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Evaluation of the impact of vine pruning periods on grape production and composition: an integrated approach considering different years and cultivars

Isabella Ghiglieno[1], Luca Facciano[1,*], Leonardo Valenti[2], Federico Amari[2], Gabriele Cola[2]

[1] Department of Civil, Environmental, Architectural Engineering and Mathematics, Agrofood Research Hub, University of Brescia, Brescia, Italy.
[2] Department of Agricultural and Environmental Sciences - Production, Landscape, Agroenergy, University of Milan, Milan, Italy.

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*correspondence:
luca.facciano@unibs.it

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ABSTRACT

Several studies have already highlighted how late pruning, conducted after bud break, can result in a delay in phenology and, consequently, in ripening. However, the effects of pruning periods on vegetative and productive parameters are less well-known. This study aimed to evaluate the effect of pruning periods on ripening kinetics, grape composition at harvest and yield parameters, considering the grapevine cultivar and year. The experimentation was conducted from 2011 to 2013 in two of the main Italian wine-growing areas: Franciacorta, in Northern Italy, and Montefalco, in Central Italy. In Franciacorta: Chardonnay and Pinot noir were considered while in Montefalco, the varieties included were Sauvignon blanc, Grechetto di Orvieto, Sagrantino, and Sangiovese. Six different pruning periods were compared: at leaf fall (NOV), during dormancy (DEC, JAN, FEB), in the pre-bud break period (MAR), and late, post-bud break (APR). Results obtained showed that the effects of the pruning period are clear and sufficiently replicable only considering pre-bud break pruning (MAR). The observation of the ripening kinetics highlighted in fact a delay in grape ripening for APR in both contexts as well as a lower value for the sugar-acidity ratio at harvest. In terms of grape yield, a moderately negative effect of APR was observed in Montefalco, while a more severe effect was observed in Franciacorta. This analysis gives a comprehensive understanding of the effects of pruning timing on grape yield and composition, providing viticulturists with transversally applicable information, useful for an aware management of the vineyard.

KEYWORDS: grape composition, yield, pruning period, late pruning, pre-bud break pruning, post-bud break pruning, integrated approach

INTRODUCTION

Climate change has become one of the major threats to viticulture worldwide. Rapid temperature rises associated with more frequent extreme weather events are posing additional challenges to growers in areas traditionally suited to wine production, thereby reducing adaptability in hot and dry zones (Mosedale *et al*., 2016). Many studies have addressed this issue, given that climate is one of the environmental factors that best define a region's identity by establishing direct effects on grape composition and vineyard performance in terms of grape yield and quality (Fraga *et al*., 2012, Fraga *et al*., 2016; Mira de Orduña, 2010; Ollat *et al*., 2017). Increased temperature resulting in increased availability of thermal resources in spring causes the advancement of phenological stages, with particular reference to budburst, flowering, and veraison (Coombe, 1988; Costa *et al*., 2019; Schultze *et al*., 2014). Furthermore, in most viticultural areas, global warming also accelerates grape ripening, causing a shift of the ripening period to the hottest summer months and a compression of the ripening period (Palliotti *et al*., 2014). In this scenario, grapes show a rapid sugar accumulation in the berries with a marked reduction in the acidic content of musts. This condition is particularly detrimental in the production of sparkling wines, where both good acidity and balanced must composition are required as these properties are strongly related to wine quality (Gatti *et al*., 2018; Jones *et al*., 2014). In other settings reserved for the production of red wines and fine white wines, the shift of ripening into warmer conditions led to the decoupling between technological maturity and aromatic and phenolic maturity. This results in high levels of total soluble solids (TSS) at the expense of phenolic concentration and flavour development (Palliotti *et al*., 2014; Sadras & Moran, 2012). For all these reasons, the wine-making sector needs adaptation strategies to safeguard the quality of wine production, including the preservation of yield. The measures put in place are needed to offset detrimental effects and adapt to climate change, now and, more importantly, in the future (Palliotti *et al*., 2014). Among the vineyard agronomic practices, winter pruning is one of the most effective as it makes it possible to optimise vineyard management in relation to yield and the general vine balance (Moran *et al*., 2019; Moran *et al*., 2018). Different pruning times can be chosen according to viticultural goals. More specifically, by exploiting the inherent grapevine acrotony, late pruning is used to delay the burst of basal buds, protecting the vines from late frost damage (Poni *et al*., 2022). The effect of pruning times on grape ripening is less clear, although, as a general rule, late winter pruning helps to delay ripening (Poni *et al*., 2022). Several studies indicate that late pruning, performed at BBCH 12, causing a delay in phenology, can be used to postpone grape ripening and the harvesting window (Palliotti *et al*., 2017; Petrie *et al*., 2017). In particular, pruning periods, it has been noted that pruning from November to March does not significantly affect bud break, while late winter pruning delays bud break (Wample, 1994). However, other studies have observed that late pruning does not always influence ripening delay, highlighting how the effect is strongly influenced by environmental context (Gatti *et al*., 2016). Late winter pruning, especially after budbreak, has generally been associated with reduced yield. A low-to-moderate decrease in yield has been observed when pruning occurs before the development of two or three unfolded leaves (Poni *et al*., 2022). Most studies investigated the effect of late winter pruning (post-budbreak) compared to pruning performed during the dormancy period. However, other studies have observed different effects, for both wine and table grapes, even for pruning during other phenological stages: for instance, from late leaf fall (Williams *et al*., 2023), at various stages during dormancy (Ahmed *et al*., 2017), to vine bleeding (Deloire & Pellegrino, 2022; Ferrara *et al*., 2022). Pruning time can also influence must composition. A delay in ripening can contribute to obtaining must with lower sugar content and wines with lower alcohol concentration, while simultaneously improving the colour and aromatic characteristics. Simultaneously, this delay can enhance the colour and aromatic characteristics of the wine (Petrie *et al*., 2017). Despite these potential benefits in terms of sugar accumulation, studies indicate that late pruning might not always achieve the desired delay in ripening (Gatti *et al*., 2016), and the impact can vary based on environmental conditions.

To the best of our knowledge, most of the previous studies investigated the effect of the pruning period on one or a few cultivars in just one geographical setting, while few studies covered different cultivars and viticultural areas. This three-year study made an integrated assessment of the effect of the pruning period on different cultivars, associated with different winemaking targets, in two different vine-growing areas in Italy: Franciacorta and Montefalco. In both areas, the effects of the current warm climate phase are the advance in grapevine phenology that translates into a higher risk of late frost damage, shortening, and advance of grapes ripening, this latter occurring under more stressful high temperatures, affecting the quality of grapes and musts (Biasi *et al*., 2019; Fraga *et al*., 2016; Vercesi *et al*., 2023). This study aims to adopt an integrated approach that, taking into account specific features related to geographical area, allows to investigate the effect of pruning time on ripening kinetics, grape composition at harvest and yield. Although knowing the specific behaviour of different pruning periods from year to year and from cultivar to cultivar remains important, viticulturists need indications regarding transversally applicable practices, beyond the specificities of cultivar and year. Wineries can thus use data-driven insights to make informed decisions about the pruning period based on replicable results in different production scenarios.

MATERIALS AND METHODS

1. Wine region characterisation and treatment layout

The trial was conducted in 2011–2013 in the two relevant wine-growing Italian areas of Franciacorta and Montefalco.

TABLE 1. General characterisation of the two wine-growing regions and vineyards.

	Castello Bonomi Tenute (Franciacorta)	Arnaldo Caprai Estate (Montefalco)
Climate	Köppen Cfa, moderated by Lake Iseo. Average annual temp.: 14.3 °C, winter: 8.8 °C, summer: 19.9 °C. Winkler index: 2170. Annual precipitation: 956 mm, summer: 508 mm.	Köppen Cfa. Average annual temp.: 14.3 °C, winter: 7.6 °C, summer: 21 °C. Winkler index: 1983. Annual precipitation: 814 mm, summer: 38 mm.
Grape varieties	Chardonnay (clone 95), Pinot noir (clone 292), grafted on Kober 5BB, planted in 2004. Vine density: 6250 vines/ha.	Sauvignon blanc (clone R3), Grechetto di Orvieto (clone G109) planted in 1994 and 1991, grafted on SO4 at 270 m a.s.l. Sagrantino, Sangiovese (clone TIN10) planted in 1998 and 2000, grafted on 420A at 340 m a.s.l.
Elevation	165 m a.s.l.	270 m a.s.l. (Sauvignon blanc, Grechetto), 340 m a.s.l. (Sagrantino, Sangiovese)
Location	Coccaglio, Franciacorta, Province of Brescia, Northern Italy (45°34′17″N, 9°58′04″E).	Montefalco, Province of Perugia, Central Italy (42° 55′ 20″ N, 12° 38′ 30″ E).
Orientation	N-S	N-S
Row spacing	2 m (inter-row)	2.2 m (inter-row)
Intra-row spacing	0.8 m (Chardonnay, Pinot noir)	0.8 m (Sauvignon blanc, Sagrantino, Sangiovese), 0.9 m (Grechetto di Orvieto)
Vine density	6250 vines/ha	5680-5050 vines/ha

The characterisation of the two wine regions and vineyards is described in Table 1.

In both Franciacorta and Montefalco, the cordon was tied to the horizontal support wire set at 0.8 m above the ground, while three pairs of upper wires produced a canopy wall extending 1.2–1.4 m above the main wire. Vines were spur-pruned cordon trained maintaining approximately 6 vegetative points of 2 visible buds each for each vine. For each vineyard and each cultivar, two blocks of about 120 vines were identified. Among each block, 20 consecutive vines were randomly assigned to each treatment. Six different pruning periods were compared, based on the timing of vine pruning, from November to April. Once a month the pruning was performed: in November (NOV) on the average corresponding to the end of leaf fall (BBCH 97), December (DEC), January (JAN), and February (FEB) during dormancy (BBCH 00), March (MAR) on the average corresponding to the pre-bud break phase (BBCH 01–05) and April (APR) during the post-budbreak phase (BBCH 08–13). Soil management (*e.g.*, tillage, fertilisation) and canopy management (*e.g.*, topping, thinning) within the same year and for the same cultivar were standardised across all treatments according to the farm management practices.

2. Agrometeorological characterisation

The agrometeorological characterisation of the two experimental sites was based on two weather stations:

- The Chiari (BS) weather station, which is part of the Agrometeorological Network of the Province of Brescia, is located 4 km South-West away from the experimental vineyards. Chiari data are in strong agreement with measurements taken during different seasons in the experimental vineyards. The choice to adopt Chiari data is based on the availability of continuous data over a long-time span, allowing a robust characterisation of the different growing seasons;
- The Montefalco (PG) Arnaldo Caprai weather station is located less than 500 m from the experimental vineyards.

A synthetic characterisation of the experimental seasons for the two sites was obtained considering the following indices:

- WINK—Winkler index (Amerine and Winkler 1944). It accounts for the availability of thermal resources for grapevine growth based on daily mean temperature. Assuming a base temperature of 10 °C, growing degree days are cumulated from April 1st to October 31st;
- HW—Heat waves, as the count of the annual number of days with maximum temperatures above 32 °C. It accounts for high-temperature grapevine stress;
- RR_Y—Yearly precipitation. Accumulation of yearly precipitation;
- RR_AS—Summer semester precipitation. Accumulation of precipitation from April to September. It accounts for water availability during the grapevine development season;
- RR_JA—Summer quarter precipitation. Accumulation of precipitation from June to August. It accounts for water availability during the most stressful summer period, with specific regard to grape ripening.

For each of the above indices, based on the current climatic normal 1991–2020 (WMO, 2024), the mean value and standard deviation were calculated, and each year was classified as follows:

- NORMAL—when the year value is within the range of mean ± 1 standard deviation;
- HIGH—when the year value is above mean + 1 standard deviation;
- LOW—when the year value is below mean - 1 standard deviation.

To describe the satisfaction of chill requirements of grapes and the accumulation of heat requirements, the chill hours CH (Weinberger, 1950) were calculated since October 1st for each season and site. Specific CH thresholds are not available for all the varieties considered in this study. For this reason, Chardonnay (136 CH) and Cabernet sauvignon (392 CH) thresholds were considered representative of LOW CH and HIGH CH requirements (Anzanello *et al*., 2018).

3. Grape ripening kinetics

The evolution of ripening was monitored for all cultivars, from the end of veraison of the earliest treatment until harvest, through sampling with an average interval of 7 days for the six treatments. Seventy berries were collected from each randomised block (35 berries collected from both the eastern and the western sides and then grouped together in a single sample). These samples were then manually crushed, and the total soluble solids (TSS) concentration and titratable acidity (TA) were measured in the grape juice. The measurements were determined using a traditional handheld refractometer (Reichert Technologies, Buffalo, NY, USA) for TSS and a Crison compact titrator (Crison Instruments S.A., Spain) analyzer for TA.

4. Harvest parameters and timing

All treatments within the same cultivar were harvested on the same day. Every year, each cultivar was harvested when the vines pruned during the JAN period reached the TSS level corresponding to the oenological goal: between 18.5 and 19.5 °Brix for Chardonnay and Pinot noir (sparkling wines), between 20.5 and 21.5 °Brix for Sauvignon blanc (fresh and young wines), between 21.0 and 22.0 °Brix for Grechetto (long-ageing white wines), between 22.0–23.0 °Brix for Sangiovese (fresh and young red wines) and between 26.0–27.0 °Brix for Sagrantino (long-aging red wines). A total of 10 vines for each of the two randomised blocks were selected. For each vine selected, total production, average bunch weight (ABW), and bud fertility (BF) were determined. BF was calculated as the ratio between the total number of bunches and the total number of buds, including shoots and unsprouted buds, remaining after any thinning. A sample of three bunches was collected to check juice composition. As for grape ripening kinetics, these measurements were determined using a traditional handheld refractometer for soluble solids concentration and a Crison compact titrator analyzer, respectively, for pH. The ratio between TTS and TA (TSS/TA) will be shown and discussed in the article.

5. Statistical analysis

For the ripening curves, to summarise the information acquired from the collection of these data based on the sampled data for each cultivar, treatment, and season, quadratic regressions between sugar content (°Brix) and the sampling date expressed as a day of the year (DOY) and between sugar content and total acidity (g L^{-1}) were set up. In this way, it was possible to calculate the day of occurrence of different sugar levels for each ripening curve, and more specifically:

- 11 and 18 °Brix for Chardonnay and Pinot noir;
- 11 and 20 °Brix for Sauvignon blanc;
- 13 and 20 °Brix for Grechetto;
- 13 and 22 °Brix for Sangiovese;
- 14 and 27 °Brix for Sagrantino.

For each cultivar, the lower threshold was chosen to represent the early ripening stage. This was the lowest sugar level always measured in each sampling series, allowing for reliable regressions. On the other side, the upper threshold was specifically chosen to represent the technical maturity of each cultivar, representative of the two viticultural areas considered. The levels of total acidity concurrent with the above-listed sugar content thresholds were also obtained. Quadratic regression tests were performed using Excel software (Microsoft Corp., Redmond, WA, USA).

For the integrated analysis of the effects of pruning periods on harvest parameters, a split-split-plot (SSP) experimental design was employed with two replications (corresponding to the two randomised blocks). The SSP design is an extension of the split-plot design to accommodate a third factor: one factor in the main plot, another in the subplot, and the third factor in the sub-subplot (Gomez & Gomez, 1984). In an SSP design, if a factor is considered more important for assessing its significance, it is set as the sub-subplot; in turn, the subplot and main plot are set based on the already known effect. In this study, the cultivar was considered as the main plot, as it is known that *Vitis vinifera* varieties differ in berry composition and yield parameters (Prathiksha & Hegde, 2022). The year was considered as a sub-plot, as it is known that meteorological factors such as temperature, rainfall, and water availability can influence the composition of *Vitis vinifera* berries and yield parameters (Zhu *et al*., 2020). Finally, the treatment was considered as the sub-subplot, to highlight the effects of pruning periods beyond varietal specificity and the study year. The reason why an SSP experimental design, considering treatment as a sub-subplot (*i.e*., a more important factor), was chosen lies in the general objective of the paper and in the type of information that it wants to transfer to the viticulturist. The choice of winter pruning period by viticulturist must, in fact, be made before knowing the weather conditions of the current year. Although knowing the specific behaviour of different pruning periods from year to year and from cultivar to cultivar remains important, viticulturists need indications regarding transversally applicable practices, beyond the specificities of cultivar and year. The SSP analysis allows us to highlight those effects which, albeit with limited variations between cultivars and years, are significant and, therefore, sufficiently generalisable to generate guidance for viticulturists.

The effects of cultivars, years, and treatments were analysed using R software version 4.2.3 (R Core Team, 2023) and the ‘SSP.plot’ functions of the ‘agricolae’ package applied to split-split-plot analysis (spp analysis) (Mendiburu, 2010). Pairwise comparisons were conducted using the R package ’agricolae’ with the LSD test and Bonferroni P-value adjustment (1,2). The ‘stats’ package was used to perform Analysis of Variance (ANOVA) models on each variety and year. The results, available in the supplementary materials, include multiple comparisons of treatments using the Tukey method, with a default significance level of 0.05.

RESULTS

1. Agrometeorological characterisation

As shown in Table 1, in Coccaglio in 2011, the level of WINK was high, despite an average level of HW due to warm temperatures during spring. Yearly precipitation was normal with a high contribution in both RR_AS and RR_JA, determining very good conditions for grapevine development and ripening. The year 2012 was normal for all the indices, with the only exception of a high number of heat waves. This could also have been increased by the lowest, even if statistically normal, RR_JA,. 2013 showed normal values for all the agrometeorological indices. In Montefalco, 2011 was characterised by normal thermal indices but low values of RR_Y and RR_AS, with higher water stress for grapevine, and 2012 was characterised by a high level of HW and low precipitation in summer (RR_JA), even if statistically normal. Similarly, to Coccaglio this could have determined stressful conditions for grape ripening. The year 2013 was normal for all the agrometeorological indices. With reference to chill requirement satisfaction, Table 2 shows the date of occurrence of low and high chill hours requirements for Coccaglio (BS) and Montefalco (PG). LOW and HIGH requirements are generally satisfied between the second half of November and the first half of December, with the exceptions of 2010–2011 in Montefalco when the HIGH request is satisfied only on December 18.

2. Grape ripening kinetics

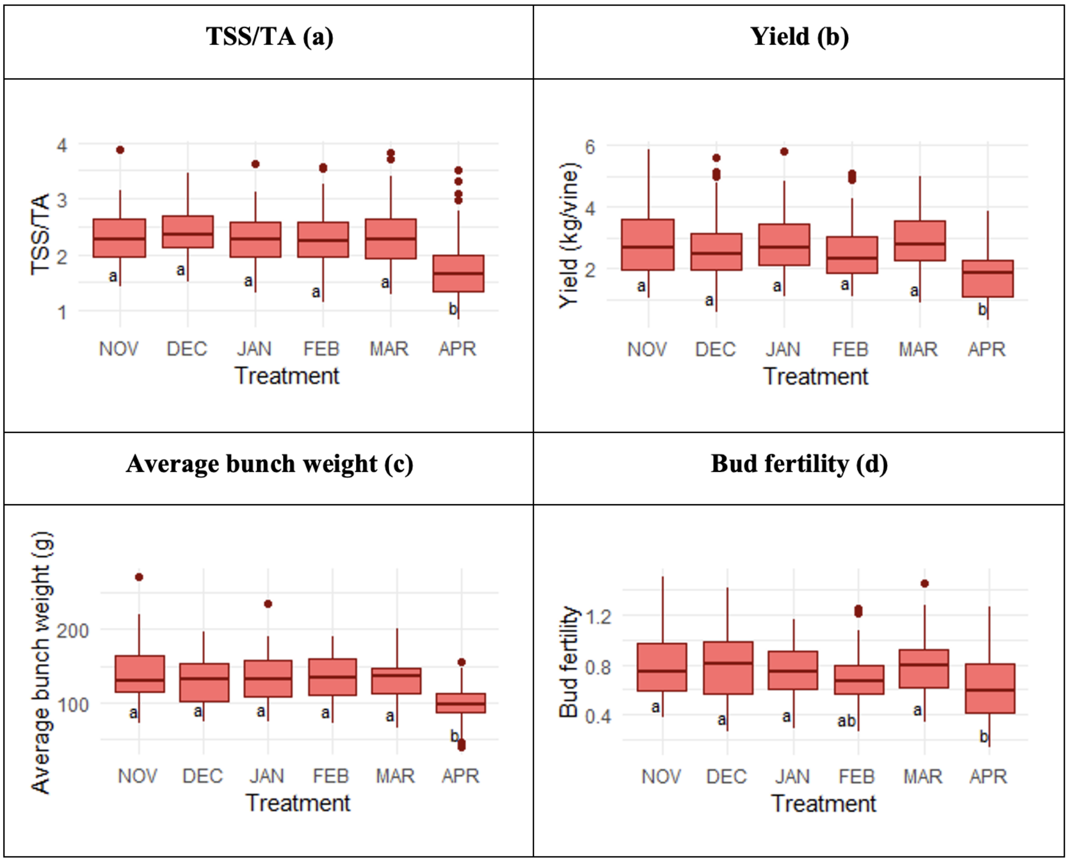
A first analysis of the effects of the pruning date was performed considering the lower and upper threshold of sugar accumulation specific for each cultivar. Considering the averages of the three seasons, for each cultivar, Table 2 shows the average day of achievement of the lower and upper threshold of sugar accumulation, the average advance/delay of each pruning period, the average acidity level, and the variation of acidity of each pruning period. In Chardonnay, the variation of the date of occurrence of 11 °Brix was lower than about one day for the first five pruning periods, while APR showed an average delay of 4 days when compared to the average date. A more gradual behaviour was observed for 18 °Brix, moving from the 2 days of advance of NOV

TABLE 2. Days of chill hour satisfaction for low and high requirement cultivars in Coccaglio (BS) and Montefalco (PG) from 2011 to 2013, and classifications of agrometeorological indices. For the indices normal values are shown in white cells, while high values are highlighted in orange and low values in light blue.

Coccaglio (BS)								Montefalco (PG)							
	LOW CH	HIGH CH	WINK	HW	RR_Y	RR_AS	RR_JA		LOW CH	HIGH CH	WINK	HW	RR_Y	RR_AS	RR_JA
2011	18-nov	03-dec	2434	43	1061	699	416	2011	26-nov	18-dec	1878	37	531	187	136
2012	15-nov	30-nov	2261	59	1051	585	131	2012	12-nov	29-nov	2036	66	810	290	90
2013	17-nov	08-dec	2158	38	1090	584	220	2013	26-nov	12-dec	1957	22	878	364	133

TABLE 3. Average dates of reaching lower and upper thresholds of sugar accumulation, average advance/delay for each pruning period, average acidity levels, and variation in acidity across pruning periods.

		Chardonnay		Pinot noir		Sauvignon blanc		Grechetto		Sangiovese		Sagrantino	
Sugar accumulation		11 °Brix	18 °Brix	11 °Brix	18 °Brix	11 °Brix	20 °Brix	13 °Brix	20 °Brix	13 °Brix	22 °Brix	14 °Brix	27 °Brix
Average Date		29 Jul	14 Aug	25 Jul	10 Aug	3 Aug	22 Aug	9 Aug	31 Aug	9 Aug	30 Aug	7 Aug	17 Sep
Advance / Delay [n days]	Nov	–1.2	–2.3	0.2	–0.9	–1.1	–2.6	–1.4	–0.8	–0.8	1.3	–0.1	–1.3
	Dec	–1.2	–1.6	0.6	–2.6	–0.1	–0.2	–3.1	–4.8	–3.5	–2.5	–0.7	–0.7
	Jan	–0.8	–0.6	–0.4	0.1	0.3	–0.2	–0.8	–2.5	–0.2	–0.7	–1.1	–3.7
	Feb	–0.2	1.4	–3.1	–1.3	–0.7	1.3	–2.1	–2.3	–2.2	0.0	–2.1	–0.7
	Mar	–0.8	0.1	–1.4	0.4	–0.1	0.4	1.2	4.2	1.5	1.6	–0.1	1.7
	Apr	4.2	3.1	4.2	4.4	1.6	1.4	6.2	6.2	5.2	6.3	3.9	5.0
Average Acidity		22.9	9.4	22.5	9.1	31.5	9.4	16.9	7.7	21.7	8.6	17.0	8.4
Acidity variation [g/l]	Nov	–0.4	0.0	–0.1	0.9	–1.2	0.2	1.2	–0.7	–0.5	–0.2	–0.2	0.6
	Dec	–1.1	0.4	–0.6	0.5	1.7	–0.9	–0.5	0.3	–0.6	0.2	–1.1	–1.9
	Jan	–0.5	–0.5	–0.3	–0.7	–0.5	–0.7	–0.1	0.2	0.1	–0.4	–0.8	0.3
	Feb	–1.1	–0.3	–2.8	0.0	0.6	0.2	–2.1	–0.4	–1.3	0.1	0.1	1.2
	Mar	0.9	–0.3	0.8	–0.1	0.5	–0.8	1.5	–0.1	0.5	–0.5	–0.4	1.3
	Apr	2.3	0.6	3.0	–0.7	–1.0	2.1	0.0	0.7	1.7	0.9	2.4	–1.5



TSS/TA (a)

Yield (b)

Average bunch weight (c)

Bud fertility (d)

FIGURE 1. Box plots illustrating the TSS/TA ratio, yield, average bunch weight, and bud fertility for each treatment (Sub-sub-plot) in the Franciacorta area, with significance levels from the least significant difference (LSD) test for the split-split plot design.

to the 3 of delay of APR. Regarding titratable acidity, only APR showed sensible higher values when compared with the other periods of pruning. In the case of Pinot noir, the first five pruning periods exhibited comparable average dates of occurrence for both 11 and 18 °Brix, while APR had a delay of more than 4 days. For titratable acidity, no difference was observed at 18 °Brix, while at 11 °Brix, APR showed a higher level (+3 g L^{-1}). Regarding Sauvignon blanc, the delay of APR was limited at both 11 and 20 °Brix (less than two days). The titratable acidity showed the highest values for APR at 20 °Brix (+2.1 g L^{-1}). In the case of Grechetto, the first four pruning periods reach 13 and 20 °Brix within 2 days of variation, while MAR and APR showed relevant delay, especially at 20 °Brix with 4 and 6 days of delay respectively. Regarding the acidity levels, APR showed higher values (+1.7 and +0.9 g L^{-1} compared to the average at 13 and 20 °Brix). In terms of sugar accumulation, Sangiovese showed similar behaviour to Grechetto, with an average delay of 5 and 6 days for 13 and 22 °Brix, respectively. Regarding acidity level, APR had the highest values at 13 (+1.7 g L^{-1} compared to the average) while the variation at 22 °Brix was less clear and limited.

3. Harvest parameters

3.1. Franciacorta area

The SSP analysis on harvest data (Figure 1a) indicated that APR had a significantly lower TSS/TA compared to other treatments. Concerning yield, the SSP analysis revealed that APR had a significantly lower yield than all other treatments (Figure 1b). Similarly, the SSP analysis for ABW (Figure 1c) indicated a significantly lower ABW for APR, consistent with the yield data. For BF, the SSP analysis indicated that APR had a significantly lower BF value compared to all treatments except FEB (Figure 1d).

The results for each individual year (Table S1) showed that for Chardonnay, APR had significantly lower TSS/TA in 2011 and 2012. For Pinot noir, TSS/TA in APR was consistently low, with significant differences in 2011 and 2012. In 2013, no statistical significance was observed among treatments, though APR still showed the lowest average value. When examining yield by individual year, although some yearly variations in statistical significance can be underlined, APR consistently showed lower yields. Specifically, results showed that for Chardonnay, APR had a significantly lower yield than all treatments in 2011 and 2012, except for DEC. In 2013, both APR and FEB were significantly lower. For Pinot noir, the trend was less consistent; although APR generally had the lowest production, it was not always statistically inferior to other treatments (*e.g.*, compared to NOV and DEC in 2011). By year, ANOVA conducted separately for each cultivar revealed that in Chardonnay, APR generally had a lower ABW, though this was not always statistically significant compared to other treatments. Chardonnay tended to have higher ABW values in NOV. For Pinot noir, no

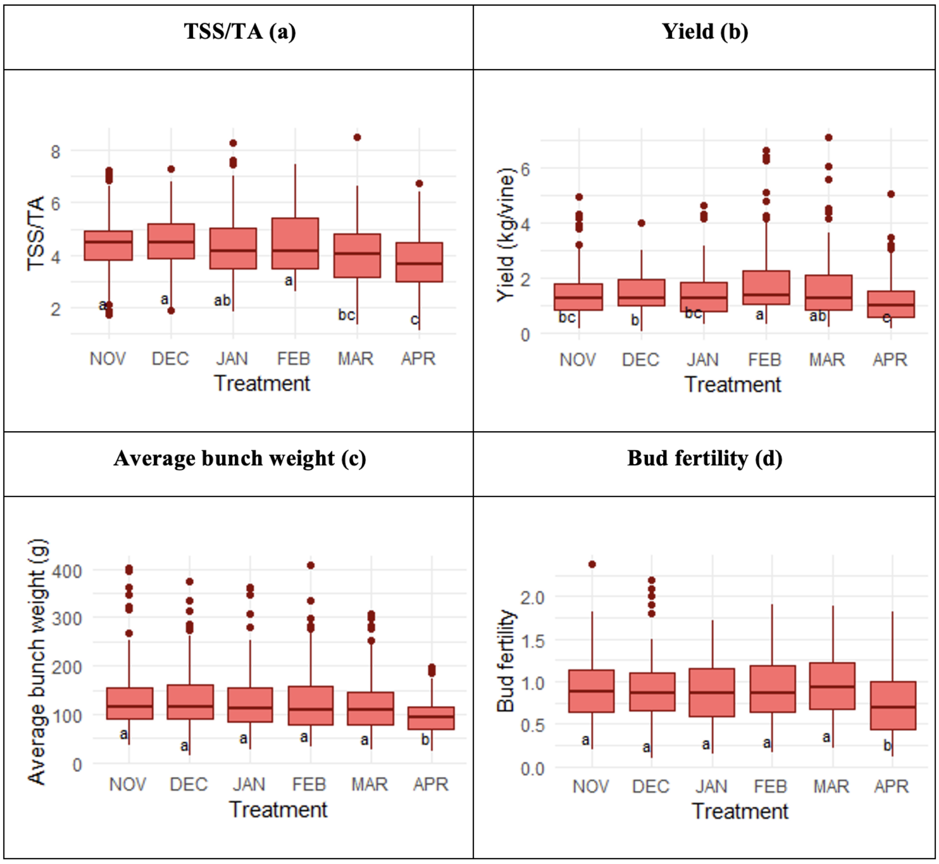


FIGURE 2. Box plots illustrating the TSS/TA ratio, yield, average bunch weight, and bud fertility for each treatment (Sub-sub-plot) in the Montefalco area, with significance levels from the least significant difference (LSD) test for the split-split plot design.

significant differences in ABW were observed in 2012 and 2013, although APR generally showed lower values. Yearly analysis of BF showed that for Chardonnay, APR had a lower BF in 2012 and 2013, with no significant differences in 2011. For Pinot noir, APR showed a lower BF in 2012, although significance was not consistent across treatments, with FEB often showing similar results to APR.

3.2. Montefalco area

As expected, the integrated SSP analysis confirmed the lower TSS/TA of APR, although it was not significantly different from MAR (Figure 2a). In terms of yield, the SSP analysis indicated that APR maintained the lowest values overall, with the greatest difference compared to MAR and FEB (Figure 2b). For ABW, the SSP analysis confirmed a significantly lower value for APR (Figure 2c). For BF, the SSP analysis indicated a consistently lower value for APR compared to other treatments (Figure 2d).

A detailed look at individual years and cultivars (Table S2) showed subtle distinctions in 2011 for Sangiovese and Sagrantino. However, APR showed a significantly lower TSS/TA in 2011 for Sauvignon blanc and Grechetto compared to other treatments. In 2012, the lowest TSS/TA was recorded for MAR in Grechetto and Sangiovese, with statistical significance only when compared to JAN and NOV, respectively. APR had lower values in 2012 for Sauvignon blanc and Sagrantino, with significance only compared to NOV and DEC, respectively. In 2013, lower values of MAR and APR were again confirmed for Grechetto, while APR was the lowest for Sangiovese and Sagrantino. For Sauvignon blanc, statistical significance in 2013 was observed only for FEB, which had the highest TSS/TA value. When examining individual years for yield, the cultivar-specific analysis showed less consistency in Montefalco than in Franciacorta. In years with no significant differences (*i.e.*, 2011 for Grechetto, 2013 for Sauvignon blanc, and 2011 and 2012 for Sagrantino), APR did not always have the lowest yield. However, APR maintained the lowest values for Grechetto in 2012 and 2013, for Sangiovese in 2011, and for Sagrantino in 2013. MAR and/or FEB had significantly higher yields than APR in Grechetto in 2012, in Sauvignon blanc in 2012 (with JAN similar to FEB), and in Sangiovese in 2011 and 2012. In the analysis of ABW by individual years and cultivars, Sangiovese consistently showed lower ABW for APR across all years, while other cultivars responded less uniformly to APR. No significant differences were observed for Grechetto and Sagrantino in 2011. In 2012 and 2013, Grechetto had lower ABW values for APR, with statistical significance only relative to certain treatments, while Sagrantino recorded the lowest ABW for APR only in 2013. Sauvignon blanc showed no significant differences across the years. For BF, a detailed analysis of individual years and cultivars showed that APR generally recorded lower BF values except in years without

TABLE 5. Montefalco—ANOVA summary for TSS/TA, Yield, Average Bunch Weight, and Bud Fertility. Split-split plot design: Cultivar (whole-plot), Year (split-plot), Treatment (split-split plot). Alpha = 0.05. Significance codes: *** (0.001), ** (0.01), * (0.05).

	TSS/TA			Yield			Average bunch weight			Bud fertility		
	DF	*F*	*P-value*	*DF*	*F*	*P-value*	*DF*	*F*	*P-value*	*DF*	*F*	*P-value*
Cultivar	1	15.16	0.026*	1	4.77	0.116	1	13.93	0.029*	1	111.32	0.001**
Year	2	53.68	2.313e-05***	2	4.02	0.062	2	16.50	0.001**	2	18.52	0.001***
Cultivar:Year	2	12.08	0.001**	2	34.53	2.699e-05***	2	11.05	0.002**	2	7.39	0.006**
Treatment	5	12.86	1.652e-08***	5	9.61	8.943e-07***	5	10.31	3.632e-07***	5	8.13	6.589e-06***
Treatment:Cultivar	5	1.92	0.039*	5	1.96	0.034*	5	3.30	5.045e-04***	5	1.13	0.351
Treatment:Year	10	1.73	0.094	10	2.57	0.012*	10	0.94	0.503	10	3.78	0.001***
Treatment:Cultivar:Year	10	2.04	0.009**	10	2.26	0.004**	10	1.37	0.149	10	2.04	0.010**

significant differences (*i.e.*, 2011 and 2013 for Grechetto and Sagrantino, and 2011 and 2012 for Sangiovese). For Sauvignon blanc, APR had the lowest BF only in 2013.

DISCUSSION

The possibility to define a common and sufficiently replicable behaviour among different cultivars targeted at different oenological goals was allowed taking into consideration two cultivars in Franciacorta and four cultivars in Montefalco. The replicability of behaviour over the years was guaranteed by the sufficiently differentiated weather of the three seasons considered, as confirmed by the agrometeorological characterisation. Over the three-year study, variations in weather conditions significantly influenced grapevine ripening. In 2011, warm spring temperatures in Franciacorta and low rainfall in Montefalco led to early ripening, whereas in 2013, more average temperatures and rainfall resulted in slower, more gradual ripening. Late pruning (APR) consistently delayed ripening for both white and red cultivars in Franciacorta and Montefalco, especially in 2011 and 2012, helping maintain higher acidity levels. In 2013, however, the delay effect of late pruning on ripening was less consistent.

From the integrated approach adopted in this study and allowed by SSP analysis, it is clear that the effects of the pruning period are clear and sufficiently replicable only considering post-bud break pruning (APR) and, limited to the Montefalco area, to pre-bud break pruning (MAR). A general lateness of maturation can be in fact observed both for white and red cultivars in Franciacorta and in Montefalco in relation to late pruning treatment (APR). This treatment showed a delay in ripening, as proven by the sugar accumulation time and concurrent preservation of acidity. The lateness of late pruning on ripening dynamics has already been observed in previous studies. The research conducted by Petrie *et al*. (2017) for the 2011-2012 period in a Shiraz and Cabernet-Sauvignon vineyard in South Australia reported a delay in ripening in treatments involving late pruning (E-L 9 scale). In Palliotti *et al*. (2017) delays were also observed in the ripening of Sangiovese in Umbria between 2014 and 2016 due to late pruning performed at BBCH 14. No clear patterns can be observed in other pruning periods, except for pre-budbreak pruning (MAR), which led to slow ripening above all in Grechetto and, less evidently, in Sangiovese and Sagrantino. The effect of pruning done during the bleeding phase (March) in delaying sugar accumulation at harvest was also highlighted by Deloire and Pellegrino (2022), although these authors emphasise that the effect is always influenced by both cultivar and climate. In line with these results, in a study conducted between 2014 and 2017 in Veneto (Italy), Falginella *et al*. (2022) reported a delaying effect on budbreak but not on ripening for vines pruned in the bleeding phase (E-L 1/2 scale). A similar general pattern was observed for the impact of the pruning period on the composition of grapes at harvest.

The results obtained in terms of TSS/TA suggest that late pruning can significantly influence the composition of grapes. Notably, the APR showed low TSS/TA both in Franciacorta and in Montefalco, while the integrated analysis for Montefalco revealed a significant effect in technological ripening even in MAR. Both Palliotti *et al*. (2017) for Sangiovese and Gatti *et al*. (2018) for Pinot noir observed a significant delay in technological ripening with late pruning, resulting in low sugar-acidity ratios at harvest. In a study conducted between 2020 and 2022 in a Chardonnay vineyard in Franciacorta, Vercesi *et al*. (2023) highlighted how any delayed winter pruning, even done at the beginning of budbreak, has the potential to delay phenology and hence ripening. In view of the results obtained over the years by different pruning periods, the effect of delay in terms of low TSS/TA is evident for most years and cultivars for APR. As observed in ripening kinetics, the effect of MAR in reducing the TSS/TA is limited to some cultivars and years, though without clear patterns. To address the problems related to early harvesting due to climate change, the possibility of achieving late ripening even with pruning before budbreak may be of interest to viticulturists. The opportunity to stagger delayed pruning periods, rather than tackling them all at once, is an advantage in operational terms as it requires a timely execution of works, especially for bigger farms. However, the varying responses obtained from MAR pruning mean that a uniform strategy cannot be defined for all cultivars and years, as is generally the case for late pruning in APR. With regard to grape composition, it would be valuable to compare the effects of secondary metabolites, particularly polyphenols and flavonoids, to gain insights into the impact of delayed pruning. Studies such as that by Silvestroni (2018) have reported significant increases in phenolic compounds in treatments with delayed pruning. These findings suggest that the accumulation of secondary metabolites, especially flavonoids and other phenolics, may be more responsive to specific pruning periods.

Despite the benefits that late pruning provides in terms of reduced sugar accumulation, the effect on yield cannot be overlooked. In fact, the results obtained from the integrated analysis revealed the general negative impact of pruning performed after budbreak (APR) on grapevine yield. This is particularly evident in Franciacorta, where late pruning (APR) entails a 30 %–50 % reduction, compared to the average yield of the other periods. The same effect is also reported by previous studies carried out in a Chardonnay vineyard in Franciacorta where an average loss of 44.83 % in yield/vine (kg) was observed with pruning at 2/3 unfolded leaves (Vercesi *et al*., 2023). The decrease in yield is less evident in the integrated analysis done in Montefalco with results of no statistical significance among APR and JAN, NOV, while MAR and FEB recorded higher production and DEC an intermediate value. The decrease obtained following late pruning (APR) in Montefalco is much less evident than in Franciacorta, accounting only for –26 % compared to the average yield obtained with other pruning periods. This decrease is in line with previous observations made on Sangiovese (Gatti *et al*., 2016) that revealed a 28 % decrease in yield associated with late pruning (2/3 unfolded). It should be noted, however, that the average yield of the Montefalco cultivars generally started from lower levels, even in cases of non-late pruning, compared to Franciacorta. This is also related to the production potential of the two areas, which align with their respective oenological goals: sparkling wine production in Franciacorta versus still white and red wine production in Montefalco. Therefore, although the percentage reduction in yield due to the APR treatment was more pronounced in Franciacorta compared to other treatments, it is important to highlight that the productivity of the varieties in this region was generally higher. Consequently, while the effects of the APR treatment are more noticeable in Franciacorta, impacts on grape yield are also observed in Montefalco, though to a lesser extent.

It is worth noting that, in our research, the same grapevines were pruned in the same periods. It is therefore interesting to evaluate whether the cumulative effect in yield reduction can be noticed considering the first year (2011). However, it is not possible to define a homogeneous pattern because the cumulative effect can be observed only in some cultivars. In Chardonnay and Sangiovese no cumulative effect was observed. APR showed in fact for both cultivars a reduction in yield already starting from 2011. This evidence was confirmed by Silvestroni *et al*. (2018) in treatments on Sangiovese trained to spur-pruned cordon. Conversely, the yield decreases due to late pruning became evident in Sagrantino only in the last year of the research (2013) and a cumulative effect was also observed in Pinot noir and Grechetto, with a reduction reported as from 2012. Cumulative effects were observed on Pinot noir grown with the Guyot pruning system by Gatti *et al*. (2018) but on ripening delays rather than on production parameters. An experimental project lasting more than three years would be needed to better evaluate cumulative effects over time.

Considering the role of ABW and BF in yield reduction, an integrated contribution of both factors can be highlighted in the case of Chardonnay throughout almost all the years considered, while with Pinot noir a major role was played by the ABW. This impacts the result of the integrated analysis, which in the Franciacorta treatments, shows no significant differences in BF between APR and FEB. A significant effect of late pruning on ABW was also observed on Chardonnay by Vercesi *et al*. (2023) in Franciacorta. Regarding BF, in an experiment conducted in Trentino Alto Adige, Bertamini and Faralli (2023) also observed a negative impact of late pruning on bud fertility in Chardonnay trained with spur pruning in 2019 and in Pinot noir trained with Guyot in 2021. Yield decrease is mostly related to a reduced ABW in the case of Sagrantino and Sangiovese, while an integrated effect of reduction of the ABW and BF can be associated with Grechetto. Considering the results obtained in the Montefalco area from the integrated SSP analysis, a significant reduction in both the ABW and the BF can be highlighted in the case of APR. Silvestroni *et al*. (2018) reported a significant decrease in ABW for two out of three years of study on Sangiovese pruned late (3/4 expanded leaves). Conversely, Palliotti *et al*. (2017) did not observe any significant effects on ABW reduction on Sangiovese, but they reported variations in the number of clusters per plant.

CONCLUSIONS

This research aimed to evaluate the effect of the pruning period on spur-pruned cordon grapevines' ripening kinetics and composition and on vine yield. The integrated approach adopted in the data analysis provides a comprehensive understanding of the effects of pruning periods on grape yield and ripening, offering valuable insights for the broader viticultural community. The opportunity to study different cultivars in two distinct Italian production areas, Franciacorta and Montefalco, helped emphasise the importance of considering the geographic context in defining recommendations for making strategic management decisions for viticulturists. The results obtained in Franciacorta confirmed the observations made in previous studies regarding the effect of late pruning (APR) in delaying the ripening of grapevines suitable to produce a sparkling wine base. Although this result is interesting in addressing the problem of early ripening caused by climate change, the reduction in yield caused by late pruning (APR) makes it necessary to carefully assess the opportunity to adopt this technique. In Montefalco, the effectiveness of late pruning (APR) in delaying ripening is confirmed, while the reduction in yield is less evident than in Franciacorta. This result makes this practice interesting in pursuing the objective of slowing down maturation without having significant yield losses. Some interesting results were also obtained for pre-budbreak pruning (MAR) in Montefalco but with a less clear pattern than APR. This means that it is not possible to define univocal indications of behaviour for viticulturists in the case of pre-budbreak pruning, as is instead the case of post-budbreak pruning (APR). The novelty of the research lies in an integrated approach to studying the effects of different pruning times on grape yield and composition. The opportunity to work in two distinct contexts and to integrate the results obtained across different cultivars and years provides practical insights that can support grape growers in making informed pruning time decisions. The results obtained highlighted that late pruning can significantly influence grape yield and composition, regardless of the cultivar and production year. Future developments could also include the evaluation of secondary metabolites, such as polyphenols and flavonoids, to enrich our understanding of the impact of pruning periods on grape composition. This additional focus would provide further insights to refine viticultural management strategies in response to evolving environmental conditions.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

CONFLICTS OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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