

Early pruning vs. late pruning in Pinot Noir and Sauvignon Blanc

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Abstract

The study examines the effects of early versus late pruning on the growth, yield, and grape quality of Pinot Noir and Sauvignon Blanc from Recaș region, Romania, with a focus on the influence of pruning timing on canopy and ripening characteristics. Over three growing seasons (2021–2023), a randomized complete block design was used with 15 vines per pruning treatment (early and late) for each variety. Early pruning was conducted during dormancy, and late pruning post-budburst. Key parameters such as bud break timing, shoot length, yield components, and berry quality (sugar content, titratable acidity, and pH) were recorded. Early pruning increased bud break percentage, shoot length, and sugar levels, promoting faster ripening, while late pruning delayed bud break, retained acidity, and maintained a fresher profile. Pinot Noir responded with higher sugar and pH under early pruning, whereas Sauvignon Blanc retained vegetative growth with late pruning. Early pruning accelerated ripening, enhancing sugar and pH, beneficial for cooler climates, whereas late pruning preserved acidity and vegetative growth, favorable for maintaining freshness in warmer regions. These findings support pruning adjustments based on climate and desired wine styles.

Key words: bud brake, grape, vines, Guyot training, canopy, shoots

Introduction

Pruning is an essential viticultural practice that shapes grapevine growth, yield, and fruit quality by controlling the plant's vegetative and reproductive balance [14]. Among the factors affecting pruning outcomes, timing is particularly critical, as it can influence bud break, vine vigor, and susceptibility to environmental stresses [27]. Traditionally performed during winter dormancy, pruning is often timed early or late in the season to achieve distinct outcomes [24]. Recent research has suggested that pruning timing may impact phenological development, pest and disease susceptibility, and the balance between vegetative and reproductive growth. Despite its significance, the comparative effects of early and late pruning on vine physiology, grape composition, and overall fruit quality across various grapevine cultivars remain insufficiently explored [3].

Early pruning, typically performed during the winter dormancy period, can offer significant advantages by promoting consistent bud break and potentially accelerating the onset of flowering and ripening, which can be beneficial in regions with shorter growing seasons [29]. However, early pruning also comes with notable disadvantages, as it can expose young buds to late frost damage, reducing yields and impacting overall vine health. Additionally, early pruning may affect the vine's carbohydrate reserves, influencing vigor and fruit development later in the season. Understanding the balance of these advantages and disadvantages is essential for optimizing pruning practices, as the timing of this intervention has a lasting impact on vine resilience, productivity, and grape quality [20]. Early pruning in grapevines, can significantly influence grape berry quality by impacting key ripeness parameters, including sugar accumulation, titratable acidity, and pH. By initiating an earlier

bud break and extending the fruit's maturation period, early pruning often accelerates sugar accumulation in berries, potentially leading to higher final sugar levels by harvest [6]. This increase is valuable for producing wines with richer body and increased alcohol content, which is desirable in many winemaking styles. However, early pruning also affects the balance of acids within the grape berries [25]. While prolonged exposure to sunlight and warmth can enhance sugar levels, it simultaneously leads to faster degradation of organic acids, which can lower titratable acidity and raise pH. These changes may influence the taste, freshness, and longevity of the wine, as low acidity and high pH can impact color stability and increase susceptibility to spoilage. Therefore, the effects of early pruning on grape berry quality are multifaceted, influencing sugars, titratable acidity, and pH in ways that require careful consideration, especially in light of vineyard location and climate conditions [34].

Late pruning in grapevines is a viticultural technique gaining attention for its impact on vine development, yield, and fruit quality [21]. Unlike early pruning, which is typically performed during winter dormancy, late pruning is carried out closer to bud break in early spring. This delayed timing can provide several advantages, such as reducing the risk of frost damage to young buds, particularly in regions with unpredictable spring temperatures [8]. Late pruning can also help to delay bud break and potentially extend the ripening period, which is advantageous in warmer climates where earlier ripening may compromise grape quality [30]. However, late pruning has its disadvantages as well; it may lead to reduced vine vigor due to altered carbohydrate allocation, impacting both vegetative and reproductive growth [32]. Additionally, delayed pruning can increase labor demands and complicate vineyard scheduling, as precise timing becomes more critical [4]. By delaying vine growth, late pruning shortens the period between bud burst and harvest, effectively slowing down the berry ripening process. This approach often results in lower sugar levels at harvest, which may be beneficial in regions with warmer climates where excessive sugar accumulation and high alcohol content could detract from the desired wine profile [22]. Late pruning can also help retain higher acidity in grape berries by slowing the degradation of organic acids, leading to higher titratable acidity and lower pH at harvest [9]. These changes contribute to a fresher, more balanced profile in the resulting wine, enhancing its structure, aging potential and microbial stability. While these benefits can improve wine quality in warm climates or during warmer growing seasons, late pruning may also pose challenges, such as an increased risk of under-ripening in cooler regions [1]. As a result, the influence of late pruning on grape berry quality provides a valuable tool for winemakers aiming to optimize berry composition in alignment with vineyard conditions and desired wine style [15].

For cultivars like Pinot Noir and Sauvignon Blanc, which are particularly sensitive to environmental conditions, the choice between early and late pruning can significantly impact outcomes in terms of vine development, bud break timing, and resilience to climatic stresses. Early pruning is generally associated with promoting early bud break and uniformity in growth, potentially enhancing grape ripening in cooler climates but also increasing susceptibility to late frosts [31]. In contrast, late pruning can serve as a frost management strategy, delaying bud break to protect young shoots from spring frost damage, although it may also influence grape composition and delay maturity. Given the nuanced responses of Pinot Noir and Sauvignon Blanc to these treatments, understanding the comparative impacts of early and late pruning on growth patterns, yield, and quality traits is essential [10].

This study aims to evaluate the impact of early and late pruning on the physiological and agronomic responses of Pinot Noir and Sauvignon Blanc, with a focus on understanding how pruning timing may affect yield, grape quality, and overall wine characteristics.

Material and Method

The study was conducted over three growing seasons (2021–2023) in a vineyard located in Recaş area, Timiș County, Romania, known for producing Pinot Noir and Sauvignon Blanc. The vineyard is situated at an altitude among 150–200 meters and experiences a continental climate with some Mediterranean influences. The average annual rainfall is around 600–700 mm, and the average temperature is 11°C.

A randomized complete block design was employed, with two pruning treatments applied to both Pinot Noir and Sauvignon Blanc vines. Early pruning was conducted during dormancy in late winter (before budburst) around 25.02.2021, 21.03.2022 and late pruning was conducted post-budburst (after bud swell) around 20.04.2021, 22.03.2022 and 21.04.2023. Each treatment was applied to 15 vines of each variety, with three replicates per treatment for each variety. Control vines were managed according to standard vineyard practices for the region, excluding pruning timing. Rows of vines in each block were randomly assigned to either early or

late pruning. The vineyard consists of 12-year-old Pinot Noir (6 250 vines/hectare) and Sauvignon Blanc (5000 vines/hectare). The vines are trained to simple Guyot trellis system.

In the early pruning treatment, vines were pruned during the dormant season (before budburst) to remove excess canes and shoots, leaving 2–4 buds per cane]. In the late pruning treatment, pruning was delayed until after budburst, typically during the swollen buds.

Shoot length, number of buds per vine, average shoots length and shoots per vine, were measured to evaluate the effects of early versus late pruning on vine growth in Pinot Noir and Sauvignon Blanc.

Data were collected for each growing season from budburst through harvest, including the following parameters: budburst timing was recorded weekly starting from mid-March to observe the impact of pruning time on bud development; shoot growth (shoot length was measured at regular intervals (every 10–14 days) starting at budburst and continuing until flowering); yield components (number of clusters per vine, cluster weight, and total vine yield were recorded at harvest) and fruit quality (grapes were sampled at maturity to measure berry weight, total soluble solids (°Brix), titratable acidity (TA), and pH).

The data from Figure 1 reflects typical seasonal variability but also highlights significant annual differences, especially in terms of extreme winter lows in 2022 and distinct precipitation patterns. These variations likely influence grapevine growth stages and the quality of grapes harvested in each respective year, potentially impacting the resulting wine characteristics in the Recaş region. The climatic data were taken and processed from the weather station Timisoara

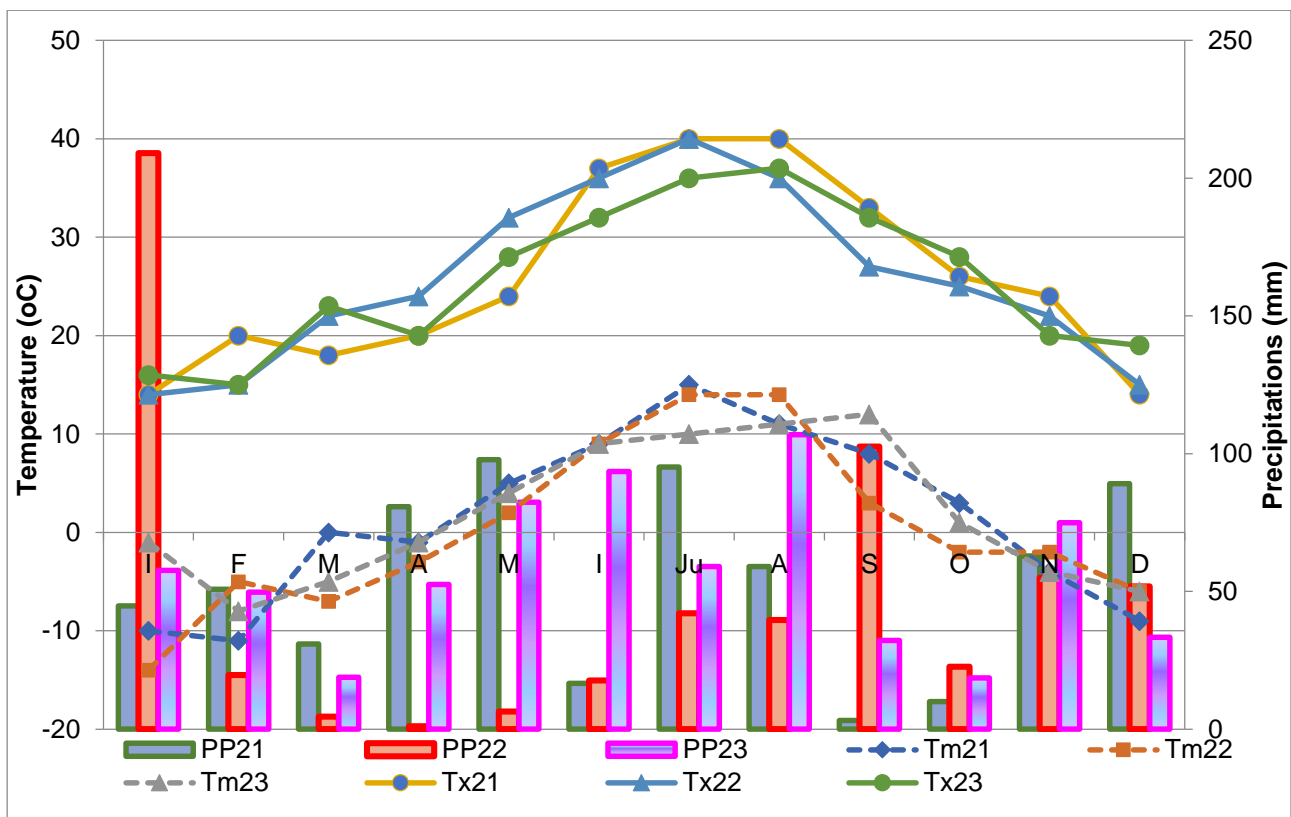


Figure 1. The climate parameters in the Recaş area over three growing seasons (2021, 2022, and 2023) (minimum temperatures (Tm), maximum temperatures (Tx), and precipitation (PP))

The observed low temperatures in winter 2022 could pose risks of frost damage to grapevines, especially if they persisted. The high summer temperatures in all years may accelerate grape ripening, potentially impacting grape composition, such as sugar accumulation and acidity. The uneven precipitation in 2022, with lower rainfall in summer, might lead to water stress, affecting grape yield and quality, particularly in non-irrigated vineyards.

Statistical Analysis

Data were analyzed using XLSTAT (Addinsoft's XLSTAT software, version 2016.7.5) to compare the effects of early and late pruning on vine growth, yield, and fruit quality for both Pinot Noir and Sauvignon Blanc. Analysis of variance (ANOVA) was performed to assess significant differences between treatments, with a significance level set at $p < 0.05$. Post-hoc Tukey tests were conducted to further compare the means where significant differences were found.

Results and discussions

The correlation of climate parameters with early or late pruning in grapevine is crucial because it enables grape growers and winemakers to make informed decisions that optimize grape quality and yield. The data in Table 1 highlights the distinct impacts of early versus late pruning on key growth parameters in Pinot Noir and Sauvignon Blanc, including bud number, bud break percentage, average shoot length, and shoots per vine.

Table 1. The influence of early versus late pruning on various growth parameters (bud number, bud break percentage, average shoot length, and shoots per vine) in Pinot Noir and Sauvignon Blanc

Year	Grape Variety	Pruning type	Buds /vine	Bud break (%)	Average shoot length (cm)	Shoots/vine
2021	Pinot Noir	Early Pruning	18	85	85	15
		Late Pruning	20	75	72	13
	Sauvignon Blanc	Early Pruning	19	88	78	16
		Late Pruning	21	78	66	14
2022	Pinot Noir	Early Pruning	18	90	92	16
		Late Pruning	20	80	78	14
	Sauvignon Blanc	Early Pruning	19	92	85	17
		Late Pruning	21	81	71	15
2023	Pinot Noir	Early Pruning	17	87	88	15
		Late Pruning	20	77	75	14
	Sauvignon Blanc	Early Pruning	18	89	82	16
		Late Pruning	21	79	70	15

Buds per vine. Across all years, late-pruned vines had a slightly higher average number of buds per vine than early-pruned vines for both Pinot Noir and Sauvignon Blanc. Late pruning generated a slight increase in the number of buds per vine, likely due to delayed pruning that allowed for additional bud development or preservation. However, this difference was small suggesting pruning type had minimal impact on bud count.

Bud break percentage. Early pruning results in a consistently higher bud break percentage in both varieties compared to late pruning. Higher bud break percentages for early pruning were likely due to the vines experiencing favorable growing conditions earlier in the season, encouraging bud development. Early pruning led to more uniform and predictable buds break, potentially improving vineyard management and yield consistency. The higher bud break in early pruning suggests that these buds experienced less stress and more optimal temperatures at the onset of the growing season. These findings are consistent with those of Palliotti et al. (2017) [19], who observed that early pruning allows buds to experience favorable temperatures, resulting in more uniform and predictable bud break. Higher bud break rates are advantageous for vineyard management, as they can improve yield consistency and simplify canopy management.

Average shoots length. Early-pruned vines shown significantly longer shoot growth across all years compared to late-pruned vines. Longer shoots in early pruning indicated that these vines benefited from a longer growth period and greater access to sunlight and resources, allowing shoots to extend further. This growth was beneficial for canopy formation but also required more management to prevent excessive shading or vine vigor. Consistent with findings by Hunter et al. (2020) [11], longer shoots support robust canopy development, which can be beneficial for photosynthetic efficiency and fruit ripening, but may require additional canopy management to avoid excessive shading and vine vigor. This need for management is especially crucial, as overly vigorous shoots can reduce light penetration to lower leaves and fruit clusters, impacting grape quality and maturation [13].

Shoots per vine. Early-pruned vines consistently produced more shoots per vine compared to late-pruned vines. Early pruning encouraged the growth of a higher number of shoots, potentially due to an earlier start in the growing season. This positively impacted the overall yield on additional shoots with fruiting clusters, but which also

required more canopy management to maintain optimal sunlight exposure for all shoots. This result aligns with studies by Frioni et al. (2019) [7], who found that early pruning tends to increase shoot productivity, though additional shoots require careful management to prevent overcrowding, which can affect sunlight distribution across the canopy.

General trends and correlations with climate data. Observing yearly data reveals that parameters like shoot length and bud break percentage tend to be higher in warmer, more favorable growing conditions (e.g., higher minimum and maximum temperatures in 2022 and 2023). Early pruning generally led to higher bud break and shoot length, likely due to alignment with optimal temperature and sunlight availability during early spring. The influence of climate parameters, particularly warmer temperatures and higher sunlight availability in early spring, appears to amplify these effects, with optimal early-season conditions supporting initial vine growth and bud development. The observed trends align with the climate-dependent growth responses documented by Netzer et al. (2019) [17], who highlight that temperature and sunlight play a pivotal role in regulating bud break and shoot elongation in grapevines, suggesting that early pruning may be particularly beneficial in regions or years with favorable early-season climate conditions.

Pruning timing, when synchronized with climate conditions, can significantly impact the ripening process, sugar accumulation, acidity, and overall grape composition—factors that directly influence wine style, flavor, and quality. The data presented (Table 2) shows the impact of early vs. late pruning on grape quality parameters—sugar content (°Brix), titratable acidity, and pH—for Pinot Noir and Sauvignon Blanc from 2021 to 2023.

Table 2. The impact of early vs. late pruning on grape quality parameters in Pinot Noir and Sauvignon Blanc

Year	Grape variety	Pruning type	Sugars (°Brix)	Titratable Acidity (g/L)	pH
2021	Pinot Noir	Early Pruning	23.5	5.6	3.60
		Late Pruning	22.0	6.1	3.40
	Sauvignon Blanc	Early Pruning	22.0	6.2	3.55
		Late Pruning	20.8	6.5	3.45
2022	Pinot Noir	Early Pruning	24.0	5.4	3.62
		Late Pruning	22.5	5.8	3.45
	Sauvignon Blanc	Early Pruning	23.5	5.9	3.50
		Late Pruning	21.7	6.2	3.40
2023	Pinot Noir	Early Pruning	25.0	5.2	3.65
		Late Pruning	23.0	6.0	3.42
	Sauvignon Blanc	Early Pruning	24.0	6.1	3.53
		Late Pruning	22.3	6.4	3.47

Sugars (°Brix). Early-pruned vines in both Pinot Noir and Sauvignon Blanc consistently exhibit higher sugar levels than late-pruned vines each year. This trend suggests that early pruning leads to earlier grape maturity, resulting in higher sugar accumulation. In 2021 growing season, early pruning results in a sugar level in both Pinot Noir and Sauvignon Blanc, slightly higher than their late-pruned counterparts. An increase in sugar content in 2022 growing season was observed for both pruning types due to high summer temperatures, with early-pruned Pinot Noir reaching 24.0 °Brix and Sauvignon Blanc at 23.5 °Brix. This aligns with 2022's generally lower precipitation and warmer conditions, which would enhance sugar accumulation in the berries. The highest sugar levels were observed in 2023, with the highest early-pruned Pinot Noir and Sauvignon Blanc °Brix. This reflects the higher temperatures and moderate rainfall, which promote photosynthesis and sugar development. This trend aligns with findings by Petrie and Clingeleffer (2006) [23], who noted that early pruning, exposes vines to more favorable ripening conditions, resulting in greater sugar accumulation. Additionally, climatic conditions in 2022 and 2023, which included warmer temperatures and moderate rainfall, appear to amplify this effect, as higher temperatures are associated with increased photosynthesis and sugar production [28]. Notably, 2023 saw the highest sugar levels across both varieties, likely reflecting a synergistic effect between early pruning and favorable weather conditions.

Titratable Acidity (g/l). Late-pruned grapes consistently show higher titratable acidity than early-pruned ones. This is likely because late pruning delays the ripening process, resulting in berries with more retained acidity. In the first growing season (2021) late-pruned Pinot Noir shows higher acidity (6.1 g/L) compared to early-pruned

(5.6 g/L). The trend is similar in Sauvignon Blanc, with 6.5 g/L for late-pruned versus 6.2 g/L for early-pruned. This corresponds with moderate temperatures and precipitation in the 2021 season, which may have preserved acidity levels. In the following year, acidity levels decrease slightly across both pruning types due to high summer temperatures, which promote acid degradation. Early-pruned Pinot Noir and Sauvignon Blanc show titratable acidity levels of 5.4 and 5.9 g/L, respectively, while late-pruned vines retain higher acidity. A further reduction in acidity was seen in early-pruned grapes from 2023, in both Pinot Noir and Sauvignon Blanc. However, late-pruned grapes maintain higher acidity, likely due to moderate rainfall and delayed ripening under cooler conditions. The trend is in line with results from Reynolds et al. (2010) [26], who observed that late pruning delays fruit maturity and thus maintains higher acidity by slowing the breakdown of organic acids. Particularly in 2021 and 2022, moderate temperatures and controlled precipitation seem to have preserved acidity, while warmer temperatures in subsequent years led to gradual acid degradation, especially in early-pruned grapes, which matured faster and reached peak ripeness earlier.

pH levels. Early-pruned grapes generally have higher pH levels than late-pruned grapes, indicating lower overall acidity. pH values in 2021 were moderately low across both pruning types, with early-pruned Pinot Noir at 3.60 and Sauvignon Blanc at 3.55, while late-pruned counterparts are slightly lower. The pH levels in 2022 slightly increased across both varieties and pruning types, likely due to higher temperatures. Early-pruned grapes for Pinot Noir and Sauvignon Blanc reach 3.62 and 3.50, while late pruning maintains slightly lower pH. The highest pH values were observed in 2023, especially in early-pruned grapes, reflecting lower acidity as a result of accelerated ripening. Late-pruned grapes have lower pH values, indicative of higher acidity retention.

This outcome aligns with research by Kar et al. (2024) [12], who noted that earlier ripening correlates with increased pH due to acid degradation during warmer growing periods. These results collectively highlight the substantial impact of pruning timing on grape ripening and quality, with early pruning favoring faster ripening and sugar accumulation, while late pruning enhances acidity and retains freshness—key factors in tailoring grape composition to desired wine profiles [33].

The principal component analysis (PCA) biplot illustrates the relationships among different pruning treatments (early and late pruning) and grapevine parameters across years (2021-2023) for Pinot Noir (PN) and Sauvignon Blanc (SB). The two principal components, F1 and F2, explain 76.27% and 16.00% of the variation in the data, respectively, indicating that together, they capture a substantial portion (92.27%) of the total variance in the dataset.

Sugars, pH, and average shoot length parameters are strongly correlated and tend to increase together in the samples with higher F1 values, which are mainly associated with early-pruned Pinot Noir from 2022 and 2023. Titratable Acidity (TA) and Buds per Vine (B/v) variables are inversely related to the ripeness factors (sugars and pH) but positively associated with more vegetative traits and late pruning treatments. Shoots per Vine (S/v) and Bud Break Percentage (Bb%) are moderately correlated with ripening traits but also have a component associated with increased vegetative activity, particularly in early-pruned Sauvignon Blanc in 2021–2023.

Early-pruned samples of Pinot Noir, from 2022 and 2023 (PNep22, PNep23) were characterized by high sugars, pH, and average shoot length, and indicate that early pruning promotes ripeness and shoot extension [18]. Early pruning in Sauvignon Blanc (SBep21, SBep22, SBep23) variables are in the upper quadrants near the vectors for shoots per vine and bud break (%), suggesting early pruning also enhances these parameters for Sauvignon Blanc, though with somewhat lower sugar and pH levels compared to Pinot Noir.

Pinot Noir samples from late pruning (PNlp21, PNlp22, PNlp23) suggests that this variety retains higher acidity and favors more vegetative growth (more buds) rather than ripeness. Sauvignon Blanc samples (SBlp21, SBlp22, SBlp23) show less alignment with ripening parameters and more with vegetative and acidic characteristics. This grouping suggests that late pruning in Sauvignon Blanc also slows sugar accumulation and ripeness, which aligns with previous research.

Early pruning significantly enhances sugar levels and pH, especially in Pinot Noir. This effect is consistent across multiple years and highlights the ability of early pruning to accelerate ripening. These results are consistent with findings in viticultural studies indicating that earlier pruning aligns the vine's growth cycle with warmer temperatures in spring and early summer, promoting ripeness [2]. Late pruning maintains higher titratable acidity and increases bud count, particularly in Pinot Noir. This suggests that late pruning can be beneficial for preserving freshness, a desired trait in cooler climates or for certain wine styles.

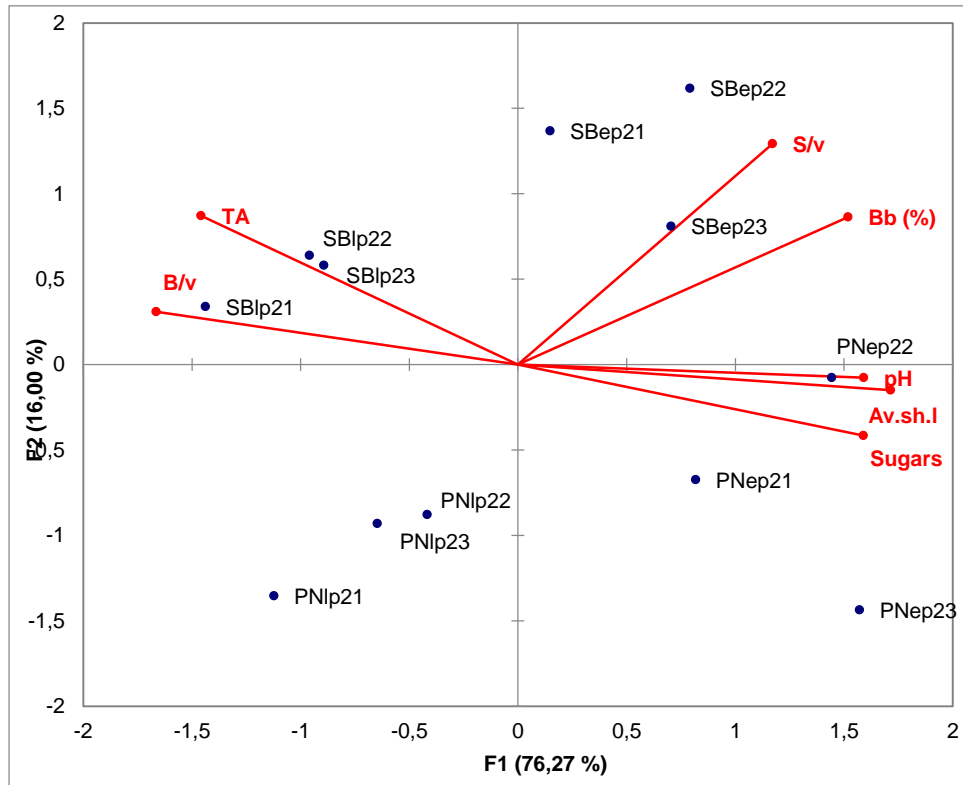


Figure 1. PCA diagram for the relationships among different pruning treatments (early and late pruning) and grapevine parameters across years (2021-2023) for Pinot Noir (PN) and Sauvignon Blanc (SB) (PN = Pinot Noir, SB (Sauvignon Blanc); ep = early pruning; lp = late pruning; S = sugars; TA = titratable acidity; B/v =buds per vine; Bb (%)=bud break (%); Av.sh.l.=average shoots length; S/v –shoots per vine).

The trade-off, however, is that ripening metrics such as sugars and pH do not progress as quickly, potentially leading to less mature fruit at harvest. The association of shoots per vine and bud break (%) with early pruning, especially in Sauvignon Blanc, indicates that early pruning may lead to more vigorous canopy development. This could require additional canopy management to avoid excessive shading and ensure proper sunlight exposure for clusters.

The correlation matrix (Table 3) reveals significant relationships between various viticultural and oenological parameters, providing insights into how early and late pruning affects grapevine development and grape composition.

Table 3. Correlation matrix (Pearson (n)).

Variables	Sugars	TA	pH	B/v	Bb (%)	Av.sh.l	S/v
Sugars	1	-0.834***	0.744***	-0.884***	0.641*	0.886***	0.454
TA	-0.834***	1	-0.734**	0.812***	-0.483	-0.878***	-0.206
pH	0.744**	-0.734**	1	-0.883***	0.741**	0.832***	0.540
B/v	-0.884***	0.812***	-0.883***	1	-0.735**	-0.909***	-0.470
Bb (%)	0.641*	-0.483	0.741**	-0.735**	1	0.805***	0.926***
Av.sh.l	0.886***	-0.878***	0.832***	-0.909***	0.805***	1	0.592*
S/v	0.454	-0.206	0.540	-0.470	0.926***	0.592*	1

Values in bold are different from 0 with a significance level alpha=0,05

(PN = Pinot Noir, SB (Sauvignon Blanc); ep = early pruning; lp = late pruning; S = sugars; TA = titratable acidity; B/v = buds per vine; Bb (%) = bud break (%); Av.sh.l. = average shoots length; S/v –shoots per vine)

There is a strong positive correlation with average shoot length (Av.sh.l) and pH suggesting that early pruning, which encourages shoot growth, also promotes sugar accumulation and raises pH levels in the berries. Sugars correlate negatively with titratable acidity (TA) and buds per vine (B/v), indicating that higher sugar accumulation is associated with lower acidity and fewer buds per vine. This trend is consistent with early-pruned vines that ripen faster and experience more acidity degradation as sugars increase [5].

Titratable acidity has a strong negative correlation with average shoot length (Av.sh.l) and sugars showing that as vines develop longer shoots and accumulate more sugars, acidity tends to decrease.

There is a positive correlation with buds per vine (B/v) suggesting that late pruning, which results in a higher bud count, may help retain acidity by delaying ripening.

pH correlates positively with sugars and average shoot length (Av.sh.l), reflecting that early pruning, which increases sugars and shoot length, tends to result in higher pH, implying reduced acidity.

Conversely, pH shows a negative correlation with buds per vine (B/v) indicating that a higher bud count, associated with late pruning, maintains lower pH and thus higher acidity, contributing to a fresher wine profile.

Buds per vine has strong negative correlations with sugars, pH, and average shoot length (Av.sh.l). This pattern reflects that higher bud numbers, typical of late pruning, are linked with slower ripening and lower pH. It also positively correlates with titratable acidity (TA) (0.812), supporting the role of late pruning in enhancing acidity. Bud break (%) correlates positively with average shoot length (Av.sh.l) and shoots per vine (S/v) indicating that early pruning, which increases bud break and shoot count, enhances shoot growth and development. The correlation with sugars suggests that higher bud break rates due to early pruning may lead to increased sugar levels by promoting early and uniform ripening [16].

Average shoot length shows strong positive correlations with sugars, pH and bud break (Bb %), indicating that vines with more shoot growth (linked to early pruning) tend to achieve higher sugar content and pH levels. The negative correlation with titratable acidity (TA) further suggests that shoot length, fostered by early pruning, is associated with lower acidity due to accelerated ripening.

Shoots per vine correlates highly with bud break (Bb %), showing that early pruning, which enhances bud break, also results in more shoots, potentially requiring more management to control vigor.

Moderate positive correlations with sugars and pH indicate that a higher shoot count is associated with increased sugar and pH levels, reflecting advanced ripening in early-pruned vines.

Early pruning promotes greater bud break, shoot growth, and sugar accumulation, leading to higher pH and lower acidity, especially beneficial for ripening in cooler climates. Late pruning supports higher bud counts and acidity retention, making it advantageous for managing freshness in warmer climates. These correlations underscore the importance of tailoring pruning practices to achieve optimal grape composition based on regional climate conditions and desired wine style [14].

Conclusions

Understanding the correlation between climate parameters and pruning timing is essential for producing high-quality grapes and wines, especially in the face of climate change. This knowledge allows grape growers to tailor their practices to annual climate conditions, leading to better control over grape composition, wine quality, and vineyard sustainability. The minimal difference in bud numbers between pruning types suggests that pruning timing does not significantly influence the initial bud count. However, early pruning enhances bud break and shoot development, likely contributing to a more vigorous growth cycle. Longer and more numerous shoots in early pruning may support higher yields, as more extensive and productive canopies can lead to better sunlight interception and fruit development. Early pruning could be preferred in regions where early-season frost is minimal, as it offers potential benefits for vine growth and yield. However, in cooler climates or years with potential spring frosts, late pruning may help delay bud break, protecting buds from frost damage and reducing the risk of crop loss. Warmer years with moderate precipitation (like 2023) favor higher sugar levels in grapes, with early pruning enhancing this effect further by advancing the ripening process. Late pruning, resulting in a delayed maturity, tends to yield lower sugar content, especially in cooler or wetter years. Higher temperatures and lower rainfall (such as in 2022 and 2023) tend to lower acidity levels, especially in early-pruned grapes, as ripening accelerates. Late pruning mitigates this acid loss by extending the maturation period, which may help retain acidity in warmer growing seasons. Warmer conditions and early pruning generally lead to higher pH, which is linked to the reduction in titratable acidity. The effect is more pronounced in warmer years like 2022 and 2023, where early pruning amplifies ripening and acidity loss, resulting in higher pH levels. Advances ripening and tends to produce grapes

with higher sugar content, lower acidity, and higher pH, making it suitable in cooler regions or years with milder temperatures. However, in warm years like 2023, early pruning may lead to overly mature fruit with elevated sugars and reduced acidity, potentially impacting the balance of the resulting wine.

Late pruning delays ripening and this helps retain acidity and results in lower sugar levels and lower pH. This method may be advantageous in warmer climates or hotter years, such as 2022, to prevent excessive ripening and maintain a fresher acidity profile in the grapes. The climate conditions in each year strongly influence grape composition, with pruning timing playing a critical role in modulating these effects. Early pruning tends to accentuate the impact of warm weather, leading to riper fruit with higher sugars and pH, while late pruning can help maintain acidity and prevent over-ripeness in hot growing seasons. Therefore, pruning strategies should be adapted based on climate forecasts to optimize grape quality for desired wine characteristics. This PCA analysis illustrates that early pruning promotes ripeness, increasing sugars, pH, and shoot length, while late pruning enhances acidity and bud count, delaying maturation. The choice between early and late pruning may depend on the desired grape and wine profile, with early pruning favored for ripeness in warmer conditions and late pruning for maintaining acidity in cooler climates. These findings align with studies suggesting that climate and pruning timing can be optimized to balance ripeness, acidity, and vegetative growth in grapevines.

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