations, elevated wine alcohol levels, and altered dynamics in the accumulation of various grape compounds (Cameron *et al.,* 2021; Cameron *et al.,* 2022; Cook & Wolkovich, 2016; Droulia & Charalampopoulos, 2021; Hannah *et al.,* 2013; Parker *et al.,* 2011; Ramos & Martínez de Toda, 2020; Tiffon-Terrade *et al.,* 2023; Webb *et al.,* 2007). These changes necessitate a re-evaluation of viticultural strategies to manage sugar concentration while maintaining wine quality. This shift aligns with growing consumer preferences for lower-alcohol wines due to health and lifestyle considerations (Bragato Research Institute, 2024; Saliba *et al.,* 2013; Trought & Agnew, 2013). While technological methods exist for producing lower-alcohol wines, there is increasing demand for natural alternatives. Harvesting grapes at lower sugar concentrations offers a natural solution to both circumstances, but poses challenges in preserving other grape quality attributes.

This study is a continuation of the work by Assefa *et al.* (2024), which demonstrated that shoot trimming, by reducing the leaf area to fruit weight (LA:FW) ratio, decreased sugar accumulation and lowered total soluble solids (TSS) by 1.0 to 2.7 °Brix, without affecting berry weight or yield. In that study, pH and titratable acidity (TA) remained stable, and early trimming (pre-veraison and at veraison) was found to increase yeast-assimilable nitrogen (YAN), while post-veraison trimming had no effect on YAN. Root carbohydrate reserves were maintained only in vines that were trimmed to half canopy during post-veraison and were optimally cropped. Building on these findings, the present study expands the investigation by evaluating the impact of reduced LA:FW ratio on phenolic composition, an aspect not addressed previously. The focus is on key phenolic compounds, including anthocyanins and tannins, in Pinot noir.

Phenolic compounds are complex secondary metabolites that significantly influence grape and wine characteristics. They are essential for defining wine quality and typicity, particularly astringency (tannins) and colour (anthocyanins) in red grape cultivars (Macheix *et al.,* 1991; Singleton, 1992). Understanding the dynamics of anthocyanins and tannins during ripening is critical when implementing canopy management practices, such as shoot trimming, to reduce sugar concentrations. This is especially relevant for Pinot noir, a red variety known for its light colour and low skin tannins (Lee, 2010; Parley *et al.,* 2001), both of which are significant for winemaking.

Anthocyanin accumulation starts with that of sugar concentration in the berries at the start of the ripening phase (Coombe, 1992; Dai *et al.,* 2014; Lecourieux *et al.,* 2014; Vitrac *et al.,* 2000), with greatest increases during early ripening stages (Filippetti *et al.,* 2015; Guidoni *et al.,* 2008). Severe reductions in the LA:FW ratio before veraison, which markedly decrease berry sugar concentration, have been shown to adversely affect anthocyanin concentrations (Bobeica *et al.,* 2015; Pastore *et al.,* 2011; Pastore *et al.,* 2013; Wu *et al.,* 2013).

While minor LA:FW ratio modifications from veraison to post-veraison have no significant effects on sugar or anthocyanin concentrations (Pastore *et al.,* 2013) more severe post-veraison reductions in the LA:FW ratio (36 % to 48 %) significantly decreased sugar concentration without affecting anthocyanin concentration (Filippetti *et al.,* 2015; Palliotti *et al.,* 2013; Poni *et al.,* 2013; Valentini *et al.,* 2019). These findings suggest that the dynamics of sugar and anthocyanin accumulation can be independently influenced by precisely timed and scaled reductions in leaf area.

Tannins, another important class of phenolic compounds, contribute to wine astringency and colour stability (Ewing-Mulligan & McCarthy, 2005; Jackson, 2014; Somers, 1971). This is particularly critical for Pinot noir wines, which are often light in colour (Parley *et al.,* 2001). However, limited research exists on the effects of reduced LA:FW ratios on tannins. Filippetti *et al.* (2015) found no changes in seed tannins in Sangiovese after a 58 % post-veraison LA:FW reduction, but the effects on skin tannins, which are critical from an oenological perspective, remain unexplored.

The complex interplay between the timing and severity of leaf removal of LA:FW ratio manipulations (particularly from veraison onwards) on phenolics and carbohydrate partitioning has not thus far been systematically investigated to determine how to retain phenolic composition at a lower sugar concentration. Therefore, this study investigates how LA:FW ratio manipulations at different developmental times and severity, influence the sugar concentration, anthocyanin and tannin accumulation in the seeds and skins of Pinot noir grapevines. Unlike previous studies that were often limited to specific stages or single canopy reduction treatments, multiple timing and severity levels from pre-veraison to mid-ripening were evaluated. Phenolic compound concentrations were analysed at targeted soluble solids concentrations (°Brix) to examine compositional changes relevant to lower-alcohol wine production. Anthocyanin accumulation rates during early stages of development were evaluated. It is hypothesized that well-timed and appropriately scaled reductions in the LA:FW ratio post-veraison can lower berry sugar concentrations without adversely affecting anthocyanin and tannin composition. Conducted across three distinct wine-growing regions, this research highlights trends demonstrating the potential of canopy manipulation for climate adaptation and lower-alcohol wine production.

MATERIALS AND METHODS

1. Vineyard trials and climatic conditions

The experiments were conducted in three different Pinot noir vineyards in New Zealand during the 2015–2016 and 2016–2017 growing seasons. Vines of Pinot noir (clone 777) grafted onto 3309 rootstocks were grown in a vertical positioned trellis system. These vineyards were located

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, established in 1999, had a vine spacing of 2.4 m by 1.4 m, making 2976 vines per hectare. In Central Otago, the vines were planted in 2000, with a spacing of 2.5 m by 1.6 m (2,500 vines/ha). Vines in both vineyards were trained to bilateral cordons, with two-node spurs in Marlborough and three-node spurs in Central Otago. The Canterbury vineyard, also established in 1999, had a denser spacing of 2.5 m by 1.2 m (3,333 vines/ha) with vines pruned to two 16 node-canes. Canopy height was consistently maintained at 1.2 m across all sites.

During the study period, climatic conditions differed between the 2015–2016 and 2016–2017 seasons. Overall, the 2015–2016 season was drier, with Marlborough and Central Otago receiving less rainfall compared to their long-term averages (LTA). Particularly, pre-harvest months (March–April 2017) experienced significant rainfall in Marlborough and Canterbury, contributing 45 % and 43 % of their total seasonal rainfall (July–April), respectively. Growing degree days (GDD), calculated using the Winkler Index (1st October–30th April, base 10 °C), further classified these vineyards as Region-I cool-climate viticultural zones (Amerine & Winkler, 1963). The cumulative GDDs for 2015–2016 and 2016–2017 were 1339 and 1307 for Marlborough, 1220 and 1025 for Central Otago, and 1032 and 1037 for Canterbury. Additional climatic data are provided in the supplementary material (Figure S1).

Due to differences in climate, soil characteristics, management practices (*e.g.*, pruning types), and cropping levels, the study did not aim to statistically analyse comparisons among the three sites.

2. Experimental design and grape sampling

Field experiments were conducted over two growing seasons (2015–2016 and 2016–2017) using a randomized block design, with treatments replicated five times, each replicate consisting of one bay of five vines. In 2015–2016, a 50 % canopy trimming treatment (H) was applied, reducing canopy height from 1.2 m to 0.6 m at three phenological stages: pre-veraison (V–, E-L 34), veraison (V, E-L 35), and post-veraison (V+, E-L 36). The V-treatment was not implemented at the Central Otago site in 2015–2016. In the following season (2016–2017), the experiment was modified by introducing a quarter-canopy trimming treatment (Q) at all sites, which removed ~75 % of leaf area by trimming shoots to half their height, followed by manual leaf removal at V–, V, and V+. Additionally, lateral shoot removal for full-canopy (F) vines was applied only at the V– stage, as previous results indicated that timing had no effect. These vines were treated as experimental control. To prevent carry-over effects, new vines were used in 2016–2017. The trimming levels, phenological stages, and corresponding treatments for both seasons are summarized in Table 1.

3. Berry sample and analysis

A total of 120 berries per replicate were sampled from randomly chosen clusters on the East and West sides of the canopy. One berry at a time was systematically collected from the top, middle, and bottom positions of each cluster. The collected berries were placed into sample bags, transported to the laboratory in an insulated container, and stored at –20 °C until analysis.

Total soluble solids (TSS, measured in °Brix) were analysed using a digital refractometer (PAL-1; Atago Inc., USA).

Anthocyanins and total phenols: Fifty frozen berries, were thawed overnight at 4 °C. The samples were homogenized for 30 seconds using a Breville™ coffee grinder (New Zealand). Any material sticking to the grinder's shaft was removed, and the sample was further homogenized for an additional 15 seconds to ensure thorough breakdown of seeds and skins. After homogenization, 1.0 g subsample of the berry mixture was placed into a pre-weighed 15 mL centrifuge tube for extraction. Extraction followed the method of Iland (2000), in which 10 mL of ethanol-water solution (50 % v/v, adjusted to pH 2.0) is added to the subsample. Tubes were inverted every 10 minutes during a one-hour extraction period to facilitate compound diffusion.

TABLE 1. Canopy trimming treatments applied in 2015–2016 and 2016–2017 growing seasons, showing different levels of leaf area removal (full canopy, half canopy, and quarter canopy) and the corresponding phenological stages at which trimming occurred. F, H, and Q represent full canopy (control), ~50 % canopy removal, and ~75 % canopy removal, respectively.

Season	Trimming level	Pre-veraison (V–, E-L 34)	Veraison (V, E-L 35)	Post-veraison (V+, E-L 36)
2015–2016	Full canopy (F)	FV–	FV	FV+
	Half canopy (H)	HV–	HV	HV+
2016–2017	Full canopy (F)	FV–	-	-
	Half canopy (H)	HV–	HV	HV+
	Quarter canopy (Q)	QV–	QV	QV+

The samples were then centrifuged at 1,095 g for 5 minutes, and 1.0 mL of the resulting supernatant was incubated for three hours in 10 mL of 1 N HCl in a 1 cm path-length methacrylate cuvette. Anthocyanin concentration (mg/g) and total phenolic content (mg/g) were measured spectrophotometrically using a UV-1800 spectrophotometer (Shimadzu Corporation, Kyoto, Japan) at wavelengths of 520 nm and 280 nm, respectively.

Tannins: The concentration of tannins in grape seeds and skins was determined using a methylcellulose precipitation (MCP) assay, with results expressed in milligrams per gram (mg/g) of epicatechin equivalents (Mercurio *et al.,* 2010; Sarneckis *et al.,* 2006). Absorbance at 280 nm was measured using a UV-1800 spectrophotometer (Shimadzu Corporation, Kyoto, Japan) with methacrylate disposable cuvettes (1 cm path length) containing supernatants from both test and control samples. Deionized water served as the blank. A standard curve was generated using aqueous (–)-epicatechin solutions (Sigma-Aldrich) at concentrations of 0, 25, 50, 75, 100, and 120 µg/L.

Supporting data from previous study: As this study is a continuation of Assefa *et al.* (2024), additional data on vine physiological, vegetative, and yield responses confirming that the canopy treatments were effectively established are reported in that publication. These include measurements of leaf area and pruning weight, which were used to quantify the severity of canopy reduction, as well as assessments of cluster exposure. Grapevine physiological performance was evaluated through measurements of leaf chlorophyll concentration and stomatal conductance. Furthermore, basic fruit chemistry parameters (pH, titratable acidity (TA), and yeast-assimilable nitrogen (YAN)), yield components, and root carbohydrate reserves were assessed to understand the broader impacts of shoot trimming. These data demonstrated that the leaf area-to-fruit weight (LA:FW) ratio was successfully reduced and that the treatments were physiologically meaningful.

4. Statistical analysis

Data were analysed using analysis of variance (ANOVA), and treatment means were separated with Fisher's unprotected least significant difference (LSD) test at a significance level of $p < 0.05$ (Saville, 2003). Exponential three-parameter growth models ($y = a + br^x$) were fitted for Marlborough and Central Otago, while linear curves were used for Canterbury to estimate the days required to reach target TSS concentration, consistent with the approach described in Assefa *et al.* (2024). The selection of these models was based on the observed patterns of total soluble solids (TSS) progression at each location. Regression analyses determined the days required to reach site-specific TSS concentration targets: 18 °Brix (10 % alcohol) in Marlborough, 20 °Brix (11 % alcohol) in Central Otago, and 16 °Brix (8.9 % alcohol) in Canterbury. These targets reflected local conditions, such as pre-harvest wet and cold weather in Canterbury, which limited ripening to 16 °Brix, and Central Otago's earlier 18.8 °Brix, necessitating a 20 °Brix target compared with Marlborough. Phenolic concentrations (anthocyanin, tannin, and total phenols) were interpolated at these TSS concentrations. Additionally, the rate of anthocyanin accumulation during the initial phase (before levelling off) was assessed to identify treatment-specific differences. Mean separation was also conducted for days to reach 12 °Brix and anthocyanin concentration at 12 °Brix in 2017. Statistical analyses were conducted using the GenStat 18 software package (VSN International Ltd, UK). All Figures were plotted in Microsoft Excel 365.

RESULTS

1. Total soluble solids

Figure 1 shows the effect of a reduced leaf area-to-fruit weight (LA:FW) ratio, achieved through shoot trimming at various berry developmental stages, on total soluble solids (TSS; *i.e.*, sugar) accumulation. Trimming slowed sugar accumulation (see Table 2), resulting in lower TSS concentrations due to the reduced LA:FW ratio, consistent with findings reported by Assefa *et al.* (2024).

2. Anthocyanins

Early trimming consistently reduced anthocyanin accumulation in Marlborough and Central Otago ($p < 0.05$), while its effect in Canterbury varied by season (Figure 2). In Marlborough, anthocyanins at harvest in HV– vines (similar to HV) were 25 % lower than FV– in 2016, and 22 % lower in 2017. QV– vines showed the greatest reduction (–37 % *vs* FV–). In Central Otago, anthocyanins in HV vines were 19 % lower than FV in 2016, and 21 % lower in 2017.

QV– vines accumulated the least anthocyanins (–28 %). At 18 °Brix and 20 °Brix, QV– berries had 30 % and 15 % lower anthocyanins than FV– in Marlborough and Central Otago, respectively (Table 2). In Canterbury, anthocyanins showed no difference in 2016 due to low yield (see (Assefa *et al.,* 2024) for yield data).

In 2017, increased trimming severity (Q) reduced anthocyanins by 28 % in HV– and 24 % in HV. QV– vines had the lowest anthocyanins (–30 %). At 16 °Brix, QV– berries had 19 % lower anthocyanins (Table 2).

Across sites and seasons, HV+ (2016 & 2017) and QV+ (2017) had similar anthocyanin concentration to control vines, (Figure 2). Anthocyanins: TSS ratio confirmed that HV+ and QV+ berries retained high colour at similar sugar concentrations, unlike QV–, QV, HV–, and HV (Figure 3). The lower anthocyanin concentration plateau in early trimmed vines (Figure 2, season 2017) suggests reduced accumulation rates at all sites (Table 3). The stronger reduction in QV– *vs* HV– vines indicates that both timing and severity influenced anthocyanin accumulation.

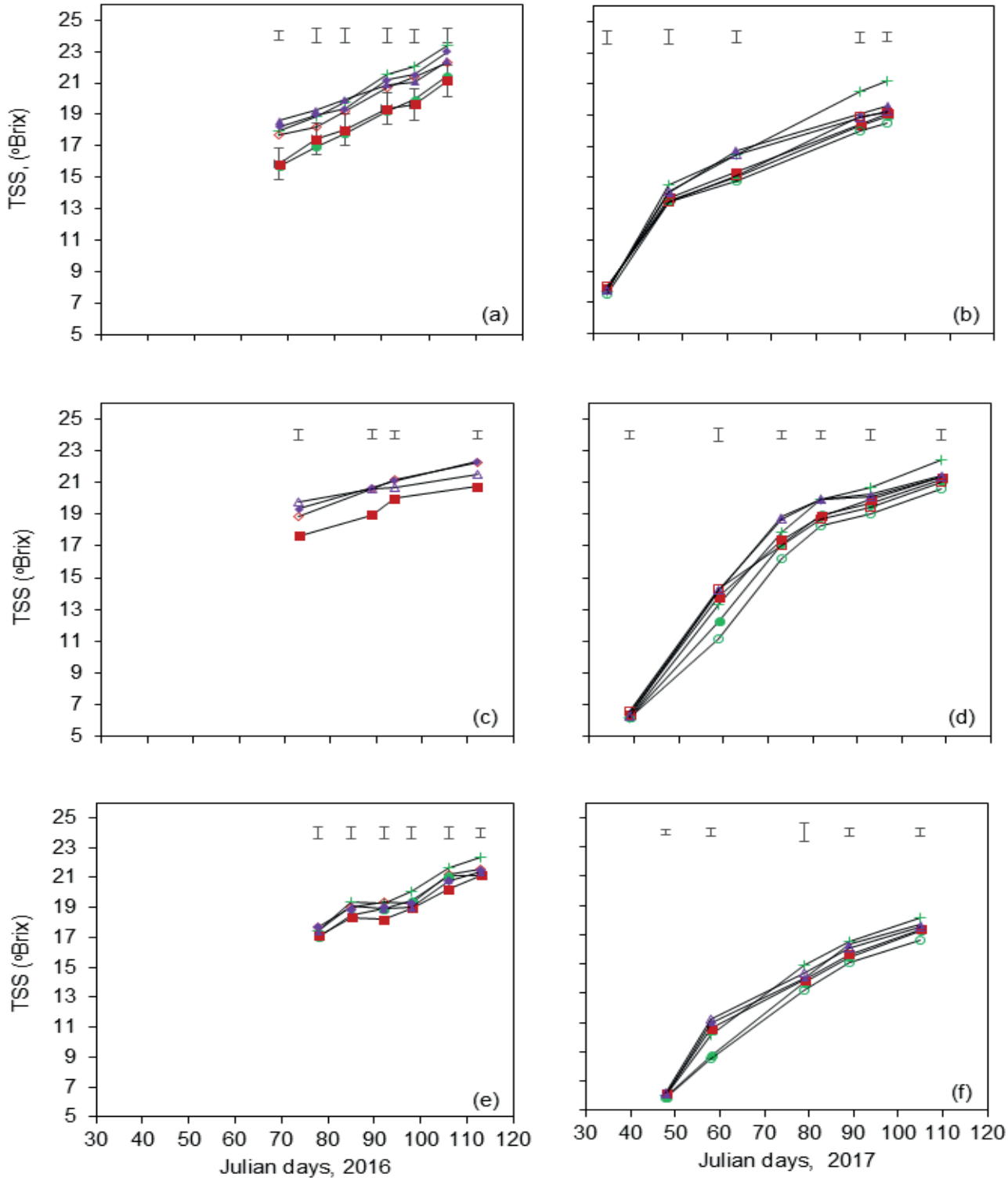


FIGURE 1. Total soluble solids (TSS) at Marlborough (a, b), Central Otago (c, d), and Canterbury (e, f) as affected by trimming levels and trimming time. FV– (+); FV (◇); FV+ (◆); HV– (●); HV (■); HV+ (▲); QV (○); QV– (□) and QV+ (△). F = Full canopy, H = Half canopy, Q = Quarter canopy; V– = Pre-veraison, V = Veraison, V+ = Post-veraison. Error bars at each time point indicate least significant differences (LSD) for Fisher's unprotected LSD ($p < 0.05$).

TABLE 2. Response of phenolic compounds at target sugar (°Brix) concentrations, as affected by trimming height and trimming time in the 2016–2017 season.

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}	73de	< 0.001	6.6
Anthocyanins (mg/g, FW)	0.83^{a}	0.71^{b}	0.72^{b}	0.86^{a}	0.58^{c}	0.70^{b}	0.83^{a}	< 0.001	0.03
Seed tannins (mg/g, DW)	95^{ab}	89^{d}	93^{bcd}	99^{a}	92^{cd}	92^{cd}	97^{ab}	0.006	5.2
Skin tannins (mg/g, DW)	23^{ab}	19^{c}	22^{abc}	23^{a}	20^{c}	21^{bc}	22^{ab}	0.005	2.2
Total phenols (AU/g)	1.06^{a}	0.96^{bc}	0.95^{bc}	1.03^{ab}	0.92^{c}	0.97^{abc}	1.01^{abc}	0.062	0.10
Central Otago									
DOY at 20 °Brix	87^{d}	95^{bc}	93^{c}	87^{d}	100^{a}	98^{ab}	88^{d}	< 0.001	5
Anthocyanins (mg/g, FW)	0.77^{a}	0.55^{b}	0.64^{b}	0.80^{a}	0.64^{b}	0.65^{b}	0.80^{a}	< 0.001	0.07
Seed tannins (mg/g, DW)	122^{ab}	120^{ab}	123^{ab}	126^{a}	118^{b}	119^{ab}	127^{a}	0.134	7.2
Skin tannins (mg/g, DW)	15.6	15.6	14.8	17.1	15.0	15.7	16.3	0.551	2.5
Total phenols (AU/g)	0.92^{ab}	0.86^{abc}	0.83^{c}	0.92^{a}	0.81^{c}	0.84^{bc}	0.89^{abc}	0.052	0.08
Canterbury									
DOY at 16 °Brix	89^{d}	94^{b}	93^{bc}	91^{cd}	97^{a}	-	91^{cd}	< 0.001	2.4
Anthocyanins (mg/g, FW)	0.71^{a}	0.61^{b}	0.58^{b}	0.75^{a}	0.58^{b}	-	0.72^{a}	0.001	0.09
Seed tannins (mg/g, DW)	114	110	113	110	107	-	107	0.587	9.8
Skin tannins (mg/g, DW)	32	30	30	34	31	-	32	0.467	4.5
Total phenols (AU/g)	1.30	1.28	1.28	1.31	1.29	-	1.29	0.967	0.07

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.

3. Seed and skin tannins

Seed and skin tannin concentrations remained largely unaffected by treatments in both seasons (Figure 4 and 5, respectively). In 2016, seed and skin tannin concentrations remained relatively stable from the first sampling date through harvest. In contrast, in 2017, tannin concentrations showed a decline over time, likely due to earlier sampling during berry development. Across all trial sites, reducing the LA:FW ratio did not affect seed or skin tannin concentrations. In 2016, concentrations were similar across treatments, except Marlborough, where FV– and HV+ vines temporarily exhibited higher seed tannins at the second sampling. Similarly, in 2017, most treatments showed no impact on tannin concentrations, with a few exceptions. Exceptions include 1) late trimming (like controls) resulted in slightly higher seed tannins in Marlborough during pre-harvest and harvest, 2) inconsistent skin tannin differences appeared at the second and third sampling dates at Central Otago, 3) brief, irregular variations in skin tannins occurred at the second sampling in Canterbury without a clear pattern. In Marlborough, HV+ and QV+ vines had higher seed and skin tannin concentrations at 18 °Brix, similar to controls. However, at 20 °Brix (Central Otago) and 16 °Brix (Canterbury), tannin concentrations did not differ among treatments (Table 2).

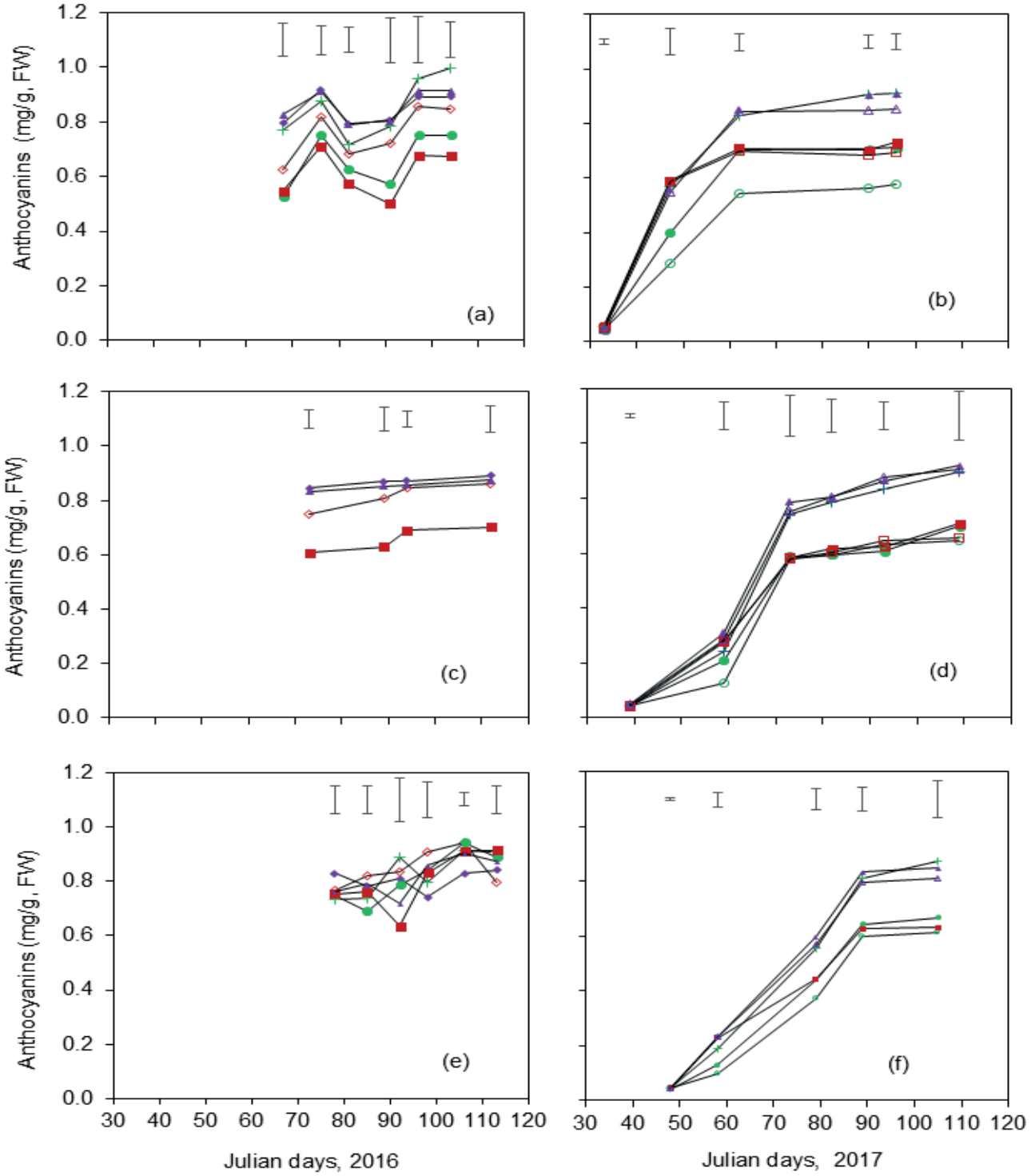


FIGURE 2. Anthocyanins (mg/g) accumulation at Marlborough (a, b), Central Otago (c, d), and Canterbury (e, f) as affected by trimming levels and trimming time. FV– (+); FV (◇); FV+ (◆); HV– (●); HV (■); HV+ (▲); QV (○); QV– (□) and QV+ (△). F = Full canopy, H = Half canopy, Q = Quarter canopy; V– = Pre-veraison, V = Veraison, V+ = Post-veraison. Error bars at each time point indicate least significant differences (LSD) for Fisher's unprotected LSD ($p < 0.05$).

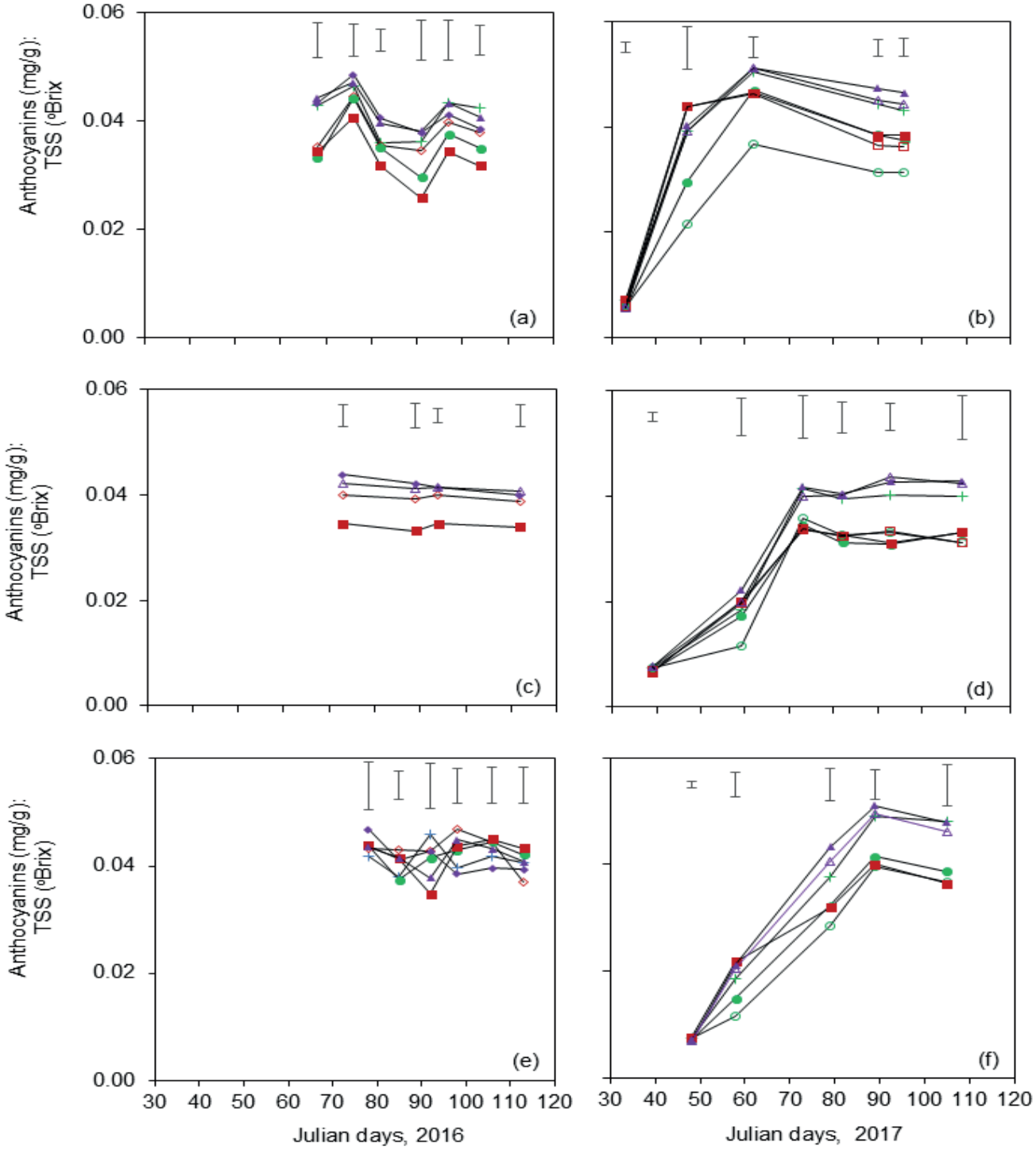


FIGURE 3. Anthocyanins (mg/g) to TSS (°Brix) ratio at Marlborough (a, b), Central Otago (c, d), and Canterbury (e, f) as affected by trimming levels and trimming time. FV– (+); FV (◇); FV+ (◆); HV– (●); HV (■); HV+ (▲); QV (○); QV– (□) and QV+ (△). F = Full canopy, H = Half canopy, Q = Quarter canopy; V– = Pre-veraison, V = Veraison, V+ = Post-veraison. Error bars at each time point indicate least significant differences (LSD) for Fisher's unprotected LSD ($p < 0.05$).

TABLE 3. Rate of anthocyanin accumulation (mg/g/day) in the initial phase +, mean separation for days to reach 12 °Brix and for the concentration of anthocyanin at 12 °Brix in 2017.

	Marlborough				Central Otago				Canterbury			
Trimming treatments	Rate (mg/g/day)	Rate difference* (%)	DOY at 12 °Brix	[anthocyanin] at 12 °Brix	Rate (mg/g/day)	Rate difference* (%)	DOY at 12 °Brix	[anthocyanin] at 12 °Brix	Rate (mg/g/day)	Rate difference* (%)	DOY at 12 °Brix	[anthocyanin] at 12 °Brix
FV–	0.027^{a}	-	42^{bc}	0.469^{a}	0.020^{a}	-	53^{c}	0.374^{a}	0.019^{a}	-	71^{bc}	0.412^{ab}
HV–	0.023^{b}	–15	44^{ab}	0.390^{b}	0.016^{b}	–22	55^{b}	0.259^{c}	0.016^{c}	–14	75^{a}	0.371^{bc}
HV	0.022^{b}	–16	43^{abc}	0.418^{ab}	0.016^{b}	–22	53^{c}	0.288b^{c}	0.014^{b}	–24	72^{b}	0.354^{c}
HV+	0.028^{a}	+4	42^{c}	0.451^{a}	0.022^{a}	+6	52^{cd}	0.339^{ab}	0.019^{a}	+4	71^{bc}	0.434^{a}
QV–	0.017^{c}	–35	45^{a}	0.298^{c}	0.016^{b}	–23	58^{a}	0.252^{c}	0.014^{b}	–24	77^{a}	0.352^{c}
QV	0.022^{b}	–16	44^{ab}	0.423^{ab}	0.016^{b}	–24	52^{cd}	0.246^{c}	-	-	-	-
QV+	0.028^{a}	+4	42^{c}	0.462^{a}	0.021^{a}	+1	52^{cd}	0.337^{ab}	0.018^{a}	+1	70^{c}	0.40^{9ab}
p-value	< 0.001		0.047	< 0.001	0.010		< 0.001	< 0.001	< 0.001		< 0.001	0.019
LSD (5 %)	0.0024		2.3	0.053	0.0042		1.806	0.057	0.0025		1.858	0.054

+ Initial phase – linear rate through data points prior to the plateau of response function (where anthocyanin accumulation levels-off, Figure 2). * Percent difference between trimming treatments and the control, FV–.

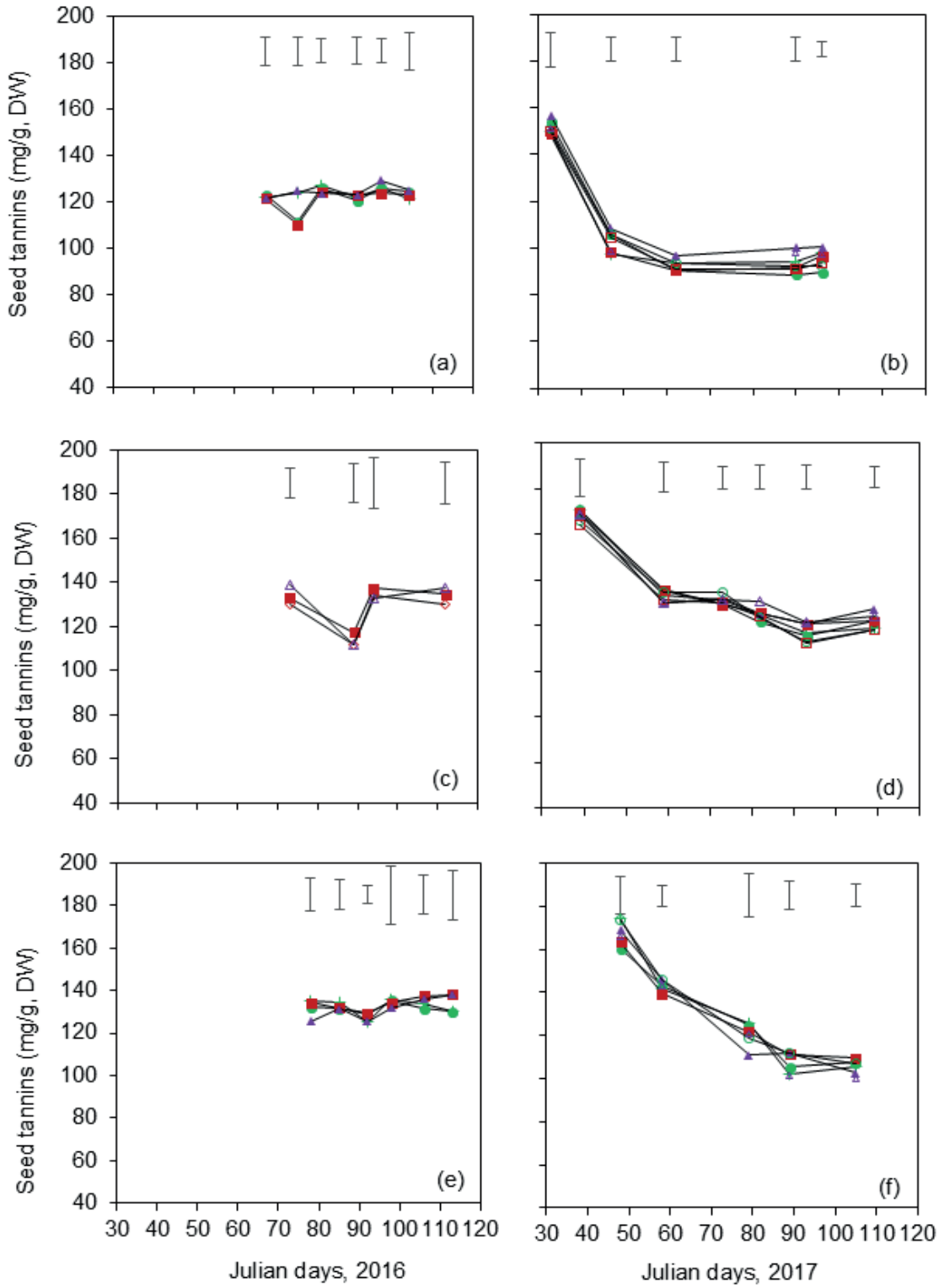


FIGURE 4. Seed tannins at Marlborough (a, b), Central Otago (c, d), and Canterbury (e, f) as affected by trimming levels and trimming time. FV– (+); FV (◇); FV+ (◆); HV– (●); HV (■); HV+ (▲); QV (○); QV– (□) and QV+ (△). F = Full canopy, H = Half canopy, Q = Quarter canopy; V– = Pre-veraison, V = Veraison, V+ = Post-veraison. Error bars at each time point indicate least significant differences (LSD) for Fisher's unprotected LSD ($p < 0.05$).

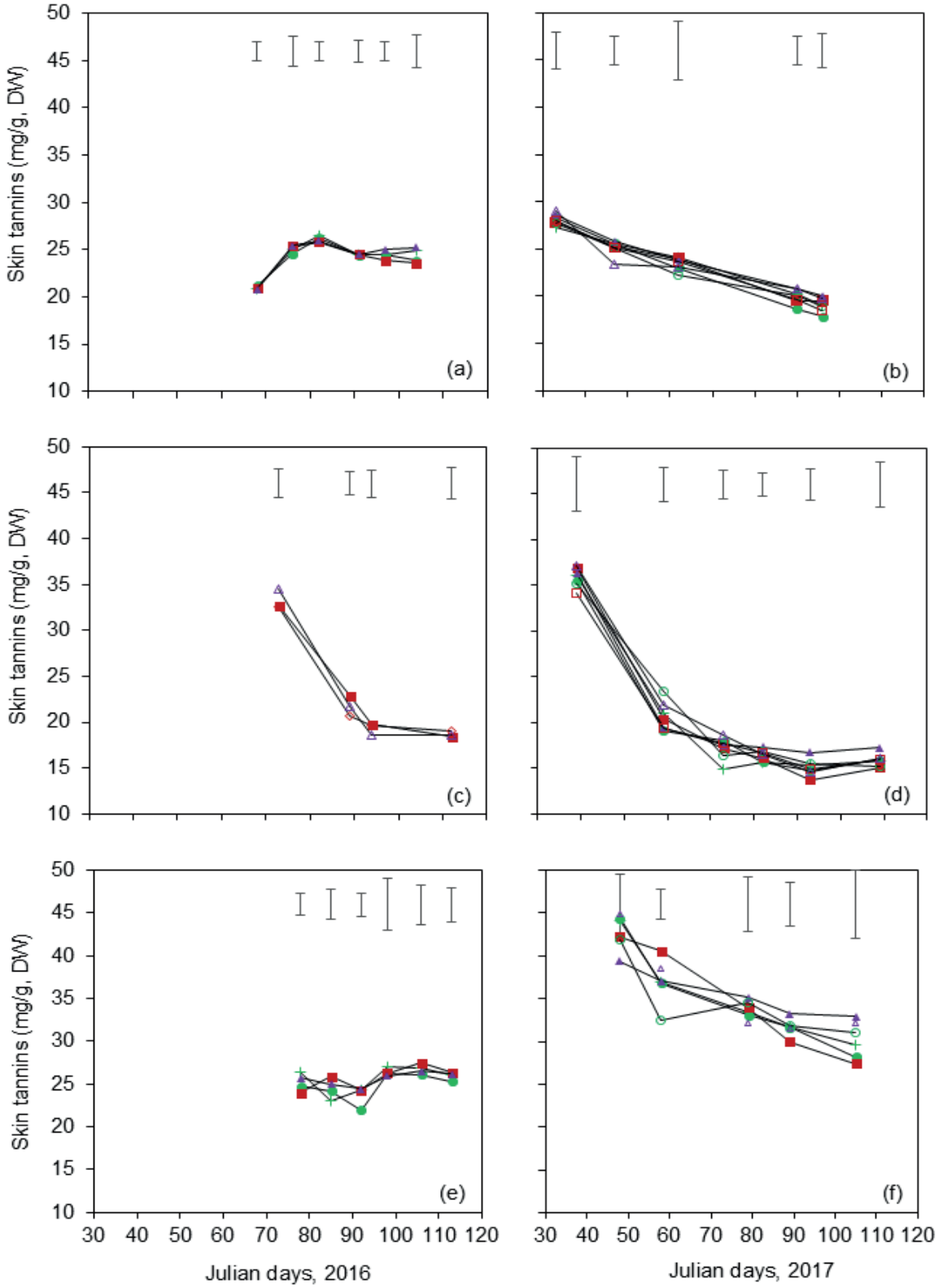


FIGURE 5. Skin tannins at Marlborough (a, b), Central Otago (c, d), and Canterbury (e, f) as affected by trimming levels and trimming time. FV– (+); FV (◇); FV+ (◆); HV– (●); HV (■); HV+ (▲); QV (○); QV– (□) and QV+ (△). F = Full canopy, H = Half canopy, Q = Quarter canopy; V– = Pre-veraison, V = Veraison, V+ = Post-veraison. Error bars at each time point indicate least significant differences (LSD) for Fisher's unprotected LSD ($p < 0.05$).

4. Total phenols

Trimming had no effect on total phenols overall (Figure 6). However, at 18 °Brix and 20 °Brix, HV+ and QV+ (similar to controls) had higher phenols than QV–, QV, HV–, and HV in Marlborough and Central Otago (Table 2). No differences were observed at Canterbury.

DISCUSSION

1. Total soluble solids

Reduced LA:FW ratio via shoot trimming significantly lowered sugar accumulation in berries (Figure 2 and Table 2). For additional details, see Assefa *et al.* (2024).

2. Anthocyanin

2.1. Pre-veraison trimming

Except in Canterbury (2016), where low yield resulted in minimal differences in LA:FW ratios (Assefa *et al.,* 2024), early trimming reduced anthocyanin accumulation at the other two sites in 2016 and 2017 (Figure 2). Assessment of the rate of accumulation prior to the plateau in anthocyanin concentration (initial phase) revealed that the reduced maximum levels observed in early trimmed vines (Figure 2) were attributable to a lower rate of anthocyanin accumulation (Table 2), likely resulting from reduced source capacity and limited sugar availability due to early canopy reduction. Previous severe leaf area reduction studies such as –83 % in Jingyan (a Chinese red table grape) at E-L 29 (Wu *et al.,* 2013), –83 % (0.67 m²/kg) at E-L 34 in Cabernet-Sauvignon and –71 % (0.33 m²/kg) at E-L 34 in Sangiovese (Bobeica *et al.,* 2015), caused 99.2 %, 74.8 % and 93.5 % reductions in anthocyanins, respectively. Likewise, approximately 50 % leaf area loss such –54 % (0.8 m²/kg) at E-L 35 in De Chaunac (Reynolds & Wardle, 1989), –48 % (0.51 m²/kg) at E-L 19 in Cabernet-Sauvignon (Poni & Giachino, 2000), 44 % (0.71 m²/kg) at E-L 34 in Grenache (Toda & Balda, 2013) and –50 % (0.6 m²/kg) at E-L 34 in Sangiovese (Pastore *et al.,* 2011) caused 25 %, 55 %, 10 % and 17 % reductions in anthocyanins at harvest, respectively. These studies also reported significant reductions in sugar accumulation at harvest due to early source limitation.

The mechanism behind reduced anthocyanin concentrations under source limitation via leaf removal has been elucidated in (Wu *et al.,* 2013), where two leaf area treatments combined with shoot girdling were applied at E-L 29 for the Jingyan variety: 2 leaves per cluster (2 L) and 12 leaves per cluster (12 L). The study showed that at maturity, total anthocyanin accumulation in the 12 L treatment (0.66 mg/g FW) was significantly higher than in the 2 L treatment (0.0053 mg/g FW). Proteomic profiling of Jingyan grape skins in the 2 L treatment revealed that only 20 % of identified proteins were upregulated, while 80 % were downregulated. Key enzymes involved in anthocyanin biosynthesis were among those downregulated, including chalcone synthase (CHS), which catalyses the first step in the flavonoid biosynthetic pathway; dihydroflavonol reductase (DFR), which converts dihydroflavonols into anthocyanidins; and UDP-glucose: flavonoid-3-O-glucosyltransferase (UFGT), the enzyme responsible for anthocyanidin stabilization and visual colour development. This downregulation may be attributed to a lack of glucose, a crucial substrate for anthocyanin production, highlighting the essential role of sugar in the biosynthesis of stable anthocyanin molecules (Larronde *et al.,* 1998).

These findings align with the report of (Bobeica *et al.,* 2015) that, under carbon-limited conditions, the accumulation of primary metabolites is prioritized over secondary metabolite production. Similarly, Palliotti *et al.* (2013) proposed that source limitation due to leaf removal (at E-L 35), which reduces the source-to-sink ratio, might downregulate genes involved in starch and sugar production, breakdown, and transport in berries. Consequently, the proteomic analysis and explanation provided by (Wu *et al.,* 2013) (early leaf removal at E-L 19) may also apply under later, severe source limitations, such as those occurring at E-L 34 (V–) and E-L 35 (V).

2.2 Post-veraison trimming

Irrespective of trial sites and seasons, late trimming (V+), regardless of canopy size, resulted in higher berry pigmentation, reflected in higher anthocyanin concentrations, comparable to the control. This suggests that trimming time plays a crucial role. By the time shoot trimming was applied (V+), anthocyanin development was already advanced (Figure 2), and berries could access additional photoassimilates from retained lateral shoots, which were removed post-veraison, late in the season.

Findings in Pinot noir align with previous studies in Sangiovese, where leaf area removal –39 % (1.08 m²/kg) at E-L 36 (Poni *et al.,* 2013), 36 % (1.13 m²/kg) at E-L 37 (Palliotti *et al.,* 2013), 58 % (0.39 m²/kg) at E-L 37 (Filippetti *et al.,* 2015), and 40 % (0.8 m²/kg) at E-L 37 (Valentini *et al.,* 2019) had no effect on anthocyanin accumulation despite reducing berry sugar concentration. These results reinforce the strong association between anthocyanins and sugar, particularly early in the season (Filippetti *et al.,* 2015; Guidoni *et al.,* 2008). In this study, HV+ and QV+ berries maintained anthocyanin concentrations similar to the control while reducing total soluble solids.

Late source limitation also tended to maintain anthocyanin-to-sugar ratios similar to the control (Figure 3). When 18 °Brix (Marlborough) and 20 °Brix (Central Otago) were reached, post-veraison shoot trimming increased anthocyanin concentrations by 14 % to 31 % (depending on the site) compared to the earliest and most severely source-limited berries (QV–).

3. Skin and seed tannins and total phenols

Condensed tannins contribute to the astringent and bitter properties of wines and are extracted from grape skins and seeds (Chira *et al.,* 2009; Sun *et al.,* 2013). Skin tannins were found to be lower in concentration than seed tannins, consistent with previous studies

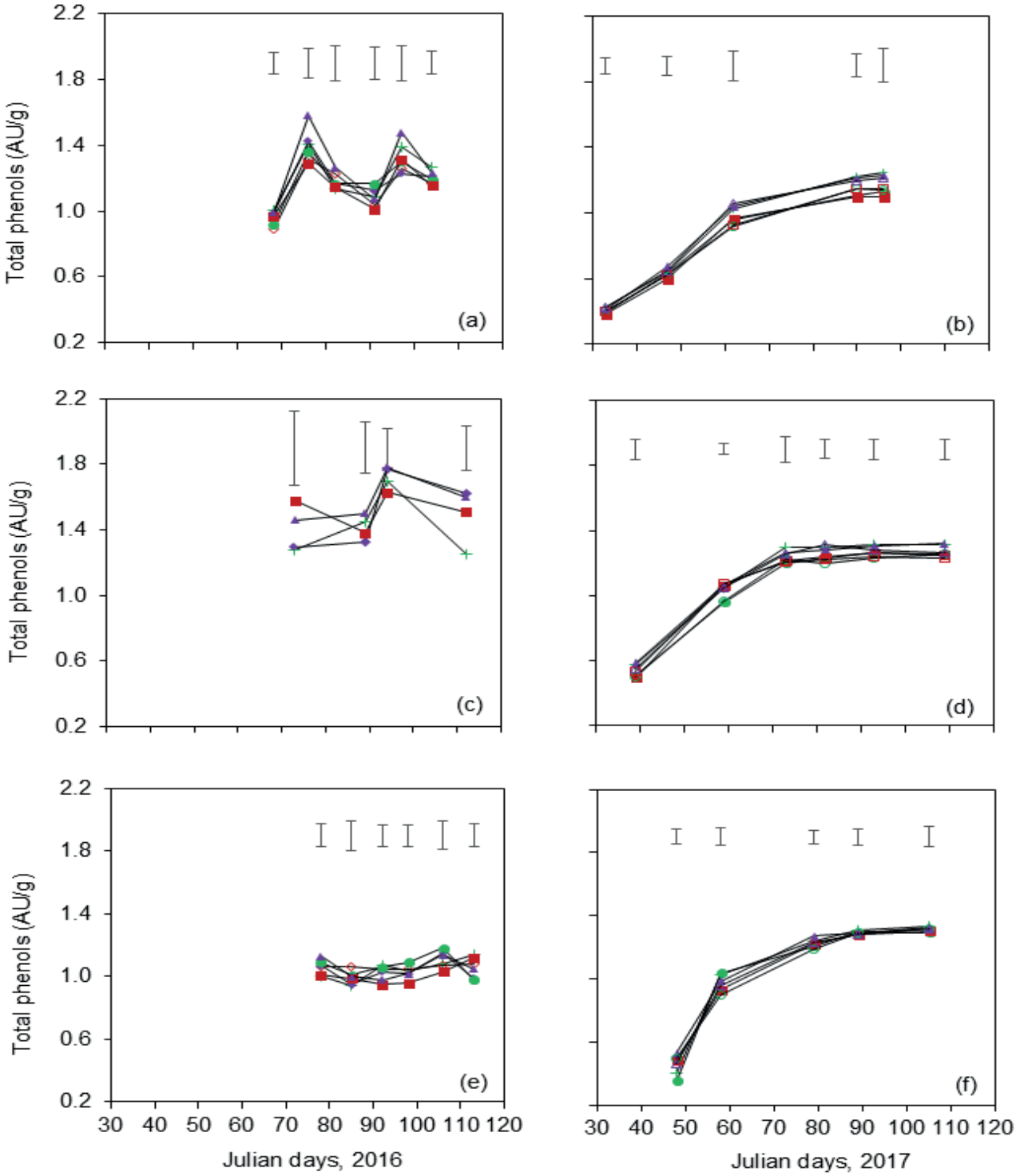


FIGURE 6. Total phenols at Marlborough (a, b), Central Otago (c, d), and Canterbury (e, f) as affected by trimming levels and trimming time. FV– (✚); FV (◇); FV+ (◆); HV– (●); HV (■); HV+ (▲); QV (○); QV– (□) and QV+ (△). F = Full canopy, H = Half canopy, Q = Quarter canopy; V– = Pre-veraison, V = Veraison, V+ = Post-veraison. Error bars at each time point indicate least significant differences (LSD) for Fisher's unprotected LSD ($p < 0.05$).

(Bonada *et al.,* 2015; Casassa *et al.,* 2015; Chira *et al.,* 2009; Obreque-Slier *et al.,* 2010; Sun *et al.,* 2013). The evolution of seed and skin tannins during ripening showed minimal change in 2016, likely due to late-season sampling. However, in 2017, both seed tannins (Kallithraka *et al.,* 2006; Kennedy *et al.,* 2001; Obreque-Slier *et al.,* 2010), and skin tannins (Bordiga *et al.,* 2011; Obreque-Slier *et al.,* 2010) showed a declining trend from ripening through to harvest. A reduced LA:FW ratio, applied at different developmental stages, had no effect on harvest seed or skin tannin concentrations. This aligns with findings from Filippetti *et al.* (2015) and Palliotti *et al.* (2013), where canopy reductions of 58 % (0.39 m²/kg) and 36 % (1.13 m²/kg), respectively, in Sangiovese did not alter tannin concentrations. This stability is likely due to tannin accumulation peaking before the earliest treatment was applied, and the results therefore indicate that season plays an important role in resulting concentrations irrespective of canopy manipulations. However, grape tannins (Figures 4 and 5) and acid parameters (Assefa *et al.,* 2024) remained stable across treatments, even at lower sugar concentrations. This stability supports the potential for producing high-quality, lower-alcohol red wine, as tannins and acidity contribute to mouthfeel and balance (Ewing-Mulligan & McCarthy, 2005). Moreover, free anthocyanins, the primary pigments in red wines, are inherently unstable. Colour stability is improved through multiple reactions, including acylation, but also anthocyanin polymerization with tannins (Conde *et al.,* 2007; Jackson, 2014; Zimman & Waterhouse, 2004). The unaltered tannin concentrations across treatments supports the idea of colour retention as wines age, particularly in HV+ and QV+ grapes destined for lower-alcohol wines, which maintained high anthocyanin concentrations at lower soluble solids. This is particularly significant given the naturally light colour of Pinot noir grapes (Parley *et al.,* 2001).

Total phenol concentrations remained largely unchanged across both seasons, potentially allowing to produce typical, but lower-alcohol, Pinot noir, as sugar content varied while phenols remained stable (particularly in QV+ and HV+) (Figure 6).

4. Practical significance

Both QV+ and HV+ vines maintained tannin concentrations and produced highly coloured grapes, similar to the control. However, from a practical perspective, only post-veraison half-canopy reduction (HV+) appears to be a viable strategy for adapting to warming climates and producing lower-alcohol wines. Unlike QV+, which failed to replenish carbohydrate reserves under the environmental conditions of our trials, HV+ did not compromise carbohydrate reserves (Assefa *et al.,* 2024), which are essential for vineyard longevity. Moreover, HV+ not only effectively reduced sugar concentrations while preserving anthocyanin and tannin levels but also maintained acidity, pH, and yeast-assimilable nitrogen (Assefa *et al.,* 2024).

CONCLUSION

This study revealed the critical role of the timing of trimming in managing anthocyanin accumulation. Early trimming consistently reduced berry anthocyanin concentrations across all sites and seasons, whereas late trimming (HV+ and QV+) preserved colour comparable to the control. Late source limited berries-maintained anthocyanin-to-sugar ratios and anthocyanin concentrations at target TSS concentrations like the control: key attributes for Pinot noir, a variety known for its light-coloured wines. Total phenols remained consistent across seasons, and seed and skin tannins were unaffected by trimming. This led to a desynchronisation of phenolics from sugar concentrations in HV+ and QV+ treatments, which supports the potential for producing lower-alcohol Pinot noir wines without compromising phenolic and colour attributes. Among the treatments tested, halving the canopy after veraison (HV+) was the most effective in balancing reduced sugar accumulation with the preservation of anthocyanin levels and root carbohydrate reserves. These findings position HV+ as a promising approach to address climate-related challenges while meeting the growing demand for lower-alcohol wines.

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REFERENCES

Amerine, M. A., & Winkler, A. J. (1963). *California wine grapes: Composition and quality of their musts and wines* (Vol. B0794). University of California, Division of Agricultural Sciences, Agricultural Experiment Station.

Assefa, M. K., Creasy, G. L., Hofmann, R. W., & Parker, A. K. (2024). 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. *OENO One*, *58*(4). https://doi.org/10.20870/oeno-one.2024.58.4.8225

Bobeica, N., Poni, S., Hilbert, H., Renaud, C., Gomès, E., Delrot, S., & Dai, Z. (2015). Differential responses of sugar, organic acids and anthocyanins to source-sink modulation in Cabernet Sauvignon and Sangiovese grapevines. *Frontiers in Plant Science*, *6*(382), 1–14. https://doi.org/10.3389/fpls.2015.00382

Bonada, M., Jeffery, D. W., Petrie, P. R., Moran, M. A., Sadras, V. O. (2015). Impact of elevated temperature and water deficit on the chemical and sensory profiles of Barossa Shiraz grapes and wines. *Australian Journal of Grape and Wine Research*, *21*, 240-253. https://doi.org/10.1111/ajgw.12142

Bordiga, M., Travaglia, F., Locatelli, M., Coisson, J. D., & Arlorio, M. (2011). Characterization of polymeric skin and seed proanthocyanidins during ripening in six Vitis vinifera L. cv. *Food Chem.*, *127*, 180–187. https://doi.org/10.1016/j.foodchem.2010.12.141

Bragato Research Institute. (2024). *Have you thought about trialling low alcohol wine this vintage?* [Https://bri.co.nz/2024/12/18/trialling-low-alcohol-wine/].

Cameron, W., Petrie, P. R., & Barlow, E. W. R. (2022). The effect of temperature on grapevine phenological intervals: Sensitivity of budburst to flowering. *Agricultural and Forest Meteorology*, *315*, 108841. https://doi.org/10.1016/J.AGRFORMET.2022.108841

Cameron, W., Petrie, P. R., Barlow, E. W. R., Howell, K., Jarvis, C., & Fuentes, S. (2021). A comparison of the effect of temperature on grapevine phenology between vineyards. *OENO One*, *55*(2), 301–320. https://doi.org/10.20870/oeno-one.2021.55.2.4599

Casassa, L. F., Keller, M., & Harbertson, J. F. (2015). Regulated deficit irrigation alters anthocyanins, tannins and sensory properties of Cabernet Sauvignon grapes and wines. *Molecules*, *20*, 7820–7844. https://doi.org/10.3390/molecules20057820

Chira, K., Schmauch, G., Saucier, C., Fabre, S., & Teissedre, P. L. (2009). Grape variety effect on proanthocyanidin composition and sensory perception of skin and seed tannin extracts from Bordeaux wine grapes (Cabernet Sauvignon and Merlot) for two consecutive vintages (2006 and 2007). *J. Agric. Food Chem.*, *57*, 545–553. https://doi.org/10.1021/jf802301g

Conde, C., Silva, P., Fontes, N., Dias, A. C. P., Tavares, R. M., Sousa, M. J., Agasse, A., Delrot, S., & Gerós, H. (2007). Biochemical changes throughout grape berry development and fruit and wine quality. *Food*, *1*.

Cook, B. I., & Wolkovich, E. M. (2016). Climate change decouples drought from early wine grape harvests in France. *Nature Climate Change*, *6*, 715. https://doi.org/10.1038/nclimate2960

Coombe, B. G. (1992). Research on development and ripening of the grape berry. *American Journal of Enology and Viticulture*, *43*(1), 101. https://doi.org/10.5344/ajev.1992.43.1.101

Dai, Z. W., Meddar, M., Renaud, C., Merlin, I., Hilbert, G., Delrot, S., & Gomes, E. (2014). Long-term in vitro culture of grape berries and its application to assess the effects of sugar supply on anthocyanin accumulation. *Journal of Experimental Botany*, *65*(16), 4665–4677. https://doi.org/10.1093/jxb/ert489

Droulia, F., & Charalampopoulos, I. (2021). Future climate change impacts on european viticulture: A review on recent scientific advances. *Atmosphere*, *12*(4), 495. https://doi.org/10.3390/atmos12040495

Ewing-Mulligan, M., & McCarthy, E. (2005). *Wine Style: Using your senses to explore and enjoy wine*. John Wiley and Sons, Inc.

Filippetti, I., Movahed, N., Allegro, G., Valentini, G., Pastore, C., Colucci, E., & Intrieri, C. (2015). Effect of post-veraison source limitation on the accumulation of sugar, anthocyanins and seed tannins in Vitis vinifera cv. Sangiovese berries. *Australian Journal of Grape and Wine Research*, *21*(1), 90–100. https://doi.org/10.1111/ajgw.12115

Guidoni, S., Ferrandino, A., & Novello, V. (2008). Effects of seasonal and agronomical practices on skin anthocyanin profile of Nebbiolo grapes. *American Journal of Enology and Viticulture*, *59*(1), 22. https://doi.org/10.5344/ajev.2008.59.1.22

Hannah, L., Roehrdanz, P. R., Ikegami, M., Shepard, A. V., Shaw, M. R., Tabor, G., Zhi, L., Marquet, P. A., & Hijmans, R. J. (2013). Climate change, wine, and conservation. *Proceedings of the National Academy of Sciences*, *110*(17), 6907–6912. https://doi.org/10.1073/pnas.1210127110

Iland, P. & P. I. W. P. (2000). *Techniques for chemical analysis and quality monitoring during winemaking*. Patrick Iland Wine Promotions.

IPCC. (2021). *Climate Change 2021: The physical science basis: Summary for Policymakers—Contribution of working group I to the sixth assessment report of the Intergovernmental Panel on Climate Change.* (T. F. Stocker, D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, & J. Boschung, Eds.). Cambridge University Press.

Jackson, R. S. (2014). *Wine science. Principles and applications*. Burlington : Elsevier Science.

Kallithraka, S., Tsoutsouras, E., Tzourou, E., & Lanaridis, P. (2006). Principal phenolic compounds in Greek red wines. *Food Chem.*, *99*, 784–793. https://doi.org/10.1016/j.foodchem.2005.07.059

Kennedy, J. A., Hayasaka, Y., Vidal, S., Waters, E. J., & Jones, G. P. (2001). Composition of grape skin proanthocyanidins at different stages of berry development. *J. Agric. Food Chem.*, *49*, 5348–5355. https://doi.org/10.1021/jf010758h

Larronde, F., Krisa, S., Decendit, A., Chèze, C., Deffieux, G., & Mérillon, J. M. (1998). Regulation of polyphenol production in Vitis vinifera cell suspension cultures by sugars. *Plant Cell Reports*, *17*(12), 946–950. https://doi.org/10.1007/s002990050515

Lecourieux, F., Kappel, C., Lecourieux, D., Serrano, A., Torres, E., Arce-Johnson, P., & Delrot, S. (2014). An update on sugar transport and signalling in grapevine. *Journal of Experimental Botany*, *65*(3), 821–832. https://doi.org/10.1093/jxb/ert394

Lee, J. (2010). Degradation kinetics of grape skin and seed proanthocyanidins in a model wine system. *Food Chem.*, *123*, 51-56. https://doi.org/10.1016/j.foodchem.2010.03.126

Macheix, J., Sapis, J., Fleuriet, A., & Lee, C. Y. (1991). Phenolic compounds and polyphenoloxidase in relation to browning in grapes and wines. *Critical Reviews in Food Science and Nutrition*, *30*(4), 441–486. https://doi.org/10.1080/10408399109527552

Mercurio, M. D., Dambergs, R. G., Cozzolino, D., Herderich, M. J., & Smith, P. A. (2010). Relationship between red wine grades and phenolics. 1. Tannin and total phenolics concentrations. Journal of Agricultural and Food Chemistry, 58(23), 12313–12319. https://doi.org/10.1021/jf103230b

Obreque-Slier, E., Peña-Neira, A., Lopez-Solís, R., Zamora-Marín, F., Ricardo-da Silva, M. A., & Laureano, O. (2010). Comparative study of the phenolic composition of seeds and skins from Carménère and Cabernet Sauvignon grape varieties (Vitis vinifera L.) during ripening. *J. Agric. Food Chem.*, *58*, 3591–3599. https://doi.org/10.1021/jf904314u

Palliotti, A., Panara, F., Silvestroni, O., Lanari, V., Sabbatini, P., Howell, G. S., Gatti, M., & Poni, S. (2013). Influence of mechanical postveraison leaf removal apical to the cluster zone on delay of fruit ripening in Sangiovese (Vitis vinifera L.) grapevines. *Australian Journal of Grape and Wine Research*, *19*(3), 369–377. https://doi.org/10.1111/ajgw.12033

Parker, A. K., De CortÁZar-Atauri, I. G., Van Leeuwen, C., & Chuine, I. (2011). General phenological model to characterise the timing of flowering and veraison of Vitis vinifera L. *Australian Journal of Grape and Wine Research*, *17*(2), 206–216. https://doi.org/10.1111/j.1755-0238.2011.00140.x

Parley, A., Vanhanen, L., & Heatherbell, D. (2001). Effects of prefermentation enzyme maceration on extraction and colour stability in Pinot Noir wine. *Australian Journal of Grape and Wine Research*, *7*, 146–152. https://doi.org/10.1111/j.1755-0238.2001.tb00203.x

Pastore, C., Zenoni, S., Fasoli, M., Pezzotti, M., Tornielli, G. B., & Filippetti, I. (2013). Selective defoliation affects plant growth, fruit transcriptional ripening program and flavonoid metabolism in grapevine. *BMC Plant Biology*, *13*, 30. https://doi.org/10.1186/1471-2229-13-30

Pastore, C., Zenoni, S., Tornielli, G. B., Allegro, G., Dal Santo, S., Valentini, G., Intrieri, D., Pezzotti, M., & Filippetti, I. (2011). Increasing the source/sink ratio in Vitis vinifera (cv Sangiovese) induces extensive transcriptome reprogramming and modifies berry ripening. *BMC Genomics*, *12:631*. https://doi.org/10.1186/1471-2164-12-631

Poni, S., & Giachino, E. (2000). Growth, photosynthesis and cropping of potted grapevines (Vitis vinifera L. cv. Cabernet Sauvignon) in relation to shoot trimming. *Australian Journal of Grape and Wine Research*, *6*(3), 216–226. https://doi.org/10.1111/j.1755-0238.2000.tb00182.x

Poni, S., Gatti, M., Bernizzoni, F., Civardi, S., Bobeica, N., Magnanini, E., & Palliotti, A. (2013). Late leaf removal aimed at delaying ripening in cv. Sangiovese: Physiological assessment and vine performance. *Australian Journal of Grape and Wine Research*, *19*(3), 378–387. https://doi.org/10.1111/ajgw.12040

Ramos, M. C., & Martínez de Toda, F. (2020). Variability in the potential effects of climate change on phenology and on grape composition of Tempranillo in three zones of the Rioja DOCa (Spain). *European Journal of Agronomy*, *115*, 126014. https://doi.org/10.1016/j.eja.2020.126014

Reynolds, A. G., & Wardle, D. A. (1989). Effects of Timing and Severity of Summer Hedging on Growth, Yield, Fruit Composition, and Canopy Characteristics of de Chaunac. II. Yield and Fruit Composition. *American Journal of Enology and Viticulture*, *40*(4), 299–308. https://doi.org/10.5344/ajev.1989.40.4.299

Saliba, A. J., Ovington, L. A., & Moran, C. C. (2013). Consumer demand for low-alcohol wine in an Australian sample. *Int.J.Wine Res*, *5*, 1–8. https://doi.org/10.2147/IJWR.S41448

Sarneckis, C. J., Dambergs, R. G., Jones, P., Mercurio, M., Herderich, M. J., & Smith, P. A. (2006). Quantification of condensed tannins by precipitation with methyl cellulose: Development and validation of an optimised tool for grape and wine analysis. Australian Journal of Grape and Wine Research, 12, 39–49. https://doi.org/10.1111/j.1755-0238.2006.tb00042.x

Saville, D. J. (2003). Basic statistics and the inconsistency of multiple comparison procedures. Canadian Journal of Experimental Psychology, 57(3), 167–175. https://doi.org/10.1037/h0087423

Singleton, V. L. (1992). Tannins and the qualities of wines. In R. W. Hemingway & P. E. Laks (Eds.), *Plant polyphenols: Synthesis, properties, significance* (pp. 859–880). Springer US. https://doi.org/10.1007/978-1-4615-3476-1_51

Somers, T. C. (1971). The polymeric nature of wine pigments. *Phytochemistry*, *10*(9), 2175–2186. https://doi.org/10.1016/S0031-9422(00)97215-7

Sun, B., De Sa, M., Leonardo, M., Caldeira, I., Duarte, F. L., & Spranger, I. (2013). Reactivity of polymeric proanthocyanidins toward salivary proteins and their contribution to young red wine astringency. *J. Agric. Food Chem.*, *61*, 939–946. https://doi.org/10.1021/jf303704u

Tiffon-Terrade, B., Simonneau, T., Caffarra, A., Boulord, R., Pechier, P., Saurin, N., Romieu, C., Fumey, D., & Christophe, A. (2023). Delayed grape ripening by intermittent shading to counter global warming depends on carry-over effects and water deficit conditions. *OENO One*, *57*(1), 71–90. https://doi.org/10.20870/oeno-one.2023.57.1.5521

Toda, F. M., & Balda, P. (2013). Delaying berry ripening through manipulating leaf area to fruit ratio. *Vitis*, *52*(4), 171–176. https://doi.org/10.5073/vitis.2013.52.171-176

Trought, M., & Agnew, R. (2013). *Vineyard management to produce reduced alcohol wines: Final report*. Plant & Food Research Marlborough, New Zealand.

Valentini, G., Allegro, G., Pastore, C., Colucci, E., & Filippetti, I. (2019). Post-veraison trimming slow down sugar accumulation without modifying phenolic ripening in Sangiovese vines. *Journal of the Science of Food and Agriculture*, *99*(3), 1358–1365. https://doi.org/10.1002/jsfa.9311

Vitrac, X., Larronde, F., Krisa, S., Decendit, A., Deffieux, G., & Merillon, J. M. (2000). Sugar sensing and Ca2+-calmodulin requirement in Vitis vinifera cells producing anthocyanins. *Phytochemistry*, *53*(6), 659–665. https://doi.org/10.1016/s0031-9422(99)00620-2

Webb, L. B., Whetton, P. H., & Barlow, E. W. R. (2007). Modelled impact of future climate change on the phenology of winegrapes in Australia. *Australian Journal of Grape and Wine Research*, *13*(3), 165–175. https://doi.org/10.1111/j.1755-0238.2007.tb00247.x

Wu, B.-H., Niu, N., Li, J.-H., & Li, S.-H. (2013). Leaf:fruit ratio affects the proteomic profile of grape berry skins. *Journal of the American Society for Horticultural Science*, *138*(6), 416–427. https://doi.org/10.21273/JASHS.138.6.416

Zimman, A., & Waterhouse, A. L. (2004). Incorporation of malvidin-3-glucoside into high molecular weight polyphenols during fermentation and wine aging. *American Journal of Enology and Viticulture*, *55*(2), 139–146. https://doi.org/10.5344/ajev.2004.55.2.139