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Comparison of methods for determining budburst date in grapevine

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ABSTRACT

Methods for determining budburst date in grapevine are poorly documented. Budburst date defined from cumulative shoots burst (or arising) and cumulative buds burst (expressed as % of total) were compared using different cultivars, pruning systems and irrigation treatments and assessed at the plant, bearer and individual bud level.

The study was conducted at three sites within an Australian vineyard over two years on mechanical pruned Chardonnay and Cabernet-Sauvignon; mechanical, spur and minimally pruned Shiraz; and control, regulated and prolonged deficit irrigated Cabernet-Sauvignon. Budburst defined as '50 % of total shoots burst' was more reliable than '50 % of buds burst' for determining budburst date when final % budburst was low, as observed under lighter (mechanical or minimal) pruning for Shiraz. Differences in final % budburst between pruning systems and deficit irrigation treatments were related mainly to the distribution (%) of bearers according to size (based on node or bud numbers) and their specific budburst percentage at each node position. The timing of budburst based on '50 % of total shoots burst' was dependent on a unique set of parameters for each cultivar, regardless of pruning treatments and irrigation levels.

The new knowledge gained in this study about the impact of pruning system and irrigation treatment on % budburst and timing may be useful for adapting phenological models to Australian vineyards.

KEYWORDS: budburst, cultivar, grapevine, bearer size, pruning, irrigation

INTRODUCTION

In the southern hemisphere, budburst in grapevine occurs from late August through to October, though mostly during September, with substantial variations in timing depending on variety, region and season (Coombe, 1988; Clingeleffer *et al*., 2013). Budburst is a key phenological stage, because it determines the start of new season grapevine growth and thus the earliness of the successive vegetative and reproductive developmental stages as influenced by seasonal climatic variations. The choice of cultivar is therefore critical for optimising the production at a given site and for limiting any negative impacts of climate like frost or heat stress (McIntyre *et al*., 1982). Although budburst variability between cultivars and between contrasted viticulture sites around the world has been documented in the literature (McIntyre *et al*., 1982; Coombe, 1988; Pouget, 1988; García de Cortázar-Atauri *et al*., 2009; Ferguson *et al*.,2014), the methods for measuring budburst date have, to our knowledge, received little attention.

Budburst is generally defined by 50 % of grapevine buds burst, an arbitrary value as the dynamics of budburst or the total number of shoots that burst is rarely provided. Different stages of budburst have been described by Coombe (1988) and Coombe (1995). Buds that remain dormant during winter are covered with two brown protective scales. The first visible stage of budburst is ‘budswell’. This is followed by ‘woolly bud’, when the scales begin to separate as the bud swells sufficiently to reveal brown woolly hairs. The ‘green tip’ stage follows, when the bud swells further showing the tip of the young shoot. Finally, there is the ‘emergence’ stage, when a rosette of young leaves appears (Coombe, 1988; Coombe, 1995). Coombe (1995) proposed a modified E-L system for identifying grapevine growth stages and used E-L stages 2-5 to cover the progressive stages in the bursting of buds. E-L stage 4 (‘green tip’) was chosen as the major stage for characterisation of budburst for a single bud. This was in agreement with Baggiolini (1952) and Huglin (1958), but in contrast with Pouget (1963), who selected the woolly-bud stage (E-L stage 3) as the most appropriate indicator for budburst.

Budburst follows on from the release of a bud from dormancy. Dormancy can be separated between two distinct periods, endodormancy and ecodormancy; endodormancy is associated with physiological limitations on bursting, whereas ecodormancy is a limitation on bursting due to environmental factors (Lang *et al*., 1987). Buds progressively enter into endodormancy along the shoot, as it lignifies during the summer, commencing at the same time as berry veraison (Pouget, 1988). Breaking of dormancy, and thus the transition to the post-dormancy period, is induced by a period of winter chilling (Pellegrino *et al*., 2020). The requirement for chilling may not be obligatory for breaking dormancy in all grapevine cultivars, although in its absence, grapevine buds will show limited, uneven and delayed budburst (Lavee and May, 1997). The generally accepted view, however, is that once sufficient cold units are received, the dormancy is broken. Normal budburst is assumed to be achieved after a chilling period of a minimum of one week with mean temperatures ranging from 0 °C to 10 °C (Pouget, 1988; Dokoozlian, 1999). Field *et al*. (2021) have shown that extended chilling during dormancy enhances burst, not only of primary shoots but also of secondary and tertiary shoots from the same compound bud. Similarly, Weinberger (1969) found that temperatures of less than 7 ºC were beneficial for the budburst of peach trees. Once endodormancy is broken, the budburst ‘date’ of a particular cultivar will rely on warm or forcing temperatures (Buttrose, 1968; Keller and Tarara, 2010). Budburst date is generally associated with the cumulated temperatures above a threshold of 10 °C, which corresponds with the base temperature for shoot development (Winkler and Williams, 1939; Lebon *et al*., 2004). However, temperatures in the range of 5 to 10 °C have been reported to be efficient for final budburst, notably in cool winter climates, and as such are considered to be suitable forcing temperatures for final budburst (García de Cortázar-Atauri *et al*., 2009; Caffarra and Eccel, 2010; Nendel, 2010; Zapata *et al*., 2016). Anzanello *et al*. (2018) showed that heat requirements for budburst were negatively correlated to duration of chilling temperatures for different grapevine cultivars.

Based on the knowledge of grapevine chilling and forcing temperature requirements for endodormancy and ecodormancy release, several attempts have been made to develop agro-meteorological models for budburst timing prediction (Pouget 1988; Williams *et al*., 1985; Swanepoel *et al*., 1990; Bindi *et al*., 1997; Parker *et al*., 2020 and references herein). The common growing degree days (GDD) models simulate grapevine budburst after a specific sum of forcing temperatures, which are accumulated generally after 1 January for the northern hemisphere (i.e., when endodormancy is assumed to be already broken) (McIntyre *et al*., 1982; García de Cortázar-Atauri *et al*., 2009). Other models simulate the chilling requirements to determine when the period of bud endodormancy ends, generally after 1 September for the northern hemisphere (i.e., when buds are assumed to be dormant). These models then predict budburst from the accumulated forcing temperature, which is set to a constant value for a given cultivar (Godwin *et al*., 2002; García de Cortázar-Atauri *et al*., 2009) or which increases as chilling temperatures decrease (Caffarra and Eccel, 2010). Reasonable agreement has been achieved between measured and simulated budburst dates for several grapevine cultivars (Zhang *et al*., 2002; García de Cortázar-Atauri *et al*., 2009), and these models are currently used to predict the future impact of climate change on budburst (Webb *et al*., 2007).

However, while there have been advances in understanding and classifying cultivar requirements in terms of chilling and forcing temperatures for initiation of budburst, there is a distinct lack of data on the effect of vineyard management practices - including pruning systems and irrigation practices - on budburst date. For Cabernet-Sauvignon, for instance, the number of nodes (or buds) per bearer retained at pruning on the same vine, ranging from 2-bud spurs to 14-bud canes, was shown to have significant impact on both budburst dynamics and the percentage budburst (Clingeleffer, 1989). The study demonstrated earlier budburst on shorter bearers; earlier budburst of distal buds next to the pruning cut (terminal dominance) with a progressive delay in budburst of up to 6 days for more proximal (basal) buds of bearers with high node (bud) numbers; and a 30 % reduction in total budburst of bearers with higher bud numbers compared to 2-bud spurs.

The present study, conducted over 2 years in the Sunraysia region of Australia, aimed at identifying the best method for determining budburst date from cumulative bud burst or cumulative shoot burst. Budburst timing and budburst percentage at different levels (i.e., plant, bearer and node levels) were assessed for different cultivars (mechanically hedged Chardonnay, Cabernet-Sauvignon and Shiraz), pruning systems for Shiraz (hand spur, mechanical hedge and minimal pruning) and contrasted irrigation levels for mechanically hedged Cabernet-Sauvignon (control irrigation ‘Con’, regulated deficit irrigation ‘RDI’ and prolonged deficit irrigation ‘PD’). The purpose of using different cultivars (either grafted or non-grafted), pruning and irrigation types over two years was to provide as wide a range of vineyard scenarios as possible for the comparison of the two methods for determining budburst date.

MATERIALS AND METHODS

1. Experimental sites and plant material

The experiments were carried out in 2004 and 2005 on three sites that were in close proximity of each other in a commercial vineyard located in the Sunraysia region of Victoria (34^{o}25’S, 142^{o}21’E), Australia. The soil was a Nookamka sandy loam (Hubble and Crocker, 1941). The sites were planted in 1994 with Chardonnay and Shiraz grafted onto Schwarzmann and own-rooted Cabernet-Sauvignon, at a density of 1366 vines per ha (2.44 m within row and 3 m between rows). Vines were trained on a two-wire vertical trellis, with wires 1.5 and 1.8 m above the soil.

In order to account for vineyard heterogeneity, a fully randomised block design across and down the rows (blocks) was arranged on the three sites, where the different treatments (pruning, irrigation) were applied. The experimental design included 2 blocks within 3 rows for Chardonnay, 3 blocks within 3 rows for Shiraz and 3 blocks within 6 rows for Cabernet-Sauvignon. Vines on all three sites were mechanically hedged. However, the Shiraz site also included vines which had been converted to spur and minimal pruning as part of a replicated trial in 2000 (Ashley *et al*., 2006). Minimal pruned vines were left unpruned, but they were skirted to keep the canopy off the ground, either in winter or during the season (Clingeleffer, 2010). The Cabernet-Sauvignon site included three irrigation treatments: a control irrigation treatment (Con), a regulated deficit irrigation (RDI) treatment and an extended deficit irrigation treatment, called prolonged deficit (PD) described by (Cooley *et al*., 2017). All sites were drip irrigated prior to budburst to bring soil water content to field capacity. Throughout the remainder of the season, apart from the periods during which the RDI and PD treatments were applied, soil water was replenished based on rainfall, neutron-probe readings and with set points determined from soil water use data of previous seasons, referred to as 100 % of estimated crop evapotranspiration (ETc) (Cooley *et al*., 2017). Cumulated rainfall over the year ranged from 173 mm in 2004 to 277 mm in 2005. Rainfall, together with other daily weather variables (maximum and minimum air temperature, global radiation, air relative moisture and wind speed) were recorded by a weather station controlled by the Australian Government Bureau of Meteorology and located in the region (34^{o}23’S, 142^{o}08’E), and they are reported in Cooley *et al*. (2017).

2. Number of buds, budburst percentage and number of shoots

Bud numbers, budburst percentage and the resulting shoot numbers were assessed in both years on 6 randomized (1 vine per block within each row), single vine replicates at each vineyard site, including the pruning treatments for Shiraz (spur, mechanical and minimal in 2004; only spur and mechanical in 2005) and irrigation treatments for Cabernet-Sauvignon (Con, RDI and PD in 2004; only Con and PD in 2005).

Total bud number per vine was counted. Bearers, defined as node bearing units, including spurs (typically 0-4 buds/bearing unit) and canes (> 4 buds per bearing unit) were counted. A 0.3 to 0.4 m section of the canopy was selected on the different vines at the same distance from the vine trunk to monitor budburst dynamics of all bearers (spurs or canes retained at pruning). The number of buds of each bearer was counted within the specific section of the canopy (0.3 to 0.4 m). The total bud number per vine was scaled up by multiplying the value observed in the 0.3 to 0.4 section to the whole vine width within the row (2.44 m). The percentage of budburst was recorded weekly, from the beginning of budburst (end of August) until budburst reached a plateau (first half of October), by monitoring the number of buds per bearer which had passed stage 4 (green tip) of the modified E-L system (Coombe, 1995). Total shoots burst per vine was calculated from the total bud number per vine and the fitted maximal budburst percentage, defined by the parameter M, which is a component of eq. 1 (see below).

3. Budburst timing

A logistic function was used to adjust the cumulative budburst percentage as a function of Julian day (eq. 1):

$$Budburst(\%) = \frac{M}{1+e^{[-a(t-t_I)]}} \qquad \text{(eq. 1)}$$

where t is the Julian day, M is the maximum value of the logistic curve, a the slope at the inflexion point of the function, and t_I the Julian day at the inflexion point.

Daily change in budburst percentage was then estimated by the derivative of eq. 1 (eq. 2):

$$dBudburst(\%) \Big/ dJulianday = \frac{aMe^{[-a(t-t_I)]}}{\left[1+e^{[-a(t-t_I)]}\right]^2} \qquad \text{(eq. 2)}$$

Budburst timing was determined from these equations as the Julian days when (i) 50 % of buds had burst, or (ii) 50 % of shoots had burst. In addition, the cumulated growing degree days (GDD) to reach budburst either defined as '50 % of buds burst' or as '50 % of shoots burst' were calculated. As the endodormancy is assumed to be released after 1 January for northern hemisphere, GDD were cumulated in the present study as from the 1 July (i.e., 6 months later), corresponding to Julian day 182 (eq. 3):

$$GDD = \sum_{n=182}^{budburstday} T(n) - T_0 \qquad \text{(eq. 3)}$$

where $T(n)$ is the mean temperature of day n and T_0 the base temperature set at 10 °C.

4. Statistical analysis

The statistical analysis of the data was performed with R-language and environment for statistical computing – (R Development Core Team (2012), R Foundation for Statistical Computing, Vienna, Austria). The parameters of eq. 1 were obtained by minimising the sum of squared residuals (i) for all individual vine replicates, and (ii) for the average of the 6 selected vines for a given cultivar, years (2004 *vs* 2005) and pruning systems or irrigation treatments.

An analysis of variance, followed by the Tukey' HSD (honestly significant difference) test for means comparisons was performed to compare (i) the total number of buds or shoots per vine, budburst percentage and the timing of budburst for a given cultivar between years (2004 *vs* 2005) and pruning systems or irrigation treatments, and (ii) the budburst percentage between node (or bud) positions for bearers with varying node (or bud) numbers for each combination of cultivar, year, pruning system or irrigation treatment.

The adjustments of budburst percentage were also compared between the bearer sizes (node or bud no./bearer) for each cultivar, year, and pruning or irrigation treatment using the *F*-test of Snedecor, which compares the sum of the residual sums of squares for individual fits to the residual sum of squares for the common fit for the whole data set.

RESULTS

1. Seasonal changes in air temperature

Changes over the cropping season of daily mean temperatures were assessed in 2004 and 2005 (Figure S1). For both years, daily mean temperatures (mean of daily maximum and minimum) were the highest in February (Julian days 32 to 60), reaching up to 37.6 °C in 2004 and 28.5 °C in 2005. They progressively declined to reach the lowest values between start of June and mid-July (days 153 to 197); i.e., 5.3 °C and 6.6 °C in 2004 and 2005, respectively. Then the daily mean temperatures progressively rose again. Over the period from February to June, the first quartile of daily mean temperatures (threshold for the lowest 25 % of mean temperatures) ranged from 11.5 °C and 13.1 °C respectively in 2004 and 2005 (Figure 1). Over the period from July to September, the median of daily mean temperatures was 11.7 °C in 2004 and 12 °C in 2005.

2. Plant bud numbers, final budburst percentage and resulting total number of shoots

The number of buds per vine under mechanical pruning in 2004 (Table 1) ranged from 622 for Shiraz, 631 for Cabernet-Sauvignon and 790 for Chardonnay. For the spur pruned Shiraz, bud number per vine decreased to a mean of 333 (for 2004 and 2005), which was about half of the values observed for mechanical pruning. In contrast, bud numbers of minimally pruned Shiraz vines (1460) were more than double that for the mechanically hedged treatment when measured in 2004. The number of buds per vine was similar between the years for mechanically and spur pruned Shiraz ($p > 0.05$). For Cabernet-Sauvignon there was no significant effect ($p > 0.05$) of irrigation treatment or year on buds per vine.

The final percent budburst for mechanically hedged vines in 2004 was 21 % higher for Chardonnay and Cabernet-Sauvignon (mean of 74.4 %) than for Shiraz (53.7 %) (Table 1; Figures 2). Thus, the total number of shoots burst per vine in 2004, calculated from total bud number per vine and final budburst, varied from 587 for Chardonnay, 469 for Cabernet-Sauvignon and 336 for Shiraz (Table 1).

For Shiraz in 2004, final percent budburst was 13 % higher for spur pruned than for mechanically hedged vines, and 24 % higher for spur pruned than for minimally pruned vines ($p < 0.05$) (Table 1; Figures 2b, 2c, 2f). In spite of higher final percent budburst, spur pruned Shiraz had fewer shoots per vine over the two years, with 57 % and 34 % of the number of shoots on mechanical hedged and minimal pruned vines respectively ($p < 0.05$). There was no effect of year on the final percent budburst and total number of shoots burst per vine for spur and mechanical pruned Shiraz ($p > 0.05$) (Table 1).

For Cabernet-Sauvignon (Table 1, Figures 2g to 2k) final percent budburst was reduced by 12 % with RDI compared with control irrigation in 2004 ($p < 0.05$), but no difference between PD and control was observed for both years (2004, 2005) ($p>0.05$). Percent budburst of Cabernet-Sauvignon was slightly lower in 2005 compared to 2004, while the total number of shoots burst per vine was similar between the years ($p > 0.05$).

3. Change of budburst percentage with bearer size and bud position along the bearer

The bearer size varied significantly across all pruning systems, with the number of buds per bearer ranging from 1 to > 10 (Table 2). However, for mechanically hedged vines (Chardonnay, Shiraz and Cabernet-Sauvignon), most bearers (> 80 %) were between 2 and 6 buds. For Shiraz, spur pruning led to smaller bearer size, ranging from 2 to 4 buds per bearer, while minimal pruning resulted in more scattered and longer bearer size ranging from 3 to 8 buds per bearer. Ultimately, while small spurs (nodes ≤ 3) represented more than 51 %

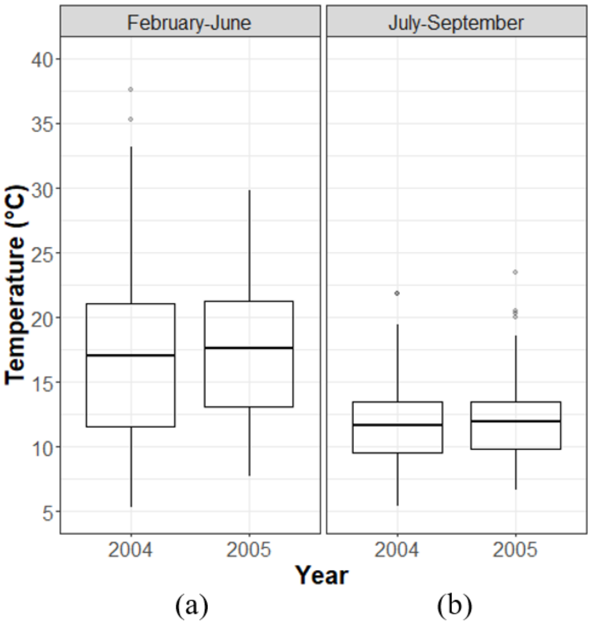

FIGURE 1. Distribution of mean temperatures (2004 and 2005) over two periods (a = from 1 February to 30 June; b = from 1 July to 30 September). Boxplots show the 25 th quartile (bottom vertical line), median (horizontal line), and 75 th quartile (upper vertical line) for each period.

of the bearers for spur pruned treatments, they represented less than 29 % of the bearers for the mechanically hedged treatment and 9 % for minimal pruning treatment (Table 2).

For comparative purposes, the dynamics of cumulative budburst percentage were assessed hereafter only for bearer sizes representing at least 10 % of total bearers for the different cultivars, pruning systems, irrigation treatments and years; i.e., bearers holding 2 to 5 buds (Table 2; Figure 3). Cumulative budburst percentage tended to decrease when the bearer buds number (range 25) increased ($p < 0.05$, Figures 3). Although the final percentage of budburst was about 20 % higher for mechanically pruned Chardonnay and Cabernet-Sauvignon than for mechanically pruned Shiraz at a given bearer size (Figures 3a, 3c and 3g), the maximal reductions in final percentage budburst values for 2-node versus 5-node spurs was similar for the three cultivars (around 20 % reduction). Cumulative budburst percentage at a given spur size was similar between pruning systems and years for Shiraz (Figure 3b to 3f). However, final budburst tended to be higher for control irrigation compared with deficit irrigation for longer bearer buds number (4-5) of Cabernet-Sauvignon both in 2004 and 2005 (around 7 % reduction from the Con to the PD treatment) (Figures 3g to 3k).

Bearers of different sizes differed in final budburst percentage per bearer and in final budburst percentage at each node position. For two node spurs, budburst was generally high, at both nodes 1 and 2 (74 % to 99 %; Figure 4). Three spurs of mechanically pruned Shiraz (2004 and 2005), control irrigated (2005) and deficit irrigated (PD; 2004, 2005) Cabernet-Sauvignon had similar final budburst percentages at each node position (Figures 4c, 4d, 4h, 4j and 4k). In contrast, mechanically pruned Chardonnay (2004), spur pruned Shiraz (2004, 2005) and both control and RDI treated Cabernet-Sauvignon (2005) showed lower final budburst percentage at node 1, relative to nodes 2 and 3 (Figure 4a, 4b, 4e, 4g and 4i). Final budburst percentage was also lower at nodes 1 and 2 for four and five node spurs of Chardonnay (Figure 4a) and for the control and PD treatments in 2005 for Cabernet-Sauvignon (Figures 4g and 4h). In contrast, final budburst percentages were similar along the four and five node spurs for spur and mechanically pruned Shiraz or other irrigation treatments and years for Cabernet-Sauvignon. For minimally pruned Shiraz, final budburst percentage was even lower for more distal buds (nodes 4 and 5) compared to proximal ones (nodes ≤ 3).

4. Budburst timing observations

Budburst was spread over a period of 3 to 4 weeks in the two years (Figure 2), enabling the two methods for determining budburst date to be compared. The first method described budburst as the date when a cumulative 50 % of total buds had burst (Figure 2, Table 3); the second described it as the date when a cumulative 50 % of total shoots had burst (Figure 2, Table 3). Budburst occurred in the second half of September (days 259 to 279). It was up to 8 days earlier when determined from '50 % of shoots burst' compared with '50 % of buds burst'.

In 2004, budburst for Shiraz occurred 17 days later than Chardonnay when it was based on '50 % of buds burst', and 12 days later when based on '50 % shoots burst'. Budburst of Cabernet-Sauvignon in 2004 was delayed by about 15 days, compared with Chardonnay, regardless of the method used ('50 % of buds burst' or '50 % shoots burst') (Table 3). No differences in budburst dates based on '50 %

TABLE 1. Number of buds per vine, final budburst percentage and the resulting number of shoots per vine for the different cultivars, pruning systems, irrigation treatments and years. Each value is the mean of 6 vines. Values between brackets are 95 % confidence intervals. Different lettering after means indicates significant differences between means for each cultivar ($p < 0.05$).

Cultivar	Year	Pruning	Irrigation	Buds number per vine	Final budburst* (%)	Shoots number per vine
Chardonnay	2004	Mechanical	Control	790 (266)	74.5 (1.4)	587 (192)
Shiraz	2004	Spur	Control	327 (50) c	66.9 (9.8) a	221 (63) c
		Mechanical		622 (194) bc	53.7 (3.2) bc	336 (109) bc
		Minimal		1460 (704) a	43.2 (14.9) c	643 (453) a
	2005	Spur	Control	339 (80) c	64.9 (7.2) ab	220 (56) c
		Mechanical		714 (108) b	61.7 (4.7) ab	442 (81) ab
Cabernet-Sauvignon	2004	Mechanical	Control	631 (267) a	74.3 (5.6) a	469 (200) a
			PD	746 (185) a	67.4 (7.5) ab	503 (130) a
			RDI	745 (200) a	61.8 (8.8) b	463 (144) a
	2005	Mechanical	Control	727 (132) a	64.3 (4.0) ab	469 (163) a
			PD	717 (116) a	59.4 (5.1) b	422 (44) a

*Final budburst percentage corresponds to parameter M in eq. 1 from the adjustment fitted for each vine.

TABLE 2. Percentage of bearers according to bearer size expressed as the number of nodes (or buds) per bearer (from 1 to > 10 nodes) for the different cultivars, pruning systems, irrigation treatments and years. Each value is a percentage calculated as the mean for 6 vines.

Cultivar	Year	Pruning	Irrigation	1	2	3	4	5	6	7	8	9	10	> 10
Chardonnay	2004	Mechanical	Control	< 5	14	31	24	15	6	< 5	< 5	< 5	< 5	< 5
Shiraz	2004	Spur	Control		17	65	18	29	5	< 5				
		Mechanical		< 5	< 5	29	31	24	6	8	8	< 5	5	5
		Minimal			< 5	9	25							
	2005	Spur	Control		16	51	27	5	7	< 5	< 5	< 5	< 5	
		Mechanical			14	25	27	14						
Cabernet-Sauvignon	2004	Mechanical	Control		< 5	32	43	19	< 5	< 5				
			PD		< 5	26	43	18	6	< 5	< 5		< 5	
			RDI		7	25	38	20	< 5					
	2005	Mechanical	Control	< 5	13	26	24	18	7	< 5	< 5	< 5	< 5	< 5
			PD	< 5	9	26	25	16	8	5	< 5			< 5

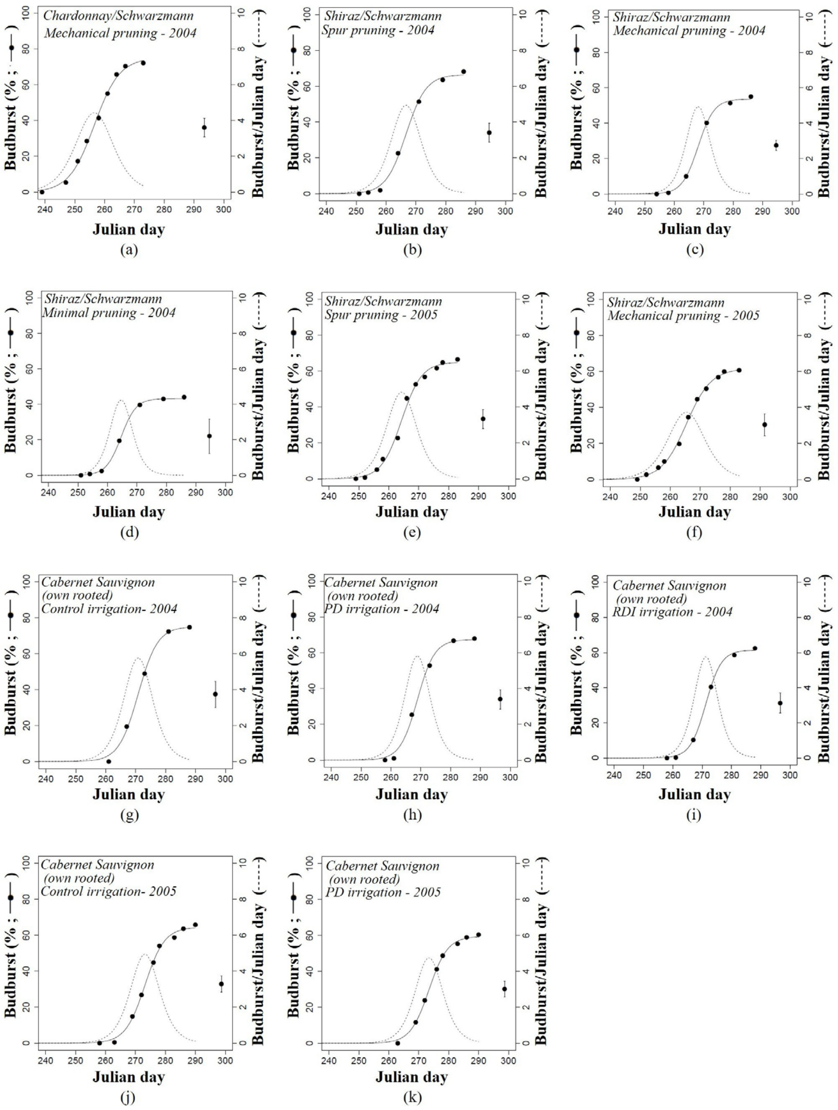

FIGURE 2. Cumulative percentage of budburst over the budburst period for the different cultivars (a = Chardonnay; b, c, d, e and f = Shiraz; g, h, i, j and k = Cabernet-Sauvignon), pruning systems, irrigation treatments and years. Data for cumulative percentage of budburst (solid line, left side Y axis) were fitted using eq. 1. The derivative of the fitting line (eq. 2, peak of budburst defined as '50 % of shoots burst') is represented by the dotted line (budburst/Julian day; right side Y axis). Each point value is the mean of 6 vines. Bars indicate average 95 % confidence intervals over the period of measurement.

of shoots burst' were observed between the pruning systems and years for Shiraz ($p > 0.05$) (Table 3). However, '50 % of buds burst' was reached for Shiraz 6 days earlier under spur pruning compared with mechanical pruning in 2004, and 4 days earlier for mechanical pruning in 2005 compared with 2004 ($p < 0.05$). It should be noted that the budburst day based on '50 % of buds burst' could not be determined for minimal pruned Shiraz as maximum budburst was 43 % for this treatment (Table 1). Thus, budburst date could only be determined from the method '50 % of shoots burst' for minimal pruning. No effect of irrigation was observed on the date of budburst defined as '50 % of buds burst' and '50 % shoots burst' for Cabernet-Sauvignon during each year (Table 2). Budburst, however, was delayed in 2005 compared with 2004, by 4-7 days (for Con and PD treatments) when defined as '50 % of buds burst' and by 4 days (for PD treatment) when defined as 50 % shoots burst'.

The cumulative growing degree days (GDD, eq. 3) to reach budburst after 1 July (i.e., after the assumed endodormancy release), was assessed for Chardonnay, Shiraz and Cabernet-Sauvignon, based on budburst timing observations (Table 3). In 2004, budburst of mechanically pruned Chardonnay occurred at 122 °Cd, followed by Cabernet-Sauvignon at 205 °Cd and Shiraz at 226 °Cd when budburst was defined as '50 % of buds burst', and from 4 °Cd (Chardonnay) to 55 °Cd (Shiraz) earlier when budburst was defined as '50 % of shoots burst'. As observed for budburst date (Julian days), budburst determined from GDD was similar among pruning treatments for Shiraz. No difference between years was

TABLE 3. Calculated Julian day or cumulated growing degree-days after 1 July for 50 % of shoots burst and 50 % of buds burst for the different cultivars, pruning systems, irrigation treatments and years. Each budburst timing value is the mean of 6 vines. Values between brackets are 95 % confidence intervals. Different lettering after means indicates significant differences between means (p < 0.05). NA indicates data not available.

				Calculated Julian day		Cumulated GDD after the 1 July (Julian day 182)	
Cultivar	Year	Pruning	Irrigation	50 % of buds*	50 % of shoots*	50 % of buds*	50 % of shoots*
Chardonnay	2004	Mechanical	Control	259 (2.2)	256 (2.2)	122 (4.6)	118 (3.8)
Shiraz	2004	Spur	Control	270 (2.6) b	267 (2.0) ab	183 (19.6) b	159 (13.7) bc
		Mechanical		276 (2.7) a	268 (1.1) a	226 (17.6) a	171 (6.1) ab
		Minimal		NA	265 (2.4) b	NA	146 (18.5) c
	2005	Spur	Control	268 (1.7) b	264 (1.9) b	199 (7.3) ab	178 (9.6) a
		Mechanical		272 (3.6) b	265 (2.0) ab	216 (21.5) a	186 (11.3) a
Cabernet-Sauvignon	2004	Mechanical	Control	273 (2.8) c	271 (2.6) bc	205 (21.2) b	190 (20.9) bc
			PD	272 (2.7) c	269 (1.2) c	202 (20.9) b	175 (9.3) c
			RDI	275 (2.4) bc	271 (1.1) abc	219 (18) b	198 (8.1) b
	2005	Mechanical	Control	277 (1.7) ab	273 (1.6) ab	251 (11.5) a	223 (11.1) a
			PD	279 (2.6) a	273 (1.0) a	263 (13.6) a	224 (5.8) a

* '50 % of buds burst' and '50 % of shoots burst' were calculated using eq. 1 from the adjustment fitted for each vine. The budburst date defined as '50 % of shoots burst' corresponds to parameter tl in eq. 1.

observed when budburst was defined as 50 % of buds burst', but budburst defined as '50 % of shoots burst' occurred 19 °Cd earlier for spur pruned Shiraz in 2004 compared with 2005. Similarly, GDD to reach budburst were similar among irrigation treatments for Cabernet-Sauvignon irrespective of the method used ('50 % of buds burst' *vs* '50 % of shoots burst'). Budburst, however, also occurred earlier for Cabernet-Sauvignon in 2004 than 2005 by about 36 °Cd ('50 % of buds burst') to 48 °Cd ('50 % of shoots burst').

DISCUSSION

Bud numbers ranged from 333 per vine on average for the spur pruned Shiraz to 712 for mechanical pruning (all cultivars) and 1460 for minimally pruned Shiraz (Table 1). This range of bud numbers was within expectations based on previous observations for similarly managed vines (Clingeleffer, 2010; Edwards and Clingeleffer, 2013).

For mechanical pruning, bud numbers were similar between years, between cultivars and between irrigation levels. No differences in final % budburst and the resulting shoot number per vine were observed between the years for Shiraz or Cabernet-Sauvignon, indicating that plant capacity to burst buds for a given total bud number in this study was insensitive to temperature variations preceding budburst (Table 1; Figures 1 and S1).

The total number of shoots per vine for Shiraz was the highest for minimal pruning, followed by mechanical pruning and spur pruning, with final budburst percentage in the reverse order; i.e., lowest for minimal, intermediate for mechanical and highest for spur pruning. Clingeleffer and Sommer (1994) showed that in spite of their lower budburst percentage, lighter pruned vines reached higher yield compared with severe pruned vines, due to the increase in both shoot and bunch numbers.

Higher budburst percentages for spur pruned Shiraz reflected the higher percentage of smaller bearers with fewer nodes (≤ 3 nodes), together with the higher budburst percentages for spurs with fewer node (bud) numbers (Table 2; Figure 3). Similarly, Cabernet-Sauvignon was shown to have a lower budburst with increasing nodes per bearer (Clingeleffer, 1989). Lighter (minimally and mechanically) pruned vines had a lower weight of one-year-wood than spur pruned vines, thus reflecting a higher competition for carbohydrates at the plant and shoot level (Clingeleffer and Sommer, 1994), given the higher shoot and bud numbers of lighter pruned vines. The lower carbon availability for longer bearers may at least be partly responsible for the reduced budbreak (Sapkota *et al.*, 2021). Although the deficit irrigation treatments (RDI, PD) applied to Cabernet-Sauvignon also tended to reduce the final percentage of budburst compared with the control treatment, they did not cause any reduction in the final number of shoots (Table 1).

The lower budburst percentage with the increasing number of nodes (buds) per bearer could also be related to the varying

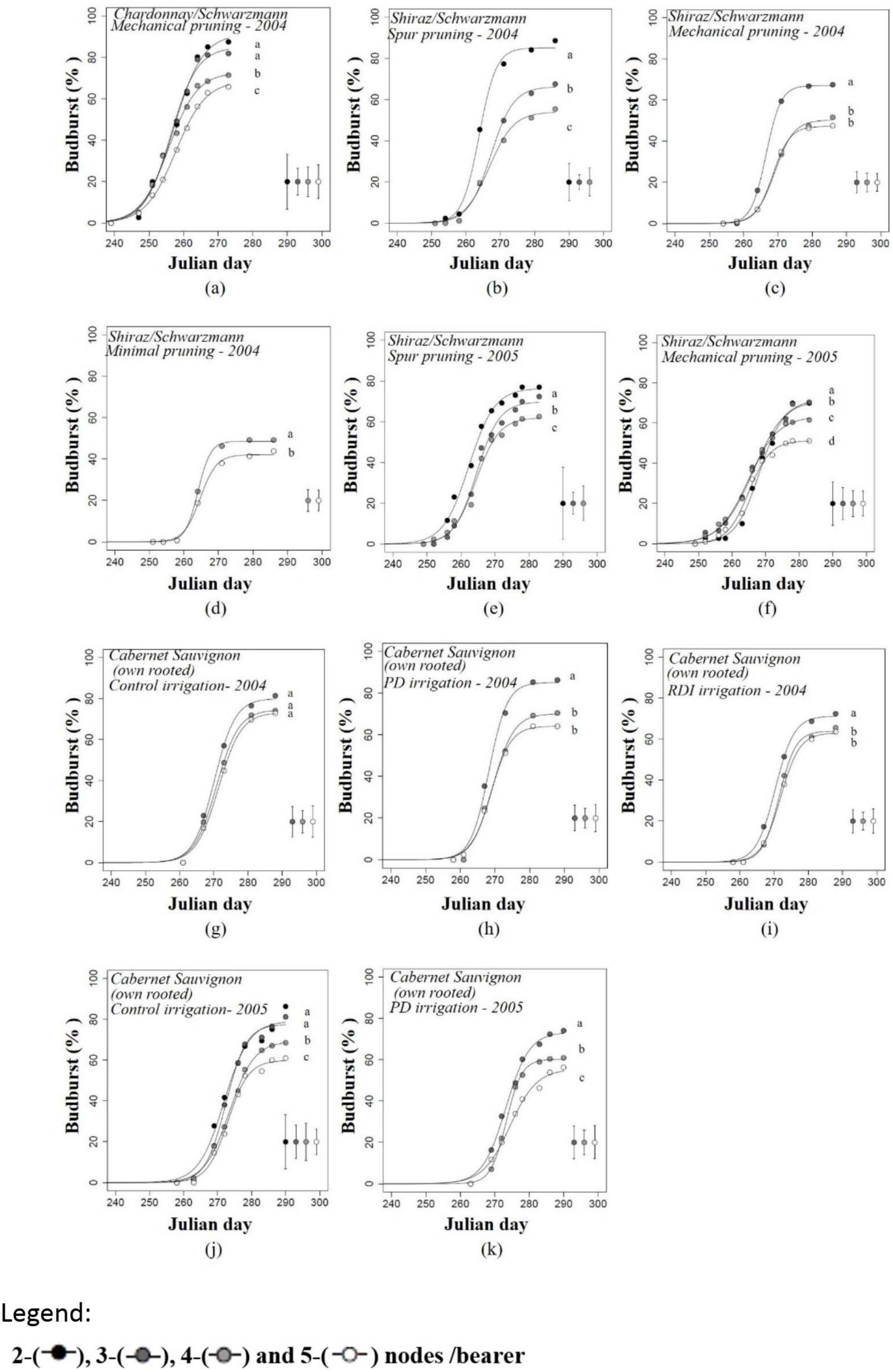

FIGURE 3. Cumulative percentage of budburst over the budburst period for bearers with varying node numbers for the different cultivars (a = Chardonnay; b, c, d, e and f = Shiraz; g, h, i, j and k = Cabernet-Sauvignon), pruning systems, irrigation treatments and years. Data for cumulative percentage of budburst (solid line) were fitted using eq. 1. Each point value is the mean of 6 vines. Bars indicate average 95 % confidence intervals over the period of measurement. Different lettering indicates significant differences in the adjustments between bearers with either 2, 3, 4 or 5 nodes ($p < 0.05$).

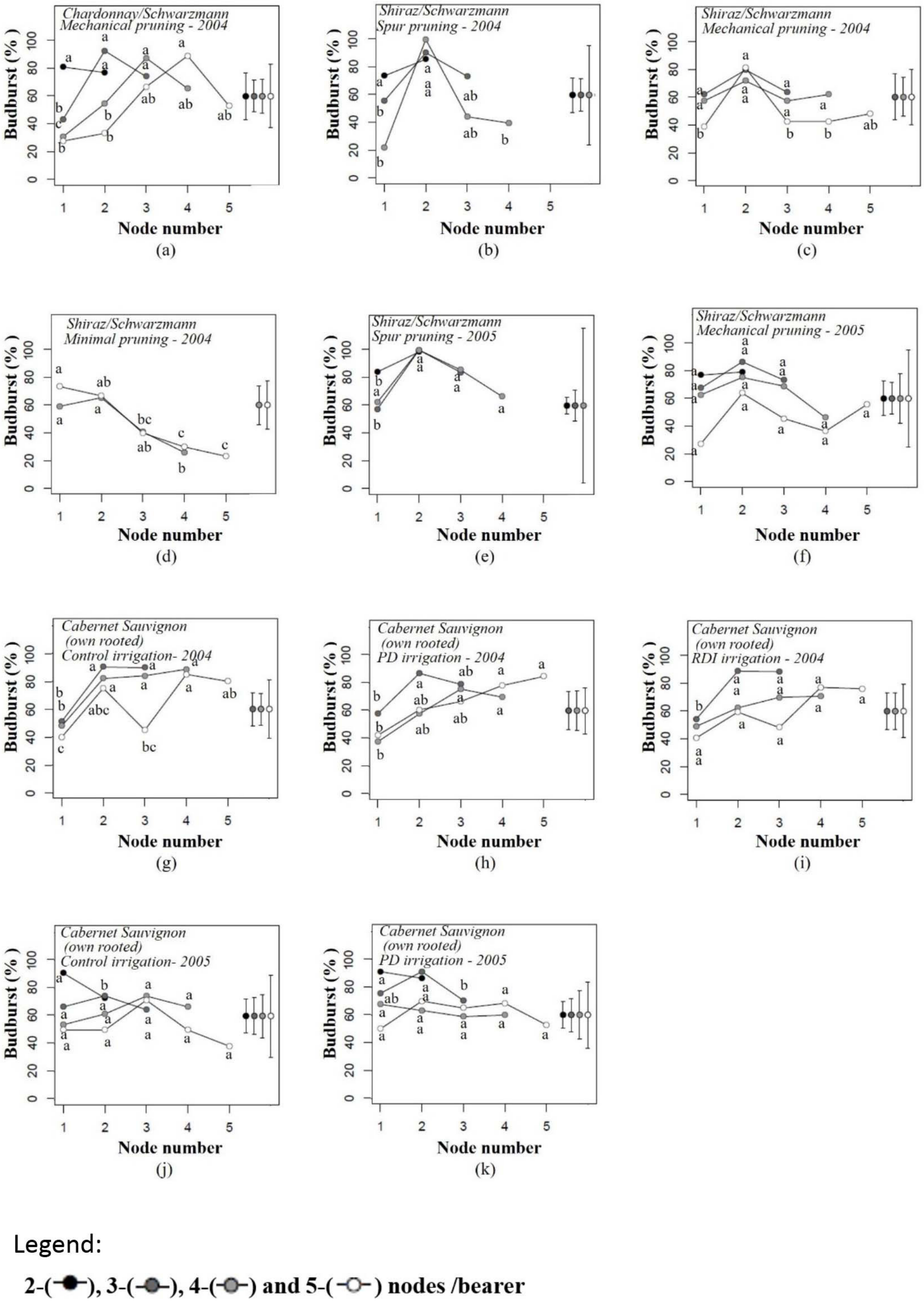

FIGURE 4. Final percentage of budburst for bearers with varying node numbers and per node position on the bearer for the different cultivars (a = Chardonnay; b, c, d, e and f = Shiraz; g, h, i, j and k = Cabernet-Sauvignon), pruning systems, irrigation treatments and years. Each value is the mean of 6 vines. Bars indicate average 95 % confidence intervals per bearer type. Different lettering indicates significant differences between node positions within a bearer ($p < 0.05$).

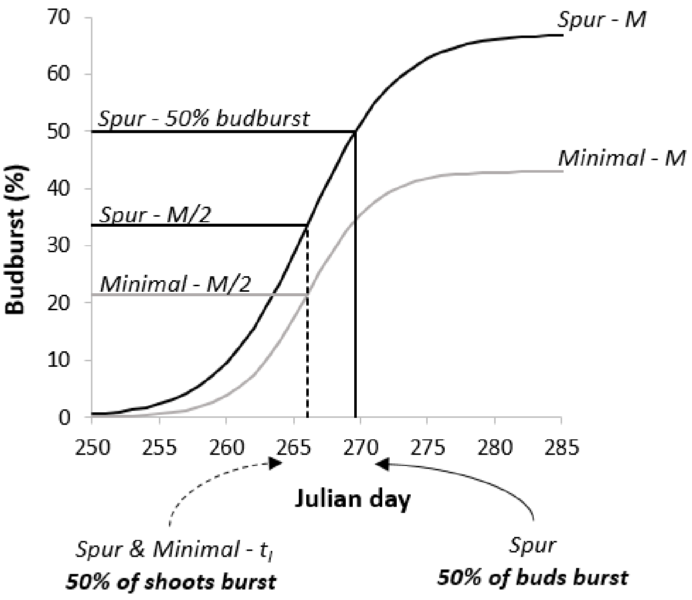

FIGURE 5. Example of budburst dates defined as '50 % of buds burst' or '50 % of shoots burst' for the Spur and Minimal pruning treatments of Shiraz in 2004. For Minimal pruning, the % of burst nodes was less than 50 % and hence budburst date defined as '50 % of buds burst' cannot be included in the Figure. The lines were fitted from eq. 1 using the following parameters (M the maximum value of the logistic curve, a the slope at the inflexion point of the function, and tI the Julian day at the inflexion point): Spur: M = 67; a = 0.30; tI = 266 & Minimal: M = 43; a = 0.39; tI =266. The fitting lines and parameters are also shown in Figure 2, Table 1 and Table 3.

final budburst trends from the proximal to the distal end of bearers (Figure 4). Spurs with 3 to 5 nodes tended to have lower final budburst % at basal (proximal) node positions (node 1 and in some cases at node 2) compared with spurs with 2 nodes. For Cabernet-Sauvignon with fruiting units longer than 3 nodes, Clingeleffer (1989) described positive linear responses between budburst percentage and node position along the fruiting unit, with the slope decreasing as node number increased. These responses were associated with earlier budburst of proximal buds on shorter bearers and of buds close to pruning cuts on longer fruiting units. The gradual budburst along the bearer reflects an acrotony (Carbonneau *et al*., 2019), as reported for a range of cultivars, and may also result from a negative gradient of bud fertility from the distal (apical or pruning cut end of the bearer) to the proximal (basal) nodes (Clingeleffer, 1989; Martin and Dunn, 2000; Friend and Trought, 2007; McLoughlin *et al*., 2011). In contrast, in minimal pruning the acrotony does not govern as there is no pruning cut.

Lastly, mechanically pruned Shiraz had a lower total shoot number per vine compared with mechanically pruned Chardonnay and Cabernet-Sauvignon in 2004, mainly due to a lower final % budburst (Table 1, Figure 3). The lower percentage of budburst in Shiraz could result from primary bud necrosis as this cultivar was shown to be very susceptible to this disorder in Australian vineyards (Dry and Coombe, 1994).

In general, this study has highlighted the difficulty of deciding on a single date for budburst timing. Individual bud burst occurs over a one-month period across a vine, revealing a peak ('50 % of shoots burst') up to one week before the usual measure of budburst date determined from '50 % of buds burst' (Figures 2 and 5; Table 3). Budburst date was similar among the irrigation treatments used for Cabernet-Sauvignon, and among the pruning treatments used for Shiraz when it was determined from '50 % of shoots burst' (parameter t_I in eq. 1, Table 3; Figure 5). However, budburst date determined from '50 % of buds burst' was delayed for the mechanically hedged treatment compared with spur pruning in 2004. The measure '50 % of buds burst' can be easily determined before the completion of budburst if the number of nodes retained at pruning is known. However, in some situations when the final budburst percentage only slightly exceeds 50 %, as observed for the mechanically pruned Shiraz in 2004, this method is likely to overestimate budburst date. Moreover, the results for minimal pruning, although only determined for one year, are clear-cut and highlight the importance of bud number and low budburst in lightly pruned systems. Indeed, final % budburst of minimally pruned Shiraz was 43 % in 2004, making the '50 % of buds burst' method impossible to use (Figure 5). Given these limitations, the method to determine budburst date based on '50 % of shoots burst' appears to be more adaptable and hence superior to that of '50 % of buds burst'. In the present study, the budburst percentage associated with '50 % of shoots burst', corresponding to half parameter *M* in eq. 1 (Table 1), ranged from 21.5 % for minimally pruned Shiraz to 37.2 % for mechanically pruned Chardonnay (both in 2004).

Although an observation of maximum budburst (M) is necessary to calculate *a posteriori* the date of budburst defined as '50 % of shoots burst', only a few weekly measures of the number of burst shoots are required for a designated period of time to reach '50 % of shoots' (parameter t_1 in eq. 1) (e.g., during the initial 3 weeks after the first observation of bud burst).

Chardonnay budburst measured as '50 % of shoots burst' and '50 % of buds burst' were both early by about two weeks (up to 104 °Cd) in 2004 compared with Shiraz and Cabernet-Sauvignon, which burst with an interval of 3 days (Table 3; Figure 2). Similar median budburst dates for these cultivars were reported for South Australian regions by Coombe (1988). However, the heat requirements for budburst (cumulated GDD) calculated for these three cultivars under northern hemisphere environmental conditions was reduced by up to two-thirds (García de Cortázar-Atauri *et al*., 2009; Zapata *et al*., 2016). Such differences in forcing temperature requirements question the use of 1 July as the date for onset of ecodormancy period in the present study. Indeed, under a warm winter climate, the chilling requirements may possibly not be fulfilled at that date. According to Webb *et al*. (2007), the reducing trend in the hours of chilling due to global warming in some Australian viticultural regions will become critical, thus causing delayed and erratic budburst. Seasonal variations in budburst measured by '50 % of shoots burst' and '50 % of buds burst' were also observed for Cabernet-Sauvignon (Con and PD treatments), with a delayed budburst in 2005 of 4-7 days, or 33-61 °Cd, compared with 2004 (Table 3; Figure 2). These results were consistent with the warmer mean temperatures measured during the period from February to June in 2005, relative to 2004 (first quartile or threshold for the lowest 25 % daily mean temperatures in the range 5-11 °C in 2004 *vs* 8-13 °C in 2005), which possibly delayed the endodormancy breakage and/or increased the GDD requirements for ecodormancy release in 2005 compared with 2004 (Caffarra and Eccel, 2010; Anzanello *et al*., 2018). Ultimately, the critical amount of chilling units required for endodormancy breakage and their potential effect on forcing unit requirements under Australian climatic conditions deserves more study. In addition, factors other than air temperature were also reported to have impacted budburst. Budburst was shown to be more heterogeneous when soil water content was lower, and to be earlier when the upper soil layers were warmer (Alleweldt and Hofacker, 1975; Li *et al*., 2016). In the present study, soil water status during the month before budburst was high for the two years (data not shown). In the future, climate change may exacerbate soil warming and drying during the ecodormancy and grapevine bleeding periods (Knight *et al*., 2006). In contrast, budburst was delayed by later winter pruning (one *vs* two-months before budburst) and varied with bud fruitfulness (Martin and Dunn 2000). Lastly, more research is required on the impact on budburst of source-sink activities and the resulting carbohydrates reserve replenishment during the previous season, as influenced by crop load and environmental factors (notably light, temperature and water).

This study has shown that variations in final % budburst between the cultivars or between the pruning systems and irrigation treatments were associated with contrasting distributions of spurs with different numbers of nodes (buds) between pruning systems, and different cumulated budburst at a given bearer size between cultivars. Budburst was reduced as spur node number increased and also tended to be reduced at basal node positions for spurs with higher node numbers. Apical dominance, bud fertility and competition for carbohydrates between buds are likely to play key roles in these responses, independently of climate variations preceding budburst, which in this study did not affect final % budburst. The same trend in variations in budburst timing was observed between the cultivars and to a lesser extent between years for Cabernet-Sauvignon, irrespective of the method used ('50 % of buds burst' or '50 % of shoots burst'; Julian days or GDD). However, the budburst timing appeared slightly delayed for mechanically hedged Shiraz compared with spur pruning in 2004 using the '50 % of buds burst' method only. Low final budburst on mechanically hedged Shiraz (53.7 %) led to an overestimation of the time to reach 50 % of buds burst, making this latter method less useful. Ultimately, final budburst percentage and timing of budburst defined by '50 % of shoots burst' for each cultivar may be useful for adapting and improving existing grapevine phenological models for Australian vineyards with contrast pruning systems.

CONCLUSION

The generally used method to set budburst date which is defined as '50 % of buds burst' was shown to be unreliable when final % budburst is low. Budburst measured by '50 % of total shoots burst' is a potential alternative practical measure in these situations. Using this method, the date of budburst was similar between the pruning systems for Shiraz, and thus was independent of bud number and final % budburst. However, budburst defined as '50 % of total shoots burst' varied among years for Cabernet-Sauvignon, although the differences were lower compared to the differences between cultivars. The higher growing degree days required to reach '50 % of total shoots burst' under warmer winter conditions suggests the need to specifically address the timing of endodormancy release and possible impacts of chilling temperatures on forcing temperature requirements under Australian climate conditions. It is also important to consider soil water status and temperature during the bud ecodormancy and grapevine bleeding periods, as well as overall growing conditions in the vineyard during the preceding year (which impact plant reserves), because these factors may also influence budburst earliness. To conclude, detailed data for accurately defining budburst date are rarely reported, especially for contrasting pruning systems. This study provides new results that could be used to improve budburst modelling approaches and be applied in crop management for better adaptation of cultivars to seasonal conditions.

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