Hindawi
Australian Journal of Grape and Wine Research
Volume 2024, Article ID 2504396, 20 pages
https://doi.org/10.1155/2024/2504396

Review Article

Impact of Cluster Thinning on Wine Grape Yield and Fruit Composition: A Review and Meta-Analysis

Joshua VanderWeide[1,2] **Esmaeil Nasrollahiazar,**[3] **Steve Schultze,**[4] **Paolo Sabbatini**[2,5] **and Simone Diego Castellarin**[1]

[1]*Wine Research Centre, Faculty of Land and Food Systems, The University of British Columbia, Vancouver, BC, Canada*
[2]*Department of Horticulture, Michigan State University, East Lansing, MI 48824, USA*
[3]*Michigan State University Extension, Leelanau County, MI 49682, USA*
[4]*Department of Earth Sciences, University of South Alabama, Mobile, AL 36688, USA*
[5]*Department of Agricultural, Forestry and Food Sciences, University of Turin, Largo Paolo Braccini 2, Grugliasco 10095, TO, Italy*

Correspondence should be addressed to Joshua VanderWeide; jvander@msu.edu

Received 5 April 2023; Revised 7 October 2023; Accepted 20 December 2023; Published 24 January 2024

Academic Editor: Amber Parker

Copyright © 2024 Joshua VanderWeide et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

For wine grape producers, achieving an optimal balance between vegetative and reproductive growth is a key factor in producing high quality fruit and meeting production quotas. This balance is often measured as the leaf-area-to-yield ratio. To increase this ratio, producers often use "cluster thinning" (CT), a management practice involving a selective removal of grape clusters from vines. Despite this, no consensus has been established regarding the optimal CT timing and severity for consistently improving fruit composition. The objective of this work was to identify whether CT "timing" (bloom, pea-size, lag phase, and veraison) or "severity" (15–35%, 36–55%, and 56–75%) influences yield and fruit composition. To achieve this objective, a meta-analysis of 160 publications on CT in grape was reduced to 78 studies via 10 data curation steps. We reported the influence of CT timing and severity on yield and fruit composition, as well as their impact on the yield-fruit composition tradeoff. First, CT timing showed little influence on fruit composition, which provides producers with greater flexibility when using this practice. Second, CT severity was impactful on improving fruit composition (TSS and pH); only the moderate range (36–55%) was effective. In conclusion, wine grape composition is more influenced by CT severity than timing. This work has important implications for grape producers and their approach to improving grape composition.

1. Introduction

Grapevines require intricate vineyard management of the relationship between vegetative and reproductive growth during canopy and fruit development to produce high quality fruit for winemaking. In fact, the leaf-area-to-yield ratio is regarded as a central component dictating fruit composition in many fruit crops [1–3]. As such, cultural practices have been developed and evaluated, allowing viticulturists to cater the balance between vegetation and yield. Selected practices focus on reducing canopy density or vigor, such as shoot thinning, shoot topping, cluster-zone leaf removal, palissage, or cover crops [4, 5]. This reduces excessive vegetative growth and lowers the source-sink balance. Meanwhile, other strategies focus on the management of the fruit, such as prebloom leaf removal or cluster thinning [6]. These practices decrease the vine's yield, which increases the source-sink balance.

Much research has been devoted to the study of cluster thinning for both wine and table grape production [7]. For wine grapes, there are two common reasons why cluster thinning may be performed. First, cool-climate growing regions provide fewer growing degree days due to shorter seasons, which limit the capacity of vines to ripen fruit [8]. For this reason, it has been suggested that a greater leaf area is required to fully ripen the fruits [9]. Cluster thinning provides a strategy to reduce yields of high- and medium-yielding cultivars to produce higher quality fruit [10, 11]. Interestingly, cluster thinning is a standard in many growing regions due to production quotas, even when vines are considered to be balanced in accordance with the climate [4, 12, 13]. This is due to an assumption that a reduction in yield will always enhance fruit composition, regardless of whether vines are balanced. Second, most *vinifera* cultivars often produce two clusters on each fruit-bearing shoot. Meanwhile, many hybrid grape cultivars and selected *vinifera* genotypes such as Sangiovese and Montepulciano are capable of producing clusters on noncount positions; therefore, 3–5 clusters can be produced on each fruit-bearing shoot [6, 14, 15]. However, inflorescence primordia formation and cluster number are subjective to environmental and climate conditions. Vines are often unable to ripen these additional fruits to an optimal maturity level because of their delayed development and smaller size, which makes them weaker sinks for photosynthates compared to more basal clusters. In these high-yielding cultivars, the most apical clusters in the shoots are removed, which improves the sink strength of remaining ones and allows them to reach higher maturity.

The physiological mechanism influencing fruit composition in response to cluster thinning involves an alteration of the source-to-sink balance (leaf-area-to-yield ratio), also termed "vine balance." Vine balance can be described as the relationship between the production of carbohydrates by "source" tissues (mature leaves) and the strength of "sinks" (young leaves, shoot tips, root tips, and clusters), or their capacity to receive carbohydrates [16, 17]. This concept is further complicated by the competition that occurs between sink tissues [18, 19]. This was best summed by Partridge [20], who stated that balance can be attained "when yield of ripe fruit is maximized with no detrimental impact on vegetative growth;" this was the first definition of vine balance. Nowadays, vine balance is a viticultural term that can be defined in different ways. One of the most accepted interpretations is the balance between vegetative growth and reproductive growth [9], which sets a level of yield per vine, under which the desired fruit composition can be reached sustainably. The index of vine balance is a ratio of yield per pruning weight (Ravaz Index) or light-exposed leaf area/yield expressed in cm^2/g [2]. Multiple metrics have been proposed that provide a guideline to manage competition between sinks or the vine balance. Using the concept of vine balance, the target value for crop load ratio is typically 5 to 10 (Ravaz Index) depending on cultivar or 7–14 cm^2/g (0.7–1.4 m^2/kg) leaf area/yield [21]. More recently, Kliewer and Dokoozlian [2] proposed that a leaf area-to-yield ratio of 8-12 cm^2/g (0.8–1.2 m2/kg) is more suitable to achieve vine balance. Values above these ranges indicate vines with excessive vegetative vigor that will outcompete clusters and compromise fruit ripening. Meanwhile, a low source-sink balance reflects a vine with excessive yield that will likely fail to properly ripen the fruit. Reduction of source tissues and source-sink balance via postfruit set leaf removal, shoot thinning, or shoot topping has been shown to enhance photosynthetic rate in remaining leaves [22–25]. In contrast, enhancing source-sink balance through cluster thinning can lead to both no alteration [22] or a reduction in photosynthetic rate [26, 27] and different carbon partitioning [28]. Ultimately, the response of photosynthetic rate and carbohydrate assimilation to cluster thinning may be related to the original vine balance in untreated plants.

Cluster thinning is performed during a wide range of grapevine phenological stages, spanning from bloom to veraison. Many studies have compared thinning at multiple timings [15, 29–35]. Among these studies comparing treatment timings to the untreated control, none revealed a clear effect of thinning timing on yield. Only the veraison (bloom + 8 weeks) treatment in [30] caused a reduction in berry weight compared to other thinning timings. This suggests that any potential timing-based compensation in berry weight and yield due to cluster thinning timing is minimal. Regarding total soluble solids (TSS), two studies found that thinning at all timings increased TSS [15, 32], while others revealed this effect in three of four seasons and only near pea-size and preveraison [35]. For pH and titratable acidity (TA), results were less consistent. Gatti et al. [15] reported that regardless of timing, thinning increased pH and decreased TA. Among the studies comparing CT timing, only five reported total anthocyanins and four measured phenolics in berries. In two studies, both parameters were significantly increased, regardless of cluster thinning timing [15, 32]. In contrast, Fanzone et al. [29] reported no effect of thinning on either parameter in berry skins across two seasons. These studies reveal that no clear consensus has arisen regarding cluster thinning timing that could aid grape producers with decision making related to crop load management to improve fruit composition harvest.

Likewise, research shows CT being performed across an extensive span of severities. Most grapevine cultivars produce a grape cluster between 2 and 3 fruitful nodes per shoot. Grape producers often remove one cluster per shoot to facilitate ripening, leading to the greater proportion of researchers evaluating cluster thinning near 33–50% severity. Multiple studies have compared thinning at different severities [36–45]. Ough and Nagaoka [40] compared 33% and 66% thinning across multiple years and observed a significant decrease in yield in both treatments. Meanwhile, a comparison across a gradient of 25–75% thinning showed greater significance in yield reduction at higher severity [38]. A three-year study revealed that thinning at 25% and 50% both reduced yield, but only in seasons when yield in the control treatment was highest [41]. Cluster thinning at both 30% and 50% significantly improved TSS and pH in Montepulciano in one season [44], whereas thinning across three years showed a more consistent effect of increasing TSS at 50% compared to 25% [41, 42]. Reščič et al. [42] also revealed a more consistent impact of thinning at 50% at reducing TA than 25%. Mota et al. [39] compared 50% and 75% cluster thinning and showed no consistent pattern of either one treatment improving anthocyanin concentration across two years in Merlot, while in another study, thinning at 10%, 30%, and 50% increased anthocyanin concentration consistently [36].

Studies which evaluate the impact of the climate and viticultural factors, such as the species, cultivar, rootstock, and vine age on the success of cluster thinning are scarce. Regarding climate, thinned Cabernet Sauvignon vines grown in two distinct climates in Chile produced similar increases in fruit chemical parameters at harvest (total soluble solids, pH, and total anthocyanins) and a decrease in total acidity [46]. Nuzzo and Matthews [47] compared four thinning levels on four rootstocks in Napa Valley-grown Cabernet Sauvignon, and revealed that rootstock and environment (temperature and soil water content) had little impact on fruit composition at harvest. Comparisons between cultivars are difficult given the differences between rootstocks and planting density used [48]. However, Karoglan et al. [49] revealed a similar response of Cabernet Sauvignon and Merlot (identical rootstock and planting density) to pea-size cluster thinning in terms of yield, berry weight, total anthocyanins, and total phenolics, although total soluble solids were increased more in Merlot. Thinning Chambourcin to one cluster per shoot in two southern Illinois vineyards consistently decreased yield and increased total soluble solids over two seasons, as well as increased pH similarly between both vineyards in one year [50]. In contrast, Santesteban et al. [51] showed that when comparing multiple Tempranillo sites over three years, cluster thinning produced inconsistent results considering these same parameters.

Our literature search revealed that the first publication to use the term "cluster thinning" was in 1970 on "Thompson Seedless" in California [52]. Meanwhile, the initial studies that met our data curation criteria were published by the same research group, where the effects on yield components and grape and wine composition were evaluated in the "Carignane" wine grape [53, 54]. The trend of published CT studies per year follows a bell curve over the past two decades, which mirrors our recent meta-analysis and systematic review on the management practice "prebloom leaf removal" [55]. These trends reflect the increase in research on cultural practices in recent years in grape [56–59], which has led to studies investigating the effects of CT with other practices, such as leaf removal [15, 60, 61], water deficit [48, 62], and shoot thinning [63, 64]. This decreasing trend in the number of studies per year provides justification for our current meta-analysis and systematic review.

In this meta-analysis and systematic review, we analyzed the available literature on cluster thinning, resulting in 78 publications meeting our data curation requirements. The first objective of this work was to understand whether application timing or severity have a distinct influence on vine production and fruit composition, particularly total soluble solids. The second objective was to discover whether categorical variables such as growing degree days, precipitation, cultivar, rootstock, or vine age correlated to changes in production and fruit composition.

2. Materials and Methods

2.1. Data Collection and Curation. Data collection, curation, and analysis were performed in a similar manner to our previous meta-analysis work [55]. A literature review was performed to identify research articles published from January 1970 to December 2020 in peer-reviewed scientific journals that focused on the topic of cluster thinning in grape. M.S Thesis and Ph.D. Dissertations were not included. We used search terms of "cluster thinning grape," "cluster removal grape," and "bunch thinning grape" in Google Scholar and Web of Science to identify works for inclusion in the final dataset. A total of 160 publications were identified that broadly centered on this cultural practice. Publications were maintained for further statistical analysis according to Figure 1.

The exclusion of publications to fit these ten criteria resulted in 78 studies (Supplementary File 1). It is important to note that data on American and French "hybrid" cultivars were originally intended for use in this meta-analysis; however, the large discrepancy in yield (kg/vine) between hybrids and *Vitis vinifera* cultivars convoluted comparisons between timings and intensities of thinning and therefore, these studies were emitted. In cases where all desirable data from a study were present in a previous publication, the more recent study was excluded. For each publication, any desired data that was present in figures was obtained using ImageJ software (Version 1.51*e*) when the treatment means (and if possible, standard deviation or error) from the respective publication were distinguishable. In the case of "yield," "leaf area/yield," "berry weight," "total anthocyanins," and "total phenolics," unit representation of some parameters was heterogeneous between studies. When possible, data were converted to a common unit. For "yield," "shoot/vine" data were converted to "yield (kg/vine)" when "shoot number per vine" data were available, and "yield/meter (row length)" or "yield/hectare" data were converted to "yield (kg/vine)" when "vine density" data were available. In the case of "total anthocyanins" and "total phenolics," data were converted to "mg/kg (fresh weight)." In the case that multiple acceptable units were presented in a publication, all were included. Such was the case only for "total anthocyanins" and "total phenolics." In a single instance, severe outliers that could likely be attributed to a miscalculation in the publication were removed prior to analysis of means. This was the case for "total anthocyanins (mg/kg) FW berry" [46].

2.2. Climate Data. Daily climate information for all sites was collected from the Global Historical Climatology Network-Daily (GHCN-Daily), Version 2 dataset, hosted by the National Center for Environmental Information. Each study area included was assigned the closest weather station which was functioning during the time of the study. For example, the authors in [43] used weather data from the 1989 growing season from a weather station that was approximately 2 miles away. Daily maximum and minimum temperature were acquired to calculate growing degree day (GDD) accumulation during the local growing season months. Total daily precipitation was calculated by summing the total precipitation over the same time frame.

2.3. Statistical Analysis. Among the 78 publications used for analysis, few reported the standard error for the parameters included in this study. Given this, the variable errors from each experiment were not utilized in statistical analysis but

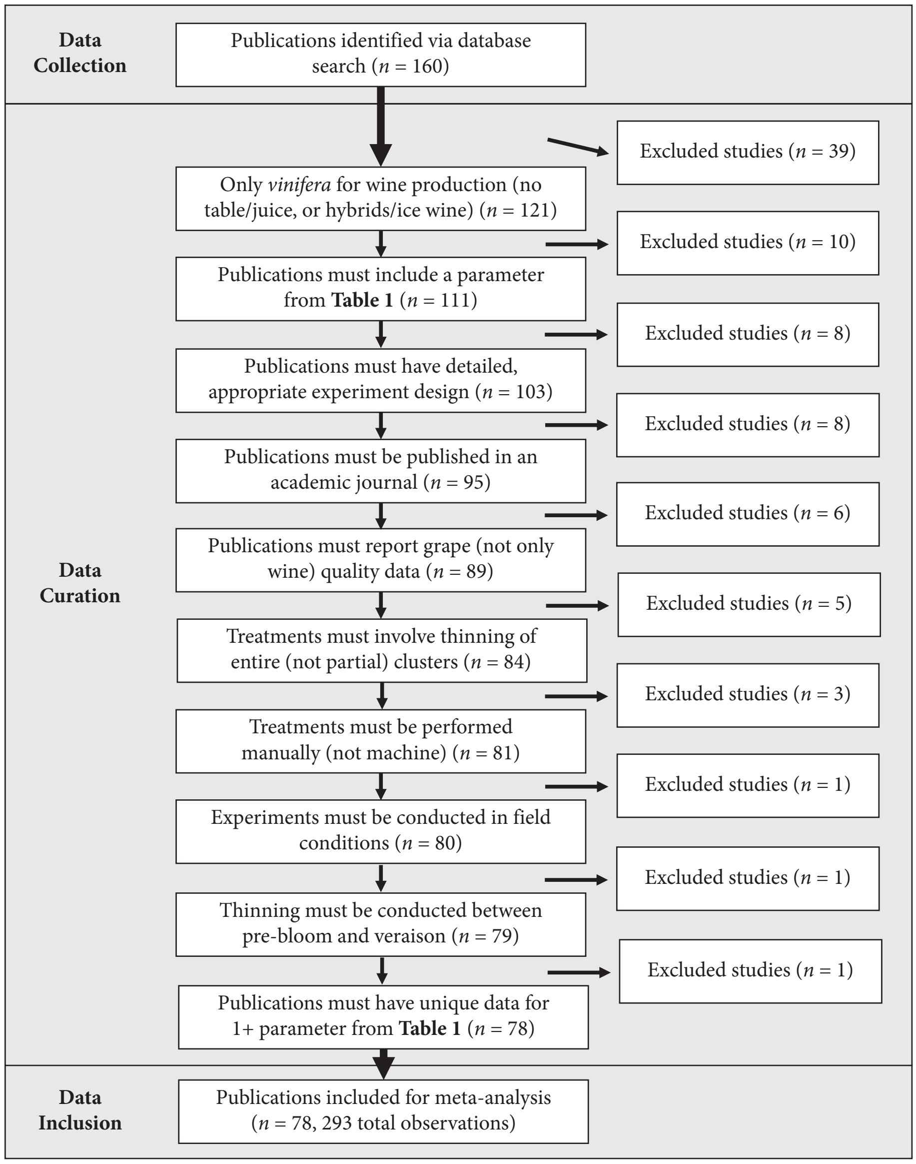


Figure 1: Flowchart demonstrating the data collection, data curation, and data inclusion process utilized in this meta-analysis.

were collected and used to calculate statistical significance (independent samples *t*-test) with the *n* value when this information was not provided in tables. For dependent variables, an independent samples *t*-test ($p = 0.05$) was used to compare cluster thinning treatments against the untreated control using IBM SPSS software (IBM, Armonk, NY, USA). In the case that multiple forms of a parameter existed in a publication ("total anthocyanins/g and/berry" and "total phenolics/g and/berry"), both were included, and the data from remaining parameters duplicated only for use in correlation analysis. Factor analysis of mixed data (FAMD) was conducted using R version 3.6.2 [65]. For FAMD, our data set contained multiple missing data points. To account for this, we utilized the missMDA R package by Josse and Husson [66] that analyzes incomplete data sets for underlying data structures. We also performed an imputation of the missing data values and reanalyzed the data set using missMDA to confirm the data structure.

While this meta-analysis provides a robust analysis of the impact of CT on grapevine yield and fruit composition parameters, the statistical limitations of meta-analyses should be recognized. Firstly, the boundaries utilized to separate studies based on "timing" and "severity" were determined subjectively. While "timing" is based on clearly defined phenological stages, "severity" was determined by dividing the total range of percentages (15%–65%) into three equal categories (low, moderate, and high). The lack of clearly predetermined categories for "severity," such as with "timing," may convolute some results. A second limitation of this meta-analysis is the inability to account for the interaction between timing and severity of CT. In this work, timing had a limited impact on the capacity of CT to modulate fruit composition compared to severity. However, some variables were still changed by CT timing, suggesting that an interaction could occur. Finally, given that correlation analysis includes data from multiple studies, a third limitation to this work may be that correlations may be influenced by external factors, such as climate conditions between studies.

3. Results

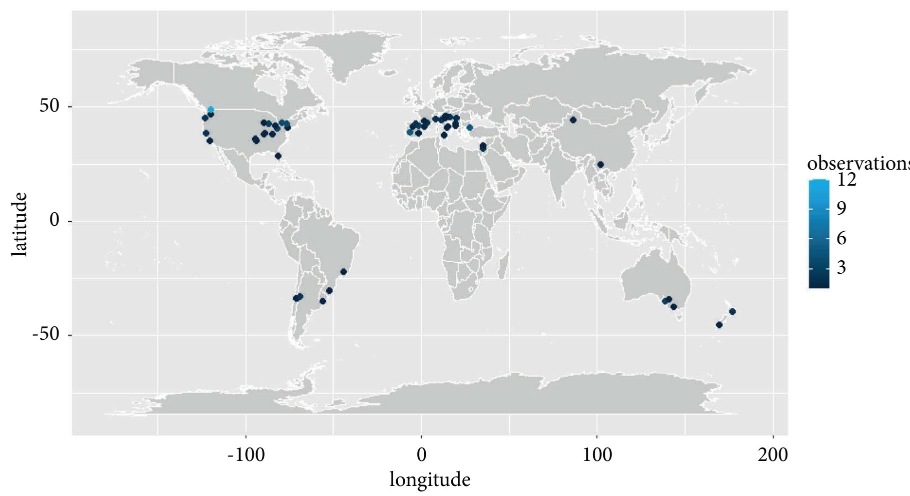
3.1. Study Location and Number. The present analysis draws upon studies conducted across five continents (Figure 2). While most of these studies were carried out in North America and Europe, research was also conducted in Asia, Australia (Figure 2(a)), and New Zealand. Within North America, a significant portion of the research was performed in states and provinces surrounding the Great Lakes, as well as in California and the Pacific Northwest of the US and Canada (Figure 2(b)). In Europe, research was largely located in Spain and Italy (Figure 2(c)). The studies were conducted in diverse climatic conditions, ranging from hot and dry to cool and moist (Supplemental Table 1). The first literature on this topic of cluster thinning in grape was carried out in the early 1970s, while the initial work included in this analysis following data curation was published in the mid-1980s (Figure 3). Over the past two decades, the number of publications has grown exponentially, with a peak in the number of studies per year observed around 2016 (Figure 3(a)). Meanwhile, those included in our meta-analysis following data curation reached a pinnacle in 2013 (Figure 3(b)). Since 2013, there has been a decreasing trend in the number of studies per year.

3.2. Influence of CT on Yield and Fruit Composition Is Mediated by Cultivar and Rootstock. Cluster thinning (CT) significantly reduced yield and increased leaf-area-to-yield ratio (LA : Y), total soluble solids (TSS), and pH (Figure 4). In this work, we found that CT resulted in a significant reduction in yield, with an average reduction of approximately 31.0% across 273 observations. On the other hand, CT led to a significant increase in LA : Y by 61.3% across 57 observations. CT resulted in a modest increase in total soluble solids (TSS) by 3.50% across 283 observations and an increase in pH by 1.71% across 253 observations. However, there was no significant effect of CT on berry weight or fruit composition, including titratable acidity, total phenolics, and total anthocyanins.

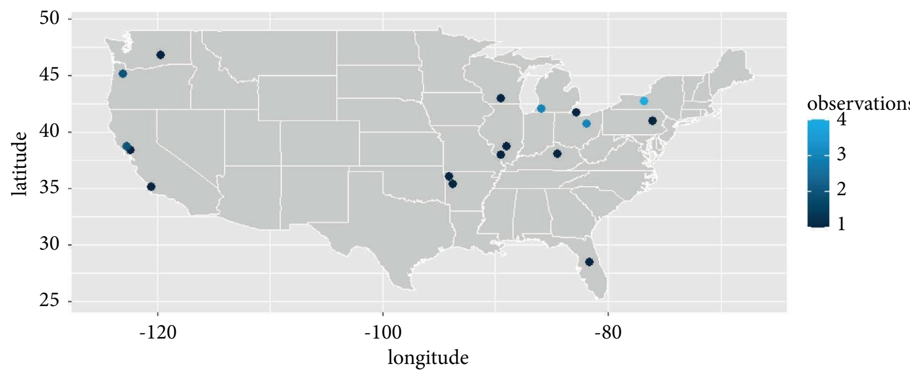
We conducted a principal component analysis (PCA) to observe potential relationships among treatment categorical variables (CT timing and CT severity), vineyard-related categorical variables (GDD, precipitation, vine age, and vine density), and vine/grape-related dependent variables (yield, LA : Y, TSS, pH, TA, and BW). Our analysis revealed that GDD and precipitation variables exhibited opposite directional changes but did not show any significant relationships with vine or grape parameters such as yield, TSS, or TA (Figure 5(a)). The analysis indicated that CT severity showed a positive correlation with grape juice pH and TSS and was inversely related to grape juice TA. No correlation was observed between CT severity and BW or yield. In Figure 5(b), the relationships among the categorical and dependent variables from each study were assessed. The categorical variables cultivar and berry color were similarly affected by both dimensions, while CT timing, vine age, and vine density were not affected by either dimension. The categorical variables rootstock, GDD, and precipitation grouped towards dimension 1, while CT severity, and the dependent variables pH, TA, and TSS were more closely aligned with dimension 2.

Figures 5(c) and 5(d) focus on the absolute differences in TSS between the CT and control treatments, separating the various observations by cultivar (panel C) and rootstock (panel D) used in the experiment. In general, the standard error bar was found to be higher for cultivars and rootstocks with fewer observations available. The average TSS change by CT for cultivar varied from +0.03 to +1.70°Brix, and for rootstock, from −0.65 to +1.22°Brix. Gewürztraminer, Cabernet Franc, and Cabernet Sauvignon did not show any remarkable increase (<0.1°Brix) in TSS when subjected to CT. Conversely, Semillon, Riesling, Blauer Portugieser, Nebbiolo, and Syrah were the cultivars that displayed the most substantial changes in TSS (>1°Brix) when subjected to CT. Considering the variability within cultivars, the results show that Merlot, Pinot noir, Cabernet Franc, and Cabernet Sauvignon had the smallest variation (standard error) in the effects of CT on TSS. Differences in TSS between CT and CN treatments appear also to be related to the rootstock used in the experiment (Figure 5(d)). On average, the largest difference in TSS was observed in 1103P, with an increase of 1.22°Brix. Interestingly, most of the rootstocks determined a change of approximately 0.8–1.0°Brix, while only 420A and 110R implied moderate changes (0–0.8°Brix) and three rootstocks (216-3C, 5C, and St. George) negative or very small changes (−0.65 to 0.02°Brix) (Figure 5(d)).

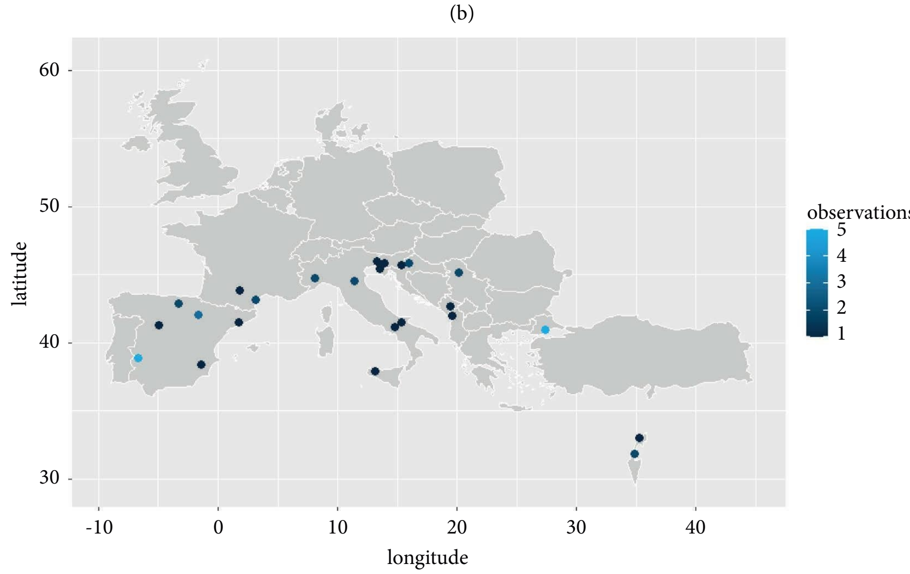
3.3. Influence of CT Timing on Production and Fruit Composition. For this work, the impact of CT timing on production and fruit composition was qualitatively evaluated by examining the percentage of observations that were significantly affected by CT. CT mostly resulted in a reduction in yield with only two observations indicating an increase at the PS timing (Table 1). Specifically, yield was consistently reduced at PS, LP, and V timings (67.5–75% of observations), while the reduction was slightly lower at B (57.5% of observations). LA : Y was evaluated in a much smaller number of studies but showed that this ratio was increased the greatest by the LP and V timings (>70% of observations), whereas this was lower at B (60% of observations) and the smallest at PS (53.5% of observations). A decrease in LA : Y was not reported in any publication. BW was not consistently regulated by CT timing, although BW was more often increased than decreased for each timing. The increase in BW by CT decreased steadily during development from B (37.8% of observations) to V (10.1% of observations). Both TSS (42.5%–57.5% of observations) and pH (33.3%–48.6% of observations) were similarly increased by CT across timings. Meanwhile, TA was not decreased consistently by CT across timing (26.6%–38.1% of observations). Except for anthocyanins ANT1 (mg/100 g berry FW), data on anthocyanins and phenolics were sparse to



(a)



(b)

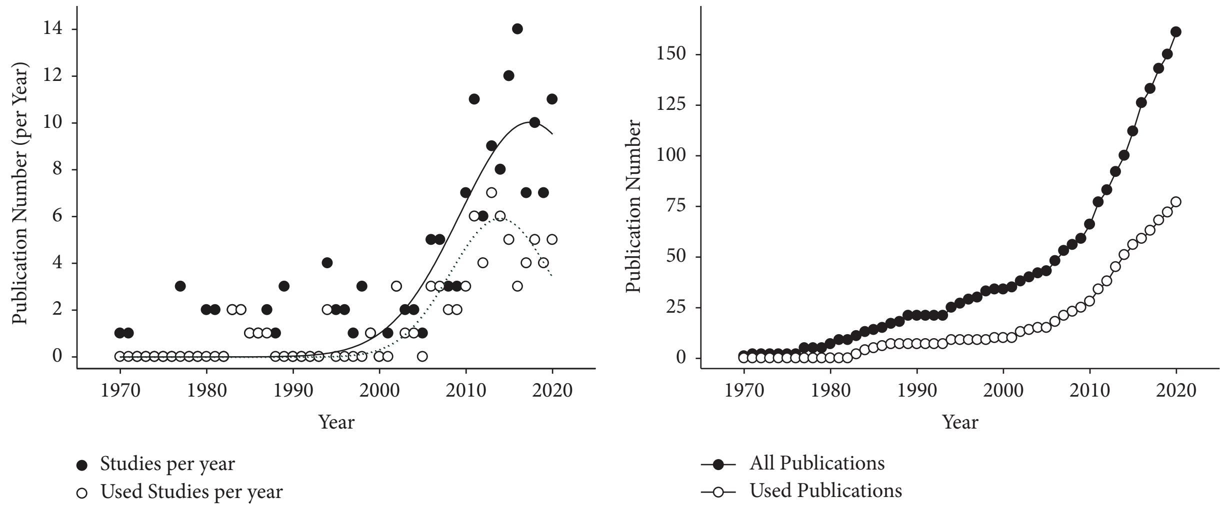


(c)

Figure 2: Dot plot heatmap depicting the location of cluster thinning studies in the (a) world, (b) United States of America, and (c) Europe. Heatmaps represent the number of experimental observations included from each location.

validate a comparison across timings. ANT1 was increased the most by CT at LP (62.5% of observations), to an intermediate consistency by PS (45.2% of observations) and V (44.4% of observations), and the least often by B (27.3% of observations).

Quantitative comparisons between CN and CT treatments within each timing revealed that yield was significantly decreased by CT at each timing (Table 2). LA : Y was subsequently increased at all timings except PS, consistently with the data from Table 1, where LA : Y was increased by CT



(a) (b)

Figure 3: The (a) publication number (per year) and (b) total publication number obtained from database searches between January 1970 and December 2020. No publications were identified prior to 1970. “Used” refers to the number of studies utilized in this meta-analysis following the data curation process.

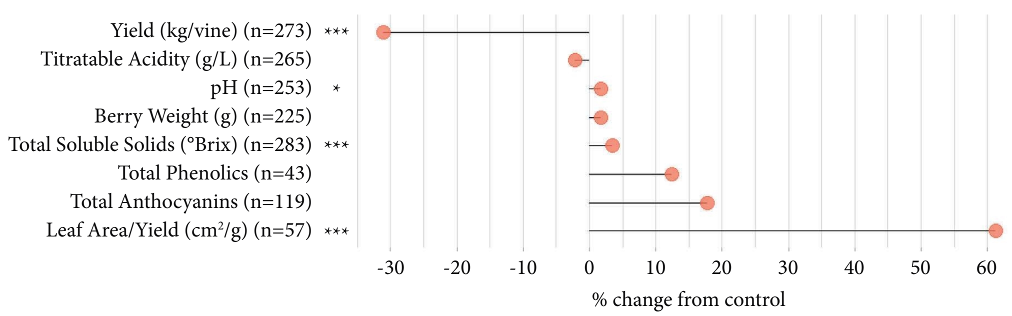
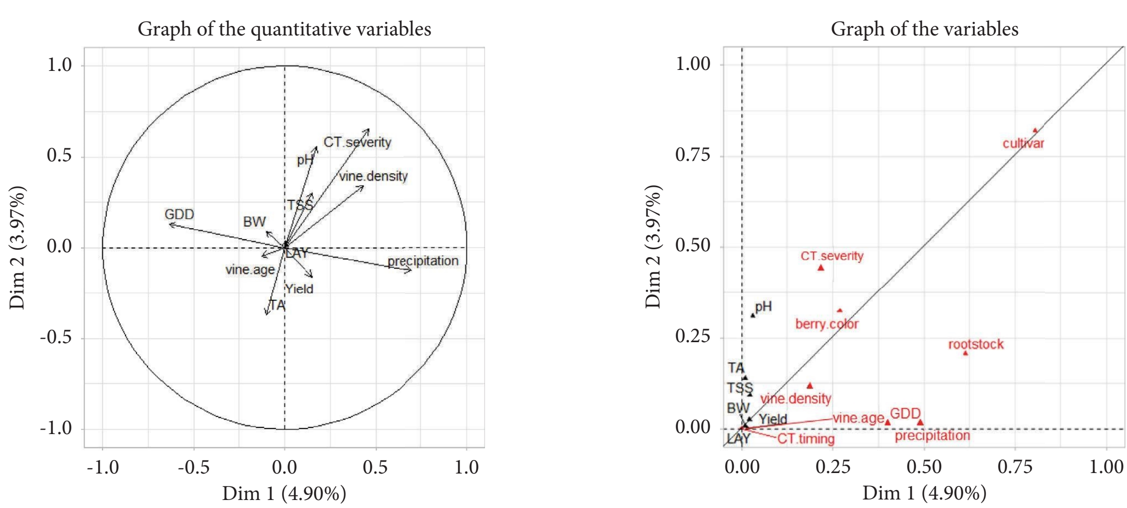


Figure 4: Lollipop plot visualizing the percent change in dependent variables by cluster thinning compared to untreated vines, regardless of thinning timing or severity. *n* represents the total number of observations used in *t*-test estimations of significant difference. *, $p < 0.05$ and **, $p < 0.001$.



(a) (b)

Figure 5: Continued.

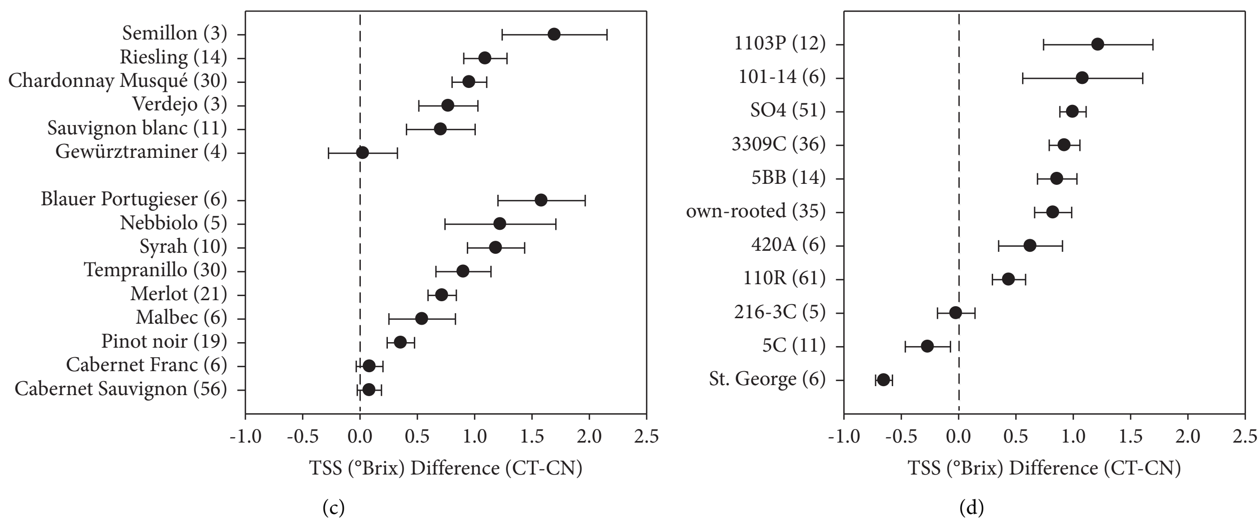


Figure 5: (a) PCA displaying the relationships between categorical variables and the percent change of the dependent variables in response to CT. (b) PCA variables visualizing the relationships between categorical and the % change of dependent variables in CT compared to CN. The influence of (c) genotype and (d) rootstock on the difference in TSS between control (CN) and cluster thinning (CT) treatments. In (a, b), data on total anthocyanin and total phenolics were excluded due to the lack of data points. In (c, d), the numbers in parentheses represent the number of observations (*n*) provided for each rootstock or genotype; genotypes or rootstocks with less than three observations were emitted. GDD, growing degree days; TSS, total soluble solids; TA, titratable acidity; LA : Y, leaf area-to-yield ratio; and BW, berry weight.

the least frequently. While some observations showed an increase for BW in CT compared to CN in Table 1, the difference was not significant at any timing. TSS was impacted by CT the most consistently among all fruit composition; values were increased by all timings compared to CN except at B. While TA was not altered at any time by CT, pH was increased compared to CN only at V. Likewise, among ANT and PHE parameters, only PHE1 (mg/100 g skin FW) saw modulation by CT at V.

A Pearson's correlation coefficient analysis was conducted between yield and LA : Y and BW and fruit composition to gain an understanding of the tradeoff between yield and fruit composition. In V, a positive linear correlation was observed between yield and BW (Supplemental Table 2). While the correlation between yield and TSS was nearly significant at PS and LP, only V showed this significant negative correlation. LA : Y was subsequently related to TSS at V. Likewise, yield and pH were strongly correlated at V. Interestingly, LA : Y was positively correlated with TA only at LP. To further explore this relationship between yield parameters and TSS, correlations were drawn between data at each timing. Although differences existed in the intercepts for yield and TSS at both CN and CT for each timing, the slopes for each correlation were nearly identical, with the lowest being at B (yield: −0.39 and LA : Y: 0.07) and highest at LP (yield: −0.66 and LA : Y: 0.12) (Figures 6(a) and 6(b)).

3.4. Influence of CT Severity on Production and Fruit Composition. Unlike CT timing, vine production and fruit composition were differentially impacted by CT severity. Most of the studies reported a decrease in yield after a moderate (MOD) CT, a treatment that was also the most efficient in increasing the LA : Y ratio (Table 3). Crop LA : Y ratios were highly correlated with the level of thinning, suggesting that yield could be linearly related to the number of clusters, especially since the BW was not impacted by CT severity. TSS increased only due to MOD CT, and most of the fruit technological parameters collected at harvest follow the same trends (Table 3). TSS also increased with increasing LA : Y even if no consistent effect of the treatments on TA was apparent in the three experimental CT treatments (Table 4). In most studies, CT was more effective when applied at a MOD level (at about 45%) to reduce yield per vine and improve source to sink ratio and TSS at harvest (Table 4).

The data were also elaborated to compare the impact of CT severity on the yield-TSS tradeoff. It is evident that CT severity impacts the relationships between yield and LA : Y with TSS. However, the trends reported by the different regressions demonstrate that the severity of CT is more efficient, if considering the slopes of the regression, at increasing TSS than the CT timing (Figures 6(c) and 6(d)). In the MOD CT severity, the trend is very similar to the timing of CT, while LOW and HIGH CT severity resulted in no changes in TSS at harvest. The regressions based on yield or LA : Y are pivotal to demonstrating how CT improves fruit composition, and specifically, TSS at harvest (Figure 6).

3.5. Cluster Thinning Effects on Aroma Volatiles. Regardless of CT timing or severity, few studies found a consistent improvement of volatile production in response to CT. Syrah grapes subjected to MOD CT at V also contained higher aroma volatiles compared to CN vines [67]. Talaverano et al. [68] reported a significant modulation of volatiles and increase in total OAV (odor-active value) by CT at PS in Tempranillo. In Verdejo, large but mostly nonsignificant increases in many alcohols, ethyl esters, acetate esters, and lactones occurred by LOW CT at PS.

Table 1: Listing of dependent production and fruit composition parameters, as well as the total number of observations (n) and percentage of significant observations for each parameter by timing of cluster thinning application.

Acronym	Parameter	Alteration by CT	Bloom (B)		Pea-size (PS)		Lag phase (LP)		Veraison (V)	
			n^a	n sign. (% sign.)[b]	n	n sign. (% sign.)	n	n sign. (% sign.)	n	n sign. (% sign.)
Production parameters										
Yield	Yield (kg/vine)	Increased	40	0 (0%)	120	2 (1.67%)	32	0 (0%)	96	0 (0%)
		Decreased		23 (57.5%)		81 (67.5%)		24 (75.0%)		70 (72.9%)
LA:Y	Leaf-area/yield (cm^2/g)	Increased	5	3 (60.0%)	13	7 (53.8%)	15	11 (73.3%)	27	19 (70.4%)
		Decreased		0 (0%)		0 (0%)		0 (0%)		0 (0%)
BW	Berry weight (g)	Increased	37	14 (37.8%)	78	19 (24.4%)	25	4 (16.0%)	69	7 (10.1%)
		Decreased		0 (0%)		1 (1.28%)		2 (8.00%)		6 (8.70%)
Fruit composition parameters										
TSS	Total soluble solids (°Brix)	Increased	48	24 (50.0%)	109	54 (49.5%)	40	23 (57.5%)	99	42 (42.4%)
		Decreased		1 (2.10%)		19 (17.4%)		1 (2.50%)		2 (2.00%)
pH	pH	Increased	30	10 (33.3%)	80	38 (47.5%)	37	18 (48.6%)	76	28 (36.8%)
		Decreased		1 (3.33%)		8 (10.0%)		1 (2.70%)		3 (3.95%)
TA	Titratable acidity (g/L)	Increased	31	0 (0%)	42	0 (0%)	45	0 (0%)	81	0 (0%)
		Decreased		11 (35.5%)		16 (38.1%)		12 (26.6%)		26 (32.1%)
ANT1	Total anthocyanins (mg/100 g) berry FW	Increased	11	3 (27.3%)	31	14 (45.2%)	16	10 (62.5%)	27	12 (44.4%)
		Decreased		0 (0%)		0 (0%)		0 (0%)		0 (0%)
ANT2	Total anthocyanins (mg/L)	Increased	3	1 (33.3%)	10	5 (50.0%)	4	0 (0%)	26	16 (61.5%)
		Decreased		0 (0%)		0 (0%)		0 (0%)		0 (0%)
PHE1	Total phenolics (mg/100 g) skin FW	Increased	1	1 (100%)	3	2 (66.7%)	4	2 (50.0%)	4	2 (50%)
		Decreased		0 (0%)		0 (0%)		0 (0%)		0 (0%)
PHE2	Total phenolics (mg/L)	Increased	7	5 (71.4%)	4	4 (100%)	4	3 (75.0%)	18	8 (44.4%)
		Decreased		0 (0%)		0 (0%)		0 (0%)		0 (0%)

[a]Number of observations compared between CN and CT at either B, PS, LP, or V. [b]Number of observations where CT was significantly larger or smaller ($p < 0.05$) than CN using statistical analysis provided in individual studies.

Table 2: Impact of cluster thinning timing on production and fruit composition variables.

Parameter	Bloom (B)		Pea-size (PS)		Lag phase (LP)		Veraison (V)		p value (trt)[c]
	CN[b]	CT	CN	CT	CN	CT	CN	CT	
Production parameters									
Yield (kg/vine)	5.47 ± 0.480[a]	**4.18 ± 0.376**	4.39 ± 0.460	**3.07 ± 0.347**	4.19 ± 0.381	**2.82 ± 0.267**	4.23 ± 0.255	**2.72 ± 0.168**	**<0.001**
Leaf-area/yield (cm^2/g)	15.4 ± 2.06	**22.6 ± 3.11**	17.8 ± 2.95	29.4 ± 5.78	15.0 ± 1.54	**22.8 ± 1.85**	13.9 ± 0.974	**22.2 ± 1.59**	**0.003**
Berry weight (g)	1.42 ± 0.041	1.47 ± 0.043	1.42 ± 0.038	1.45 ± 0.040	1.55 ± 0.062	1.59 ± 0.061	1.45 ± 0.038	1.44 ± 0.041	0.234
Fruit composition parameters									
Total soluble solids (°Brix)	22.0 ± 0.276	22.5 ± 0.250	22.0 ± 0.230	**22.6 ± 0.234**	23.2 ± 0.318	**24.1 ± 0.261**	22.5 ± 0.185	**23.4 ± 0.167**	**<0.001**
pH	3.45 ± 0.041	3.49 ± 0.041	3.42 ± 0.025	3.48 ± 0.026	3.46 ± 0.051	3.54 ± 0.056	3.47 ± 0.022	**3.53 ± 0.022**	0.065
Titratable acidity (g/L)	5.94 ± 0.430	5.98 ± 0.444	7.22 ± 0.261	7.10 ± 0.261	6.22 ± 0.293	5.94 ± 0.270	6.23 ± 0.216	5.97 ± 0.199	0.802
Total anthocyanins (mg/kg) FW berry	1404 ± 60.9	1567 ± 86.7	1251 ± 192	1347 ± 177	748 ± 194	902 ± 253	1259 ± 124	1469 ± 124	0.445
Total anthocyanins (mg/L)	76.8 ± 8.49	81.9 ± 4.87	549 ± 169	570 ± 167	292 ± 30.2	336 ± 20.9	891 ± 87.2	1081 ± 122	0.307
Total phenolics (mg/kg) skin FW	—	—	1740 ± 371	2094 ± 570	1325 ± 702	1471 ± 847	2110 ± 219	**2789 ± 101**	0.584
Total phenolics (mg/L)	954 ± 91.2	996 ± 167	2159 ± 126	2291 ± 104	4553 ± 179	4974 ± 169	1192 ± 325	1289 ± 325	0.725

[a]Data are expressed as means ± standard error. Bold values highlight significant difference ($p < 0.05$) between CN and CT treatments within each timing (B, PS, LP, or V) using an independent-samples t-test. [b]CN, untreated control; CT, cluster thinning. [c]Comparison between CN and CT treatments using data from all time points ($p < 0.05$).

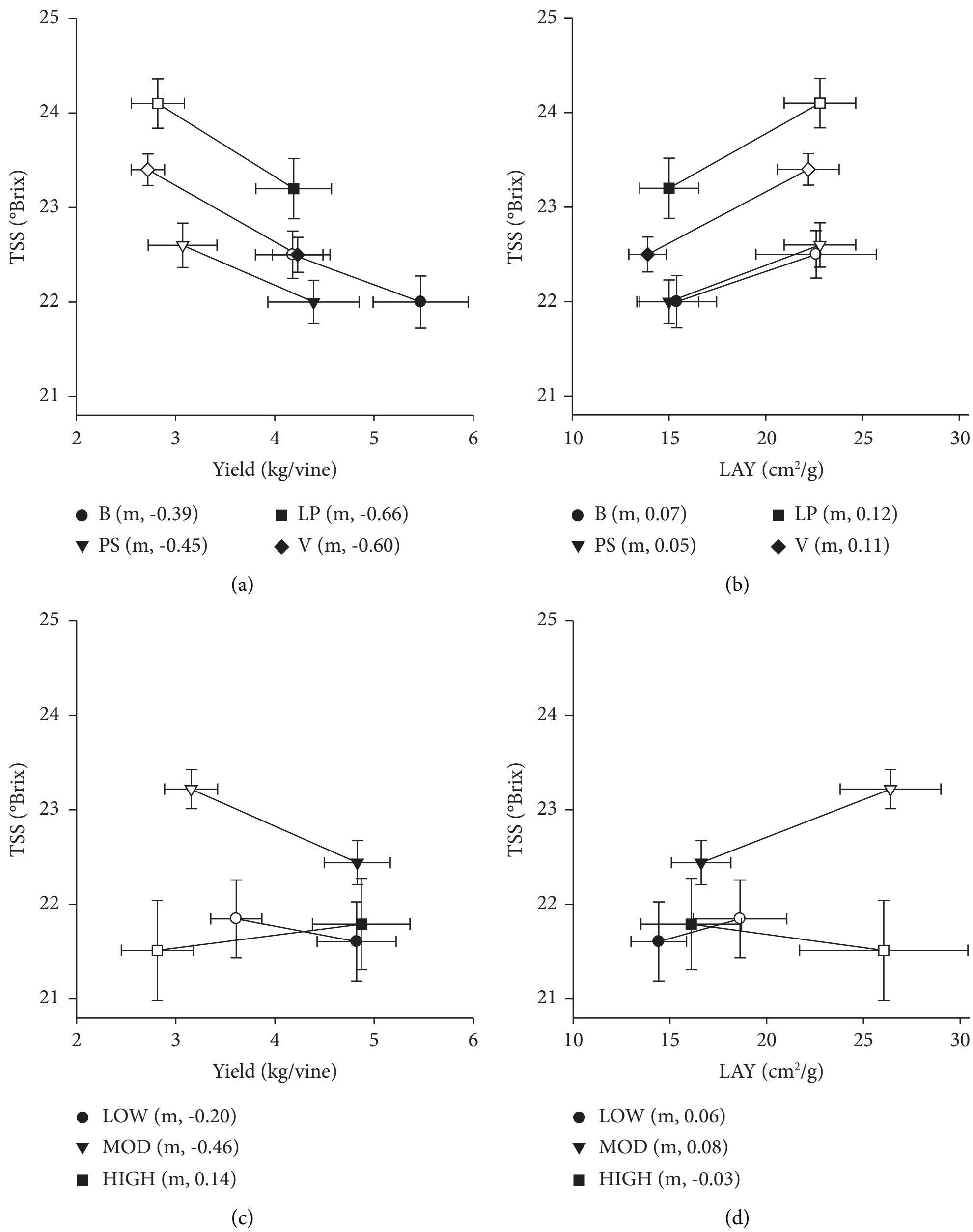


Figure 6: Influence of untreated (black shapes) and cluster thinning treatments (white shapes) on the relationship between yield (a, c) and the leaf-area-to-yield ratio (LA : Y; b, d) as per thinning timing (a, b) and severity (c, d). This relationship is visualized by the slope (*m*) between both untreated and thinned datasets.

Meanwhile others found few or no differences between CN and CT treatments [69]. Free and potentially volatile terpenes were increased by MOD CT at V in musts in two of three seasons but in wines in only one [70].

The influence of CT timing and severity on aromas has received much less attention [56]. Chardonnay Musqué vines subjected to MOD (50%) CT treatments at various timings (B, PS, LP, and V) over four seasons showed no effect of CT timing on free terpenes, but a consistent effect of increasing potentially volatile (glycosylated) terpenes at each timing [70]. In Sauvignon blanc, MOD CT at LP (1-2 weeks preveraison) enhanced free and glycosylated terpenes concentrations compared to the untreated control or CT at PS or postveraison [71]. In contrast, CT in Cabernet Sauvignon, free monoterpenes were enhanced in CT at V, but not PS, while both timings improved potentially volatile terpenes [32]. Moreover, in Cabernet Sauvignon, MOD CT at PS or V did not impact terpenes, with a limited impact on other volatile classes, while PS CT decreased varietal C_{13}-norisoprenoids [72]. Alem et al. [73] compared MOD CT at PS and V in both Chardonnay and Muscat and found a greater effect of CT at V than PS at increasing many classes of aroma volatiles in Muscat in one of two seasons, while Chardonnay was not impacted by CT in both years.

Table 3: Listing of dependent production and fruit composition parameters, as well as the total number of observations (n) and percentage of significant observations for each parameter by severity of cluster thinning application.

Acronym	Parameter	Alteration by CT	Low (~25%)		Moderate (~45%)		High (~65%)	
			n[a]	n sign. (% sign.)[b]	n	n sign. (% sign.)	n	n sign. (% sign.)
Production parameters								
Yield	Yield (kg/vine)	Increased Decreased	41	0 (0%) 26 (63.4%)	94	0 (0%) 83 (88.3%)	19	0 (0%) 16 (84.2%)
LA:Y	Leaf-area/yield (cm^2/g)	Increased Decreased	4	2 (50.0%) 0 (0%)	26	22 (84.6%) 0 (0%)	2	1 (50.0%) 0 (0%)
BW	Berry weight (g)	Increased Decreased	18	1 (5.55%) 1 (5.55%)	85	17 (20.0%) 4 (4.71%)	7	2 (28.6%) 0 (0.00%)
Fruit composition parameters								
TSS	Total soluble solids (°Brix)	Increased Decreased	32	6 (18.8%) 5 (15.6%)	103	47 (45.6%) 1 (1.00%)	15	0 (0.00%) 3 (20.0%)
pH	pH	Increased Decreased	28	8 (28.6%) 1 (3.57%)	89	30 (33.7%) 2 (2.25%)	15	1 (6.67%) 0 (0.00%)
TA	Titratable acidity (g/L)	Increased Decreased	28	1 (3.57%) 7 (25.0%)	89	7 (7.87%) 22 (24.7%)	15	0 (32.1%) 1 (6.67%)
ANT1	Total anthocyanins (mg/100 g) berry FW	Increased Decreased	6	2 (33.3%) 0 (0%)	39	20 (51.3%) 1 (2.56%)	0	n.a n.a
ANT2	Total anthocyanins (mg/L)	Increased Decreased	5	0 (0%) 0 (0%)	28	11 (0%) 0 (0%)	1	0 (0%) 0 (0%)
PHE1	Total phenolics (mg/100 g) skin FW	Increased Decreased	1	1 (100%) 0 (0%)	14	6 (42.9%) 0 (0%)	0	n.a n.a
PHE2	Total phenolics (mg/L)	Increased Decreased	0	n.a n.a	8	6 (75.0%) 0 (0%)	0	n.a n.a

[a]Number of observations compared between CN and CT at either low, moderate, or high severity levels. [b]Number of observations where CT was significantly larger or smaller ($p < 0.05$) than CN using statistical analysis provided in individual studies.

Table 4: Impact of cluster thinning severity on dependent variables.

Parameter	25% (±10%)[b]		45% (±10%)		65% (±10%)		p value (trt)[c]
	CN[b]	CT	CN	CT	CN	CT	
Production parameters							
Yield (kg/vine)	4.83 ± 0.398[a]	**3.61 ± 0.258**	4.83 ± 0.329	**3.14 ± 0.264**	4.87 ± 0.492	**2.81 ± 0.362**	**<0.001**
Leaf area/yield (cm^2/g)	14.4 ± 1.44	18.6 ± 2.41	16.6 ± 1.54	**26.4 ± 2.60**	16.1 ± 2.60	26.1 ± 4.35	**<0.001**
Berry weight (g)	1.58 ± 0.059	1.61 ± 0.071	1.54 ± 0.040	1.56 ± 0.041	1.30 ± 0.095	1.39 ± 0.144	0.298
Fruit composition parameters							
Total soluble solids (°Brix)	21.6 ± 0.420	21.8 ± 0.411	22.4 ± 0.234	**23.2 ± 0.206**	21.8 ± 0.484	21.5 ± 0.530	**0.026**
pH	3.31 ± 0.043	3.37 ± 0.049	3.46 ± 0.027	**3.53 ± 0.028**	3.47 ± 0.035	3.49 ± 0.037	**0.035**
Titratable acidity (g/L)	7.92 ± 0.467	7.71 ± 0.479	6.34 ± 0.277	6.18 ± 0.268	7.83 ± 0.611	8.00 ± 0.532	0.341
Total anthocyanins (mg/kg) FW berry	1456 ± 68.9	1712 ± 151	1109 ± 127	1236 ± 146	—	—	0.184

[a]Data are expressed as means ± standard error. Bold values highlight significant difference ($p < 0.05$) between CN and CT treatments within each severity (25%, 45%, and 65%) using an independent-samples t-test. [b]CN, untreated control; CT, cluster thinning. [c]Comparison between CN and CT treatments using data from all time points ($p < 0.05$).

Regarding severity, MOD and HIGH CT in Syrah improved glycosylated terpenols and some volatile phenols, and decreased C6 compounds, although fewer differences existed between both CT treatments [74]. Rutan et al. [12] compared LOW and MOD CT at LP on the volatile profile of Pinot noir wines across three seasons and found that while MOD CT had the greatest impact on improving some positive aromas and reducing negative ones, LOW CT produced many of the same changes without severely reducing yields. In Muscat Hamburg, MOD CT and PS enhanced monoterpene concentrations compared to LOW CT [75]. Interestingly, Kovalenko et al. [33] recently revealed that only the combination of MOD CT at LP significantly enhanced the concentrations of both free and glycosylated terpenes in Gewürztraminer grapes, while CT at LOW severity or at V did not.

4. Discussion

4.1. Geographical and Climactic Influence on CT Studies. The widespread use of cluster thinning (CT) in vineyards has prompted the output of over 150 studies on this practice in grape, with the specific aims of understanding the varied benefits on production and fruit composition. Over the past 50 years, research has largely been carried out in North America and Europe; however, works were also performed in four other continents. These studies were conducted across hot, warm, and cool climates, as well as in regions receiving high and low volumes of annual precipitation. Together, this reflects the climactic diversity in wine grape production across the world, as well as the desire of producers and winemakers to produce wine grapes in many climates in spite of environmental constraints in many regions [76]. The use of CT in diverse climates and scenarios also represents the multiple scenarios where crop load adjustment can improve fruit composition. Highly fruitful cultivars typically found in warm and hot climates require thinning to adequately ripen the crop [6, 15]. In some European countries, this also involves reducing yields to meet governmental standards for yield and total soluble solids, such as the Denominazione di Origine Controllata (DOC) in Italy. In contrast, in cool climates, season, and day length restrict daily carbon assimilation during ripening, and CT provides a higher source-to-sink balance, which can advance ripening and improve fruit composition [77].

An interesting result from this meta-analysis is that climate was not related to the modulation of any dependent variable by CT. First, this is because most cultivars and viticultural management practices are selected on a climate-specific basis to maintain year-to-year production and composition. Second, GDD and precipitation values were calculated for each experimental site and year at the end of the growing season, and CT application occurs near the early or middle part of the season. It is possible that early (or late) season climate trends (e.g., a warm spring/cool summer or a wet spring/dry summer) would mask an otherwise evident relationship if only the seasonal means are considered. Multiple studies have observed varying successes of CT to improve fruit composition in seasons characterized by obvious climactic differences. The efficacy of V CT to enhance fruit composition was reported to be directly related to the seasonal temperature evolution from veraison to harvest [8]. In the season with the cooler ripening period, CT improved fruit composition at harvest, while in the warmer season, no differences were found between treatments. In another study, CT was found to be most effective at improving Verdejo wine aroma in the coolest and wettest season [78]. Cool temperatures and reduced sunlight lower photosynthesis rates and decrease the source-to-sink balance without changing leaf area or crop load, which slows the ripening process. CT increases this balance, which promotes maturation and improves fruit composition [60]. While CT was not shown to be more effective in cool climates, it may be more impactful to fruit composition in seasons with cool ripening periods.

4.2. CT Impact on TSS Is Dependent on Cultivar. It is observed in this study that CT affects TSS accumulation on a cultivar-dependent basis. Riesling, Syrah, and Tempranillo are examples of cultivars where CT increased TSS by approximately 1°Brix or higher. Meanwhile, Cabernet Sauvignon is the most studied variety in the literature, and no impact of CT on TSS was observed across 56 studies. In some cases, the explanation for variability among cultivars may be due to a cultivar-specific response of leaf photosynthesis rate to CT. A study in Cabernet Sauvignon showed an inhibitory effect of CT on leaf photosynthetic assimilation, and no change in TSS at harvest maturity [27]. Meanwhile, other studies seeing an increase in TSS or berry sugar concentration by CT showed no difference or an improvement in photosynthesis rate compared to untreated plants [33, 79]. An increase in photosynthesis due to CT was explained by potential overcropping in the control treatment, or that more nitrogen was allocated to leaves following CT, which also facilitated greater canopy growth and photochemical efficiency compared to CT [79]. Another explanation for the range in response of varying cultivars to CT may be due to cultivar-specific resilience to changes in the source-to-sink balance. Martínez-Lüscher and Kurtural [80] recently confirmed that Cabernet Sauvignon is not sensitive to changes in the source-to-sink balance. This general characteristic of Cabernet Sauvignon is also observed in research on other viticultural practices. For example, studies have highlighted the isohydric behavior of this cultivar or Grenache to changes in soil water potential compared to an anisohydric cultivar such as Syrah [81, 82]. In addition, Cabernet Sauvignon was found to be less sensitive to environmental conditions compared to Merlot [83].

Although phylloxera resistance is the critical trait for rootstock selection, adaptation to drought or water-logging to different soil types, as well as rootstock influence on scion vigor and grape composition are other major characteristics [84–86]. Significant interactions between scion cultivar and rootstocks were found for parameters such as yield and berry weight and pH [87]. Recent studies have shown that the rootstock can affect the leaf and berry transcriptome, and the metabolism of the scion berry at maturity [88], affecting the levels of phenolics of the scion berry [89]. Our data indicate that the amplitude of response to CT was similar among most rootstocks considered. It is important to notice that, for some rootstocks, the studies considered in this analysis were conducted only in a single location and this might have affected the results or made them less representative. However, our results are consistent with the findings of Nuzzo and Matthews [47] who tested the potential interaction of CT levels with rootstocks in Cabernet Sauvignon grafted onto five different rootstocks. The study showed that grape TSS increased with the decrease in yield, but the effect of the thinning treatments did not appear to be influenced by the rootstock used.

4.3. CT Regulates Production and Fruit Composition. The current analysis encompassed studies with a wide range of yield (from 30.6 kg/vine in Freeman and Keller [53] to 1.25 kg/vine in Alem et al. [73]; as well as many different varieties, rootstocks, and training systems. In the majority of the studies considered, yield was significantly decreased by CT; however, only a few studies or specific observations (seasons and cultivars) within studies indicated no effects on yield [43, 90].

Our work indicates overall no effects of CT on BW regardless of CT timing or severity. However, significant increases in BW were associated to CT in specific studies [53, 70, 91–93] but were generally lower than 10% and rarely consistent among seasons. Negative effects of CT on BW were observed in a few experiments [34, 70, 91, 92] when CT was applied at veraison, however, were not consistent among seasons, except in one study [92]. Work in table grapes suggests that CT affects berry size only when performed early during berry development [94]. The results indicate that, in wine grapes, changes in BW due to CT are limited and inconsistent among seasons but increases in BW within specific studies were more often observed when the treatment was applied early during berry development (bloom and fruit set) than when applied at veraison. This analysis suggests that, in many of the studies analyzed, the crop load of control treatments did not reach levels that limited berry size. Interestingly, the only study that reported consistent positive effects of CT on BW was the study where yields of control vines were the highest (26.7 kg/vine on average among three seasons) among the studies considered, indicating that crop load might determine the type of response of BW to CT [53].

CT significantly increased TSS levels, indicating a consistent advancement of ripening when CT is applied. CT has been shown to stimulate the expression of hexose and sucrose transporter genes in Syrah grapes [95]. The relative change in TSS due to CT was similar regardless of the timing of treatment application. CT promotes a large increase of the leaf area to yield ratio, also known as crop load, which implies a higher amount of partitioned photosynthates per unit of fruit [96]. A minimal amount of leaf area in relation to the crop size is required to avoid impairments of yield or grape composition determined by overcropping situations, and CT allows the vine to reach this minimal amount. Kliewer and Dokoozlian [2] reported values of 0.8 to 1.2 of leaf-area-to-yield ratio as being necessary to promote maximum levels of total soluble solids, berry weight, and phenolic concentration at harvest in single-canopy trellis-training systems, and lower values (0.5 to 0.8) for horizontally divided-canopy type trellis-training systems. In the studies we considered, when LA : Y was reported or could be calculated, CT increased LA : Y by approximately 60%. However, the thresholds reported by Kliewer and Dokoozlian [2] were largely overcome also in control vines. This indicates that CT promotes TSS accumulation also in situations when the crop load is already at optimal levels.

Consistent with the increase of TSS, we observed a significant but marginal increase of pH in grapes of vines exposed to CT. The increase in pH was similar in absolute value to the average decrease in TA; however, TA decrease was not significant, even though several individual studies reported occasional significant decreases in TA in vines subjected to CT [42, 46, 67, 70]. Interestingly, the PCA analysis indicated that juice pH and TSS responses are closely related to CT severity.

Our meta-analysis revealed no overall significant increase in the concentration of anthocyanin and phenolics due to CT; however, many individual studies indicated a positive effect of CT on berry anthocyanin and phenolic concentration. Increases in anthocyanins were observed in studies performed in various wine regions that considered multiple varieties, including Nebbiolo [97], Tempranillo [51, 98–101], Syrah [100, 102], Sangiovese [15], Grenache [91], Pinot Noir [10, 34, 46, 103], Cabernet Sauvignon [27, 32, 39, 46, 104], Merlot [31], Malbec [36], Refosco [105], Tannat [92], and Cabernet Franc [8, 104]. The observed increases in grape and wine anthocyanin concentration might be determined by the increases in sugars determined by CT. Anthocyanin and sugar accumulation at the onset of ripening are strongly related [106]; however, uncoupling effects between anthocyanin and sugars may be observed during ripening when grapes are subjected to environmental stresses, such as drought or heat stress [107–109]. Despite this, we cannot rule out the role of sugars in regulating anthocyanin increase upon CT. We observed that anthocyanin increases due to CT did not always parallelly increase TSS. For example, several studies on Cabernet Sauvignon reported increases in anthocyanins and not changes of TSS under CT [27, 49, 104]. This indicates that the effects of CT on the overall composition of grapes and wine are not necessarily associated to the effects on TSS.

4.4. CT Severity Has a Greater Influence on Fruit Composition and the Yield-TSS Tradeoff than CT Timing. As leaves age, their capacity to carboxylate CO_2 follows a parabolic curve; values are greatest near the onset of ripening and decrease thereafter until senescence [110]. Additionally, primary shoot and leaf growth cease near the lag phase of vine development. Therefore, it could be hypothesized that variations in the source-to-sink balance at different stages during vine growth and development would be met with different responses in the tradeoff between yield reduction and the subsequent increase in TSS by CT. However, the results of our work suggest that there was no apparent influence of timing on this tradeoff, suggesting otherwise. This may be explained by the ability of photochemical processes to compensate for alterations in sink strength, which change during the season [111]. Wang et al. revealed that photosynthetic assimilation was reduced more by CT at PS than at V; however, TSS was not impacted at harvest maturity by either treatment compared to the untreated control [27].

Different from CT timing, CT severity impacted fruit composition, with moderate severity positively impacting fruit composition and low and high severity having little to no influence. At a low severity of CT, TSS is not improved because the competition for photosynthates among clusters is still high. The competition decreases as the CT severity increases, and the cluster can improve TSS yield. On the other end of the spectrum, when a very high severity of CT is applied, creating a very high leaf area to yield ratio, the viticultural technique does not improve TSS at harvest. This suggests that CT only improves fruit composition within a narrow crop load range, whereby crop load values below the lower threshold or above the upper threshold of this range do not impact fruit composition [112]. Gas exchange data from a recent study conducted on field-grown Pinot noir grapevines are reflective of our overall finding; moderate CT increased photosynthetic assimilation rate, stomatal conductance, and carbon assimilation to clusters compared to the untreated control and high CT treatment [79]. This significant reduction in assimilation rate and carbon partitioning to fruit under high CT can be explained by the fact that low sink activity (yield reduction by CT) of the fruit likely increased feedback inhibition, especially in the afternoon and concomitantly favoring the allocation of photosynthates to the vegetative tissues [18, 79, 113].

4.5. Cluster Thinning Effects on Aroma Volatiles. This study was able to examine five variables (TSS, pH, TA, PHE, and ANT) relating to fruit composition that are often reported in research studies on CT. Volatile organic compounds also influence grape and wine aroma and flavor; however, their modulation by CT has been studied far less than other fruit composition parameters. While most fruit quality parameters were not impacted by CT timing, timing of CT may influence aroma volatile production. Multiple studies showed a greater sensitivity to CT at particular stages [32, 33, 71–73]. This may be linked to the complex nature of aroma volatile biosynthesis compared to TSS, which occurs during the entirety of grape development rather than just during and postveraison [114]. A particularly interesting trend across these studies is the greater sensitivity of terpene aromas at CT timings nearer to V. Terpenes accumulate in fruit in a pattern similar to TSS, with certain genes encoding rate-limiting enzymes of monoterpene biosynthesis being expressed immediately before and during veraison, as was discussed by our recent work [33]. The optimal timing of CT to enhance volatile aroma concentration may be due to the relationship between the expression of genes regulating biosynthetic pathways of aroma volatile classes most represented in a particular cultivar. This connection should be explored in future research.

Like TSS and pH, MOD CT severity may best promote aroma volatile production due to MOD leading to the strongest sink strength. CT typically enhances LA : Y, which has previously been shown to regulate volatile production [115]. In some studies, the higher LA : Y increased TSS in fruit at harvest maturity [32, 33, 74]. Given that the concentration of many positive aroma volatiles often increases with hang time [116, 117], it could be assumed that this advancement in ripening could promote higher aroma volatiles production by advancing ripening above a certain TSS threshold. However, many studies also failed to observe this relationship despite an increase in desirable aroma volatiles [12, 33, 70, 75, 118]. Indeed, aroma production is thought to not be related to berry sugar content [119, 120]. By removing clusters from the fruitzone, CT may also enhance exposure of remaining clusters to solar radiation. This was observed anecdotally in Rutan et al. [12]; while no difference was seen in measurements by Mawdsley et al. [34]. Solar radiation is understood to impact the accumulation of a large number of volatiles [121, 122]. Ultimately, the impact of CT on aroma volatile production may involve both factors.

4.6. Economic and Viticultural Context for Cluster Thinning Implementation. An important aim of this work is to aid grape producers with crop load-related management decisions. This information also extends to other individuals that influence yield management quotas, regulations, and decisions, such as ownership, winemakers, and buyers [13]. Research on CT has long revealed seasonal inconsistencies relating to improved fruit composition [10, 53, 77]. Given this, it is important for producers to consider the cost-benefit principle when employing this practice. The exceptional degree of variability between production systems makes economic analysis of performing CT difficult; however, providing this information is integral to understanding the efficacy of this practice [123]. Matching an important result from our work, a study in Riesling found that only MOD (but not LOW) CT resulted in wines able to be differentiated from nonthinned treatments by consumers across two seasons, and further economic analysis revealed that a large increase in grape price (up to 143%) was required to offset the loss in yield [41]. The authors of this work suggested that the cost of implementing CT on a vineyard-scale may not outweigh the benefits in most cases, which has been echoed by other studies [35, 73].

5. Conclusions

This study presents a meta-analysis and systematic review of CT in relation to grape yield and fruit composition parameters, providing key insights into its effects on wine grape production. Our findings reveal that the timing of CT does not significantly affect yield or fruit composition. CT timing also has little effect on the yield-TSS tradeoff, which provides greater flexibility in application timing for grape producers who apply this practice. However, the impact of CT on yield and fruit composition is strongly influenced by severity, with only moderate severity increasing LA : Y, pH, and TSS, and showing a strong relationship between this tradeoff (higher TSS relative to the decrease in yield). Interestingly, the influence of CT on fruit composition was strongly influenced by cultivar and moderately by rootstock, but climate was not impactful. An overview of CT effects on grape and wine aroma volatiles suggests that aroma volatiles may be improved to a greater extent than basic fruit composition parameters, which may influence use of this practice. Finally, we provide a brief outlook on CT from an economic standpoint and suggest that use of this practice may only benefit wine grape producers in limited circumstances. Together, this work provides important information for CT to be utilized in production systems.

This work brings to light clear opportunities for future research. The cultivar of interest was identified to be a prominent determinant of CT ability to modulate berry composition. Taking into consideration studies that evaluate CT effects on important fruit and wine composition parameters such as TSS, phenolic concentration, and aroma concentration, this review suggests that Syrah, Tempranillo, and Pinot noir grapes and wines are highly sensitive to CT. Meanwhile, Cabernet Sauvignon grape and wine composition responded poorly to CT. An explanation for the difference in sensitivity of fruit composition parameters to CT is not clear and should be the focus of future research.

Disclosure

A partial elaboration of the data was presented as a poster at the "American Society for Enology and Viticulture" conference.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

All authors contributed significantly and agree with the manuscript.

Supplementary Materials

Supplementary Table 1: climatic classification of observations used in the analysis. Supplementary Table 2: Pearson's correlation coefficient analysis between yield parameters and berry weight and fruit composition by timing of cluster thinning. Supplementary Table 3: Pearson's correlation coefficient analysis between yield parameters and berry weight and fruit composition by severity of cluster thinning. (*Supplementary Materials*)

References

[1] R. Falchi, C. Bonghi, M. F. Drincovich et al., "Sugar metabolism in stone fruit: source-sink relationships and environmental and agronomical effects," *Frontiers in Plant Science*, vol. 11, p. 573982, 2020.

[2] W. M. Kliewer and N. K. Dokoozlian, "Leaf area crop weight ratios of grapevines influence on fruit composition and wine quality," *American Journal of Enology and Viticulture*, vol. 56, no. 2, pp. 170–181, 2005.

[3] R. Matsuda, K. Suzuki, A. Nakano, T. Higashide, and M. Takaichi, "Responses of leaf photosynthesis and plant growth to altered source–sink balance in a Japanese and a Dutch tomato cultivar," *Scientia Horticulturae*, vol. 127, no. 4, pp. 520–527, 2011.

[4] A. L. Reeve, P. A. Skinkis, A. J. Vance, J. Lee, and J. M. Tarara, "Vineyard floor management influences 'pinot noir' vine growth and productivity more than cluster thinning," *HortScience*, vol. 51, no. 10, pp. 1233–1244, 2016.

[5] A. G. Reynolds, C. G. Edwards, D. A. Wardle, D. R. Webster, and M. Dever, "Shoot density affects `Riesling' grapevines I. Vine performance," *Journal of the American Society for Horticultural Science*, vol. 119, no. 5, pp. 874–880, 1994.

[6] O. Silvestroni, V. Lanari, T. Lattanzi, A. Palliotti, J. Vanderweide, and P. Sabbatini, "Canopy management strategies to control yield and grape composition of Montepulciano grapevines," *Australian Journal of Grape and Wine Research*, vol. 25, no. 1, pp. 30–42, 2018.

[7] D. Kok, "Variation in Total Phenolic Compounds, Anthocyanin and Monoterpene Content of 'Muscat Hamburg' Table Grape Variety (V. vinifera L.) as Affected by Cluster Thinning and Early and Late Period Basal Leaf Removal Treatments," *Erwerbs-obstbau*, vol. 58, no. 4, pp. 241–246, 2016.

[8] S. Zhuang, L. Tozzini, A. Green et al., "Impact of cluster thinning and basal leaf removal on fruit quality of Cabernet Franc (vitis vinifera L.) grapevines grown in cool climate conditions," *HortScience*, vol. 49, no. 6, pp. 750–756, 2014.

[9] G. S. Howell, "Sustainable grape productivity and the growth-yield relationship: a review," *American Journal of Enology and Viticulture*, vol. 52, no. 3, pp. 165–174, 2001.

[10] A. L. Reeve, P. A. Skinkis, A. J. Vance et al., "Vineyard floor management and cluster thinning inconsistently affect 'pinot noir' crop load, berry composition, and wine quality," *HortScience*, vol. 53, no. 3, pp. 318–328, 2018.

[11] A. G. Reynolds, S. F. Price, D. A. Wardle, and B. T. Watson, "Fruit environment and crop level effects on pinot noir. I. Vine performance and fruit composition in British columbia," *American Journal of Enology and Viticulture*, vol. 45, no. 4, pp. 452–459, 1994.

[12] T. E. Rutan, M. Herbst-Johnstone, and P. A. Kilmartin, "Effect of cluster thinning Vitis vinifera cv. Pinot noir on wine volatile and phenolic composition," *Journal of Agricultural and Food Chemistry*, vol. 66, no. 38, pp. 10053–10066, 2018.

[13] D. M. Uzes and P. A. Skinkis, "Factors influencing yield management of pinot noir vineyards in Oregon," *Journal of Extension*, vol. 54, no. 3, pp. 2012–2014, 2016.

[14] I. Dami, D. Ferree, A. Prajitna, and D. Scurlock, "A five-year study on the effect of cluster thinning on yield and fruit composition of `Chambourcin' grapevines," *HortScience*, vol. 41, no. 3, pp. 586–588, 2006.

[15] M. Gatti, F. Bernizzoni, S. Civardi, and S. Poni, "Effects of cluster thinning and preflowering leaf removal on growth and grape composition in cv. Sangiovese," *American Journal of Enology and Viticulture*, vol. 63, no. 3, pp. 325–332, 2012.

[16] R. Lemoine, S. La Camera, R. Atanassova et al., "Source-to-sink transport of sugar and regulation by environmental factors," *Frontiers in Plant Science*, vol. 4, p. 272, 2013.

[17] S. Osorio, Y.-L. Ruan, and A. R. Fernie, "An update on source-to-sink carbon partitioning in tomato," *Frontiers in Plant Science*, vol. 5, pp. 516–611, 2014.

[18] C. E. Edson, G. S. Howell, and J. A. Flore, "Influence of crop load on photosynthesis and dry matter partitioning of seyval grapevines. III. Seasonal changes in dry matter partitioning, vine morphology, yield, and fruit composition," *American Journal of Enology and Viticulture*, vol. 46, no. 4, pp. 478–485, 1995.

[19] T. Frioni, D. Acimovic, S. Tombesi et al., "Changes in within-shoot carbon partitioning in pinot noir grapevines subjected to early basal leaf removal," *Frontiers in Plant Science*, vol. 9, pp. 1122–1211, 2018.

[20] N. L. Partridge, "Growth and yield of Concord grape vines," *American Society for Horticultural Science*, vol. 22, pp. 84–87, 1925.

[21] R. E. Smart and M. Robinson, "Sunlight into Wine," *Winetitles*, Adelaide, Australia, 1991.

[22] P. R. Petrie, M. C. T. Trought, and G. S. Howell, "Influence of leaf ageing, leaf area and crop load on photosynthesis, stomatal conductance and senescence of grapevine (Vitis vinifera L. cv. Pinot noir) leaves," *Vitis*, vol. 39, pp. 31–36, 2000.

[23] P. R. Petrie, M. C. T. Trought, G. S. Howell, and G. D. Buchan, "The effect of leaf removal and canopy height on whole-vine gas exchange and fruit development of Vitis vinifera L. Sauvignon Blanc," *Functional Plant Biology*, vol. 30, no. 6, pp. 711–717, 2003.

[24] S. Poni, L. Casalini, F. Bernizzoni, S. Civardi, and C. Intrieri, "Effects of early defoliation on shoot photosynthesis, yield

components, and grape composition," *American Journal of Enology and Viticulture*, vol. 57, no. 4, pp. 397–407, 2006.

[25] J. VanderWeide, S. Tombesi, S. D. Castellarin, and P. Sabbatini, "Canopy architecture and fruit microclimate, not ripening-related phytohormones, control phenylpropanoid accumulation in response to early leaf removal in 'Merlot' (Vitis vinifera L.) grapevines," *Plant Physiology and Biochemistry*, vol. 157, pp. 291–302, 2020.

[26] C. E. Edson, G. S. Howell, and J. A. Flore, "Influence of crop load on photosynthesis and dry matter partitioning of seyval grapevines I. Single leaf and whole vine response pre- and post-harvest," *American Journal of Enology and Viticulture*, vol. 44, no. 2, pp. 139–147, 1993.

[27] Y. Wang, Y. N. He, W. K. Chen et al., "Effects of cluster thinning on vine photosynthesis, berry ripeness and flavonoid composition of Cabernet Sauvignon," *Food Chemistry*, vol. 248, pp. 101–110, 2018.

[28] Y. Motomura, "Distribution of ^{14}C-assimilates from individual leaves on clusters in grape shoots," *American Journal of Enology and Viticulture*, vol. 41, no. 4, pp. 306–312, 1990.

[29] M. Fanzone, F. Zamora, V. Jofré, M. Assof, and Á. Peña-Neira, "Phenolic composition of Malbec grape skins and seeds from valle de Uco (mendoza, Argentina) during ripening. Effect of cluster thinning," *Journal of Agricultural and Food Chemistry*, vol. 59, no. 11, pp. 6120–6136, 2011.

[30] D. C. Ferree, G. A. Cahoon, D. M. Scurlock, and M. V. Brown, "Effect of time of cluster thinning grapevines," *Small Fruits Review*, vol. 2, no. 1, pp. 3–14, 2003.

[31] P. D. King, R. E. Smart, and D. J. McClellan, "Timing of crop removal has limited effect on Merlot grape and wine composition," *Agricultural Sciences*, vol. 06, no. 04, pp. 456–465, 2015.

[32] D. Kok and E. Bal, "Timing of Shoot and Bunch Thinning Treatments Affect the Chemical Composition and Monoterpene Profile of V. vinifera L. Cv. Cabernet Sauvignon Wine Grape," *Erwerbs-obstbau*, vol. 61, no. S1, pp. 9–16, 2019.

[33] Y. Kovalenko, J. VanderWeide, R. Tindjau, W. F. Zandberg, and S. D. Castellarin, "Timing and severity of crop load management influences technological maturity, terpene synthase expression and free terpene accumulation in Gewürztraminer grapes (Vitis vinifera L.)," *Australian Journal of Grape and Wine Research*, vol. 28, no. 4, pp. 638–650, 2022.

[34] P. F. W. Mawdsley, J. C. Dodson Peterson, and L. F. Casassa, "Multi-year study of the effects of cluster thinning on vine performance, fruit and wine composition of Pinot noir (clone 115) in California's Edna Valley AVA (USA)," *Scientia Horticulturae*, vol. 256, Article ID 108631, 2019.

[35] A. G. Reynolds, J. Schlosser, D. Sorokowsky, R. Roberts, J. Willwerth, and C. De Savigny, "Magnitude of viticultural and enological effects. II. Relative impacts of cluster thinning and yeast strain on composition and sensory attributes of Chardonnay Musqué," *American Journal of Enology and Viticulture*, vol. 58, no. 1, pp. 25–41, 2007.

[36] M. I. L. F. de Barros, D. B. Frölech, L. L. de Mello et al., "Impact of cluster thinning on quality of "Malbec" grapes in encruzilhada do sul-RS," *American Journal of Plant Sciences*, vol. 9, no. 3, pp. 495–506, 2018.

[37] B. Bravdo, Y. Hepner, C. Loinger, S. Cohen, and H. Tabacman, "Effect of crop level on growth, yield and wine quality of a high yielding carignane vineyard," *American Journal of Enology and Viticulture*, vol. 35, no. 4, pp. 247–252, 1984.

[38] D. M. Chapman, M. A. Matthews, and J. X. Guinard, "Sensory attributes of Cabernet Sauvignon wines made from vines with different crop yields," *American Journal of Enology and Viticulture*, vol. 55, no. 4, pp. 325–334, 2004.

[39] R. V. D. Mota, C. R. D. Souza, C. P. C. Silva et al., "Biochemical and agronomical responses of grapevines to alteration of source-sink ratio by cluster thinning and shoot trimming," *Bragantia*, vol. 69, no. 1, pp. 17–25, 2010.

[40] C. Ough and R. Nagaoka, "Effect of cluster thinning and vineyard yields on grape and wine composition and wine quality of Cabernet Sauvignon," *American Journal of Enology and Viticulture*, vol. 35, no. 1, pp. 30–34, 1984.

[41] T. Preszler, T. M. Schmit, and J. E. Vanden Heuvel, "Cluster thinning reduces the economic sustainability of riesling production," *American Journal of Enology and Viticulture*, vol. 64, no. 3, pp. 333–341, 2013.

[42] J. Reščič, M. Mikulič-Petkovšek, F. Štampar, A. Zupan, and D. Rusjan, "The impact of cluster thinning on fertility and berry and wine composition of Blauer Portugieser (Vitis vinifera L.) grapevine variety," *Oeno One*, vol. 49, no. 4, p. 275, 2015.

[43] A. G. Reynolds, "Riesling grapes respond to cluster thinning and shoot density manipulation," *Journal of the American Society for Horticultural Science*, vol. 114, no. 3, pp. 364–368, 1989.

[44] G. Scaglione, G. Graziani, R. Federico et al., "Effect of canopy management techniques on the nutritional quality of Montepulciano grapevine in Puglia (Southern Italy)," *Oeno One*, vol. 46, no. 4, p. 253, 2012.

[45] E. Susaj, L. Susaj, F. Voci et al., "Effect of cluster thinning on productivity indicators and wine quality of the indigenous red wine grapevine cultivar "Kallmet" in Mjeda, Shkodër, in north-western part of Albania," *Journal of Food, Agriculture and Environment*, vol. 11, pp. 1009–1014, 2013.

[46] P. M. Cañón, Á. S. González, J. A. Alcalde, and E. Bordeu, "Red wine phenolic composition: the effects of summer pruning and cluster thinning," *Agricultural Science and Research*, vol. 41, no. 2, pp. 19-20, 2014.

[47] V. Nuzzo and M. A. Matthews, "Response of fruit growth and ripening to crop level in dry-farmed Cabernet Sauvignon on four rootstocks," *American Journal of Enology and Viticulture*, vol. 57, no. 3, pp. 314–324, 2006.

[48] P. Bowen, C. Bogdanoff, K. Usher, B. Estergaard, and M. Watson, "Effects of irrigation and crop load on leaf gas exchange and fruit composition in red winegrapes grown on a loamy sand," *American Journal of Enology and Viticulture*, vol. 62, no. 1, pp. 9–22, 2011.

[49] M. Karoglan, M. Osrečak, L. Maslov, and B. Kozina, "Effect of cluster and berry thinning on Merlot and Cabernet Sauvignon wines composition," *Czech Journal of Food Sciences*, vol. 32, no. 5, pp. 470–476, 2014.

[50] S. K. Kurtural, I. Dami, and B. H. Taylor, "Effects of pruning and cluster thinning on yield and fruit composition of `Chambourcin' grapevines," *HortTechnology*, vol. 16, no. 2, pp. 233–240, 2006.

[51] L. G. Santesteban, C. Miranda, and J. B. Royo, "Thinning intensity and water regime affect the impact cluster thinning has on grape quality," *Vitis*, vol. 50, pp. 159–165, 2011.

[52] W. M. Kliewer and C. S. Ough, "The effect of leaf area and crop level on the concentration of amino acids and total nitrogen in "Thompson Seedless" grapes," *Vitis*, vol. 9, pp. 196–206, 1970.

[53] B. M. Freeman and W. M. Kliewer, "Effect of irrigation, crop level and potassium fertilization on carignane vines. II.

Grape and wine quality," *American Journal of Enology and Viticulture*, vol. 34, no. 3, pp. 197–207, 1983.
[54] W. M. Kliewer, B. M. Freeman, and C. Hosssom, "Effect of irrigation, crop level and potassium fertilization on carignane vines. I. Degree of water stress and effect on growth and yield," *American Journal of Enology and Viticulture*, vol. 34, no. 3, pp. 186–196, 1983.
[55] J. VanderWeide, C. Gottschalk, S. R. Schultze, E. Nasrollahiazar, S. Poni, and P. Sabbatini, "Impacts of prebloom leaf removal on wine grape production and quality parameters: a systematic review and meta-analysis," *Frontiers in Plant Science*, vol. 11, pp. 621585–621613, 2020.
[56] H. Alem, P. Rigou, R. Schneider, H. Ojeda, and L. Torregrosa, "Impact of agronomic practices on grape aroma composition: a review," *Journal of the Science of Food and Agriculture*, vol. 99, no. 3, pp. 975–985, 2019.
[57] G. A. Gambetta, J. C. Herrera, S. Dayer, Q. Feng, U. Hochberg, and S. D. Castellarin, "The physiology of drought stress in grapevine: towards an integrative definition of drought tolerance," *Journal of Experimental Botany*, vol. 71, no. 16, pp. 4658–4676, 2020.
[58] J. Vanden Heuvel and M. Centinari, "Under-vine vegetation mitigates the impacts of excessive precipitation in vineyards," *Frontiers in Plant Science*, vol. 12, pp. 713135–713214, 2021.
[59] E. Vukicevich, T. Lowery, P. Bowen, J. R. Úrbez-Torres, and M. Hart, "Cover crops to increase soil microbial diversity and mitigate decline in perennial agriculture. A review," *Agronomy for Sustainable Development*, vol. 36, no. 3, p. 48, 2016.
[60] T. Frioni, S. Zhuang, A. Palliotti, P. Sivilotti, R. Falchi, and P. Sabbatini, "Leaf removal and cluster thinning efficiencies are highly modulated by environmental conditions in cool climate viticulture," *American Journal of Enology and Viticulture*, vol. 68, no. 3, pp. 325–335, 2017.
[61] P. D. King, D. J. McClellan, and R. E. Smart, "Effect of severity of leaf and crop removal on grape and wine composition of Merlot vines in hawke's bay vineyards," *American Journal of Enology and Viticulture*, vol. 63, no. 4, pp. 500–507, 2012.
[62] D. Uriarte, D. S. Intrigliolo, L. A. Mancha, J. Picón-Toro, E. Valdes, and M. H. Prieto, "Interactive effects of irrigation and crop level on tempranillo vines in a semiarid climate," *American Journal of Enology and Viticulture*, vol. 66, no. 2, pp. 101–111, 2015.
[63] D. S. Intrigliolo and J. R. Castel, "Interactive effects of deficit irrigation and shoot and cluster thinning on grapevine cv. Tempranillo. Water relations, vine performance and berry and wine composition," *Irrigation Science*, vol. 29, no. 6, pp. 443–454, 2011.
[64] Q. Sun, G. L. Sacks, S. D. Lerch, and J. E. vanden Heuvel, "Impact of shoot and cluster thinning on yield, fruit composition, and wine quality of Corot noir," *American Journal of Enology and Viticulture*, vol. 63, no. 1, pp. 49–56, 2012.
[65] R Core Team, "R: A Language and Environment for Statistical Computing," *R Foundation for Statistical Computing*, Vienna, Austria, 2013.
[66] J. Josse and F. Husson, "missMDA: a package for handling missing values in multivariate data analysis," *Journal of Statistical Software*, vol. 70, no. 1, 2016.
[67] C. Condurso, F. Cincotta, G. Tripodi et al., "Effects of cluster thinning on wine quality of Syrah cultivar (Vitis vinifera L.)," *European Food Research and Technology*, vol. 242, no. 10, pp. 1719–1726, 2016.
[68] I. Talaverano, E. Valdés, D. Moreno, E. Gamero, L. Mancha, and M. Vilanova, "The combined effect of water status and crop level on Tempranillo wine volatiles," *Journal of the Science of Food and Agriculture*, vol. 97, no. 5, pp. 1533–1542, 2017.
[69] L. Moreno Luna, A. Reynolds, F. Di Profio, L. Zhang, and E. Kotsaki, "Crop level and harvest date impact on four ontario wine grape cultivars. II. Wine aroma compounds and sensory analysis," *South African Journal for Enology and Viticulture*, vol. 39, no. 2, 2018.
[70] A. G. Reynolds, J. Schlosser, R. Power, R. Roberts, J. Willwerth, and C. De Savigny, "Magnitude and Interaction of viticultural and enological effects. I. Impact of Canopy Management and yeast strain on sensory and chemical composition of Chardonnay Musqué," *American Journal of Enology and Viticulture*, vol. 58, no. 1, pp. 12–24, 2007.
[71] D. Kok, "Influences of pre- and post-veraison cluster thinning treatments on grape composition variables and monoterpene levels of Vitis vinifera L. cv. Sauvignon Blanc," *Journal of Food Agriculture and Environment*, vol. 9, pp. 22–26, 2011.
[72] Y. Wang, Y. N. He, L. He et al., "Changes in global aroma profiles of Cabernet Sauvignon in response to cluster thinning," *Food Research International*, vol. 122, pp. 56–65, 2019.
[73] H. Alem, H. Ojeda, P. Rigou, R. Schneider, and L. Torregrosa, "The reduction of plant sink/source does not systematically improve the metabolic composition of Vitis vinifera white fruit," *Food Chemistry*, vol. 345, Article ID 128825, 2021.
[74] S. M. Bureau, R. L. Baumes, and A. J. Razungles, "Effects of vine or bunch shading on the glycosylated flavor precursors in grapes of Vitis vinifera L. Cv. Syrah," *Journal of Agricultural and Food Chemistry*, vol. 48, no. 4, pp. 1290–1297, 2000.
[75] X. Yue, Y. Ju, Y. Fang, and Z. Zhang, "Transcriptomics integrated with metabolomics reveals the effect of cluster thinning on monoterpene biosynthesis in "Muscat Hamburg" grape," *Foods*, vol. 10, no. 11, pp. 2718–2720, 2021.
[76] G. Jones and H. Schultz, "Comate change and emerging cool climate wine regions," *The Wine and Viticulture Journal*, vol. 51, 2016.
[77] K. D. Hannam, G. H. Neilsen, D. Neilsen, and P. Bowen, "Cluster thinning as a tool to hasten ripening of wine grapes in the Okanagan Valley, British Columbia," *Canadian Journal of Plant Science*, vol. 95, no. 1, pp. 103–113, 2015.
[78] M. Vilanova, E. Fernández-Fernández, and J. Yuste, "Abiotic stress management and Verdejo wine composition: cluster thinning in different water regimes," *Journal of the Science of Food and Agriculture*, vol. 100, no. 4, pp. 1515–1523, 2020.
[79] Y. Yue, J. Mao, W. Li et al., "Physiological and transcriptome analyses reveal that mid-fruit load improves the strength of source and sink in grapevine (Vitis Vinifera L.)," *Scientia Horticulturae*, vol. 306, Article ID 111479, 2022.
[80] J. Martínez-Lüscher and S. K. Kurtural, "Same season and carry-over effects of source-sink adjustments on grapevine yields and non-structural carbohydrates," *Frontiers in Plant Science*, vol. 12, Article ID 695319, 2021.
[81] U. Hochberg, A. Degu, D. Toubiana et al., "Metabolite profiling and network analysis reveal coordinated changes in grapevine water stress response," *BMC Plant Biology*, vol. 13, no. 1, p. 184, 2013.
[82] T. Scholasch and M. Rienth, "Review of water deficit mediated changes in vine and berry physiology; Consequences for the optimization of irrigation strategies," *Oeno One*, vol. 53, no. 3, pp. 423–444, 2019.

[83] G. V. Jones and R. E. Davis, "Climate influences on grapevine phenology, grape composition, and wine production and quality for Bordeaux, France," *American Journal of Enology and Viticulture*, vol. 51, no. 3, pp. 249–261, 2000.

[84] J. Granett, M. A. Walker, L. Kocsis, and A. D. Omer, "Biology and management of grape phylloxera," *Annual Review of Entomology*, vol. 46, no. 1, pp. 387–412, 2001.

[85] M. Keller, *The Science of the Grapevines Anatomy and Physiology*, Elsevier, Amsterdam, Netherlands, 2015.

[86] L. Zhang, E. Marguerit, L. Rossdeutsch, N. Ollat, and G. A. Gambetta, "The influence of grapevine rootstocks on scion growth and drought resistance," *Theoretical and Experimental Plant Physiology*, vol. 28, no. 2, pp. 143–157, 2016.

[87] P. Clingeleffer, N. Morales, H. Davis, and H. Smith, "The significance of scion × rootstock interactions," *Oeno One*, vol. 53, no. 2, pp. 335–346, 2019.

[88] W. Chitarra, I. Perrone, C. G. Avanzato et al., "Grapevine grafting: scion transcript profiling and defense-related metabolites induced by rootstocks," *Frontiers in Plant Science*, vol. 8, pp. 654–715, 2017.

[89] A. Zombardo, E. Mica, S. Puccioni et al., "Berry quality of grapevine under water stress as affected by rootstock–scion interactions through gene expression regulation," *Agronomy*, vol. 10, no. 5, p. 680, 2020.

[90] J. Morris, C. Sims, R. K. Striegler, S. D. Cackler, and R. A. Donley, "Effects of cultivar, maturity, cluster thinning, and excessive potassium fertilization on yield and quality of Arkansas wine grapes," *American Journal of Enology and Viticulture*, vol. 38, no. 4, pp. 260–264, 1987.

[91] J.-M. Avizcuri-Inac, A. Gonzalo-Diago, J. Sanz-Asensio et al., "Effect of cluster thinning and prohexadione calcium applications on phenolic composition and sensory properties of red wines," *Journal of Agricultural and Food Chemistry*, vol. 61, no. 5, pp. 1124–1137, 2013.

[92] G. Gonzalez-Neves, G. Gil, and M. Ferrer, "Effect of different vineyard treatments on the phenolic contents in Tannat (Vitis vinifera L.) grapes and their respective wines," *Food Science and Technology International*, vol. 8, no. 5, pp. 315–321, 2002.

[93] X. Wang, R. De Bei, S. Fuentes, and C. Collins, "Influence of canopy management practices on canopy architecture and reproductive performance of Semillon and shiraz grapevines in a hot climate," *American Journal of Enology and Viticulture*, vol. 70, no. 4, pp. 360–372, 2019.

[94] R. J. Weaver and R. Pool, "Effect of time of thinning on berry size of girdled, gibberellin treated "Thompson Seedless" grapes," *Vitis*, vol. 12, pp. 97–99, 1973.

[95] W. Wang, Y. Liang, G. Quan, X. Wang, and Z. Xi, "Thinning of cluster improves berry composition and sugar accumulation in Syrah grapes," *Scientia Horticulturae*, vol. 297, Article ID 110966, 2022.

[96] P. Previtali, N. K. Dokoozlian, B. S. Pan, K. L. Wilkinson, and C. M. Ford, "Crop load and plant water status influence the ripening rate and aroma development in berries of grapevine (Vitis vinifera L.) cv. Cabernet Sauvignon," *Journal of Agricultural and Food Chemistry*, vol. 69, no. 27, pp. 7709–7724, 2021.

[97] S. Guidoni, P. Allara, and A. Schubert, "Effect of cluster thinning on berry skin anthocyanin composition of*Vitis vinifera*cv. Nebbiolo," *American Journal of Enology and Viticulture*, vol. 53, no. 3, pp. 224–226, 2002.

[98] M. Esperanza Valdés, D. Moreno, E. Gamero et al., "Effects of cluster thinning and irrigation amount on water relations, growth, yield and fruit and wine composition of Tempranillo grapes in Extemadura (Spain)," *Oeno One*, vol. 43, no. 2, p. 67, 2009.

[99] E. Gamero, D. Moreno, I. Talaverano, M. H. Prieto, M. T. Guerra, and M. E. Valdés, "Effects of irrigation and cluster thinning on tempranillo grape and wine composition," *South African Journal for Enology and Viticulture*, vol. 35, no. 2, pp. 196–204, 2016.

[100] R. R. Gil-Muñoz, R. Vila-López, J. I. Fernández-Fernández, and A. Martínez-Cutillas, "Effects of cluster thinning on anthocyanin extractability and chromatic parameters of syrah and tempranillo grapes and wines," *Oeno One*, vol. 43, no. 1, pp. 45–53, 2009.

[101] D. Uriarte, D. S. Intrigliolo, L. A. Mancha, E. Valdés, E. Gamero, and M. H. Prieto, "Combined effects of irrigation regimes and crop load on 'Tempranillo' grape composition," *Agricultural Water Management*, vol. 165, pp. 97–107, 2016.

[102] M. Gil, M. Esteruelas, E. González et al., "Effect of two different treatments for reducing grape yield in Vitis vinifera cv Syrah on wine composition and quality: berry thinning versus cluster thinning," *Journal of Agricultural and Food Chemistry*, vol. 61, no. 20, pp. 4968–4978, 2013.

[103] G. Mazza, L. Fukumoto, P. Delaquis, B. Girard, and B. Ewert, "Anthocyanins, phenolics, and color of Cabernet Franc, Merlot, and pinot noir wines from British columbia," *Journal of Agricultural and Food Chemistry*, vol. 47, no. 10, pp. 4009–4017, 1999.

[104] L. H. Moreno Luna, A. G. Reynolds, and F. Di Profio, "Crop level and harvest date impact composition of four ontario winegrape cultivars. I. Yield, fruit, and wine composition," *American Journal of Enology and Viticulture*, vol. 68, no. 4, pp. 431–446, 2017.

[105] P. Sivilotti, R. Falchi, J. Vanderweide et al., "Yield reduction through cluster or selective berry thinning similarly modulates anthocyanins and proanthocyanidins composition in Refosco dal peduncolo rosso (Vitis vinifera L.) grapes," *Scientia Horticulturae*, vol. 264, Article ID 109166, 2020.

[106] Z. W. Dai, M. Meddar, C. Renaud et al., "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*, vol. 65, no. 16, pp. 4665–4677, 2013.

[107] S. D. Castellarin, M. A. Matthews, G. Di Gaspero, and G. A. Gambetta, "Water deficits accelerate ripening and induce changes in gene expression regulating flavonoid biosynthesis in grape berries," *Planta*, vol. 227, no. 1, pp. 101–112, 2007.

[108] J. C. Herrera, B. Bucchetti, P. Sabbatini et al., "Effect of water deficit and severe shoot trimming on the composition of V itis vinifera L. Merlot grapes and wines," *Australian Journal of Grape and Wine Research*, vol. 21, no. 2, pp. 254–265, 2015.

[109] V. O. Sadras and M. A. Moran, "Elevated temperature decouples anthocyanins and sugars in berries of Shiraz and Cabernet Franc," *Australian Journal of Grape and Wine Research*, vol. 18, no. 2, pp. 115–122, 2012.

[110] H. R. Schultz, W. Kiefer, and W. Gruppe, "Photosynthetic duration, carboxylation efficiency and stomatal limitation of sun and shade leaves of different ages in field-grown grapevine (Vitis vinifera L.)," *Vitis*, vol. 35, pp. 169–176, 1996.

[111] F. Iacono, M. Bertamini, A. Scienza, and B. G. Coombe, "Differential effects of canopy manipulation and shading of Vitis vinifera L. cv. Cabernet Sauvignon. Leaf gas exchange, photosynthetic electron transport rate and sugar accumulation in berries," *Vitis*, vol. 34, p. 201, 1995.

[112] D. I. Jackson and P. B. Lombard, "Environmental and management practices affecting grape composition and wine quality-a review," *American Journal of Enology and Viticulture*, vol. 44, no. 4, pp. 409–430, 1993.

[113] A. Palliotti, M. Gatti, and S. Poni, "Early leaf removal to improve vineyard efficiency: gas exchange, source-to-sink balance, and reserve storage responses," *American Journal of Enology and Viticulture*, vol. 62, no. 2, pp. 219–228, 2011.

[114] J. Lin, M. Massonnet, and D. Cantu, "The genetic basis of grape and wine aroma," *Horticultural Research*, vol. 6, no. 1, p. 81, 2019.

[115] A. Escudero, I. Arias, B. Lacau et al., "Effects of vineyard 'potential' and grape maturation on the aroma-volatile profile of Grenache wines," *Oeno One*, vol. 53, no. 4, pp. 695–707, 2019.

[116] Y. Fang and M. C. Qian, "Quantification of selected aroma-active compounds in pinot noir wines from different grape maturities," *Journal of Agricultural and Food Chemistry*, vol. 54, no. 22, pp. 8567–8573, 2006.

[117] B. Wilson, C. R. Strauss, and P. J. Williams, "Changes in free and glycosidically bound monoterpenes in developing Muscat grapes," *Journal of Agricultural and Food Chemistry*, vol. 32, no. 4, pp. 919–924, 1984.

[118] A. G. Reynolds and D. A. Wardle, "Flavour development in the vineyard: impact of viticultural practices on grape monoterpenes and their relationship to wine sensory response," *South African Journal for Enology and Viticulture*, vol. 18, no. 1, pp. 3–18, 2017.

[119] M. Pollon, F. Torchio, S. Giacosa, S. R. Segade, and L. Rolle, "Use of density sorting for the selection of aromatic grape berries with different volatile profile," *Food Chemistry*, vol. 276, pp. 562–571, 2019.

[120] J. Wang, J. VanderWeide, Y. Yan et al., "Impact of hormone applications on ripening-related metabolites in Gewürztraminer grapes (Vitis vinifera L.): the key role of jasmonates in terpene modulation," *Food Chemistry*, vol. 388, Article ID 132948, 2022.

[121] M. Friedel, J. Frotscher, M. Nitsch et al., "Light promotes expression of monoterpene and flavonol metabolic genes and enhances flavour of winegrape berries (Vitis vinifera L. cv. Riesling)," *Australian Journal of Grape and Wine Research*, vol. 22, no. 3, pp. 409–421, 2016.

[122] L. He, X.-Q. Xu, Y. Wang et al., "Differential influence of timing and duration of bunch bagging on volatile organic compounds in Cabernet Sauvignon berries (Vitis viniferaL.)," *Australian Journal of Grape and Wine Research*, vol. 28, no. 1, pp. 75–85, 2022.

[123] T. Preszler, T. M. Schmit, and J. E. vanden Heuvel, "A model to establish economically sustainable cluster-thinning practices," *American Journal of Enology and Viticulture*, vol. 61, no. 1, pp. 140–146, 2010.