Effect of delaying budburst on shoot development and yield of *Vitis vinifera* L. Chardonnay ‘Mendoza’ after a spring freeze event

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**Abstract**

**Background and Aims:** Spring freeze events can result in substantial grapevine yield losses in many parts of the world. Understanding vine responses following early spring freeze events will aid in the development of decision support systems for vineyards damaged by freezing temperatures.

**Methods and Results:** The date of budburst of spur-pruned Chardonnay vines was manipulated by pruning time and/or the application of sodium alginate gel. A spring freeze event occurred at bud swell/woolly bud, killing 33% of the developing shoots. Treatments that delayed bud development expressed a lower incidence of freeze damage (as low as 3%). Where primary shoots had been killed, secondary shoots developed in their place. The yield from secondary shoots was 32% of that from primary shoots, with the majority of fruiting secondary shoots bearing only one bunch. Average bunch weight, number of berries per bunch and average berry weight of secondary shoots were comparable with those from primary shoots.

**Conclusions:** The damage to primary shoots caused by early spring freeze events can be reduced by using treatments that delay bud development. Secondary shoots develop in response to death of the primary shoot, and although they have reduced fruitfulness, they can partially mitigate the potential yield losses associated with the death of primary shoots.

**Significance of the Study:** The number and fruitfulness of secondary shoots that develop after a spring freeze event determine the extent of mitigation of yield losses associated with the death of primary shoots.

**Keywords:** alginate gel, bunch number, frost, primary shoot, pruning time, secondary shoot

**Introduction**

Frost is a significant hazard to grape production in many parts of the world (Trought et al. 1999). Depending on regional climate and vineyard topography, frost can occur throughout the growing season; however, freeze events in spring are often the most damaging, causing substantial injury to and/or death of plant tissues. The susceptibility of grapevine tissue to frost damage depends on many factors, including cultivars, pre-frost environmental conditions (dew point and the presence of surface moisture), the probability of ice nucleation events and the stage of phenological development (Trought et al. 1999).

Dormant buds of *Vitis vinifera* L. Gamay are able to withstand temperatures as low as −25.7°C (Andrews et al. 1984). Grape buds avoid ice formation and freezing damage when dormant by supercooling (Kang et al. 1998), not extra-organ freezing (Pierquet and Stushnoff 1980); whereas canes exhibit equilibrium freezing and tolerate the resulting intracellular desiccation (Jones et al. 2000). It is proposed that buds are able to supercool because of a permeability barrier in the bud axis (Jones et al. 2000); during autumn acclimation, secondary cell walls form at the base of the bud axis, and pectins fill the intercellular spaces. The apoplastic permeability of this layer is decreased, preventing the propagation of ice from the cane to the bud and enabling supercooling to occur. This ability to supercool is completely lost when xylem vessels develop from the cane into the bud axis at spring time. A high correlation between bud hardiness, water content and stage of bud development exists (Gardea 1987). The $T_{50}$ values (temperature when 50% of buds are damaged) of Pinot Noir at the phenological stages of quiescent, swollen, budburst, first, second and third flat leaf have been recorded as −14, −3, −2.2, −2, −1.7 and 1.1°C, respectively (Gardea 1987).

The risk or incidence of damage caused by a spring frost depends not only on plant susceptibility factors but also on the minimum temperature achieved and the length of time at or below the critical temperature causing damage. The colder a frost and/or longer the time at or below the critical temperature, the greater the chance of damage occurring.

A major consequence of spring freeze damage can be a reduction in vine yield. Late or relatively light freeze events may damage flowers or inflorescences on shoots, whereas early or severe freeze events can kill the whole primary shoot. Injury to flowers, leaves and shoots has the potential to affect yield not only in the current season of the freeze event but also in the following season (Trought et al. 1999). For example,
replacement of shoots killed in a late and severe spring freeze event could deplete vine carbohydrate reserves negatively affecting inflorescence initiation; or conversely, warmer conditions during inflorescence initiation could increase the number of inflorescences within the developing compound buds on the replacement shoots.

Dead primary shoots are often replaced by shoot development from usually quiescent secondary buds within the compound bud. The compound bud of grapevines typically has three shoot primordia (Pratt 1974). The fertility and hence potential from usually quiescent secondary buds within the compound bud is less than that of the primary shoot; however, the extent of this difference in fertility after a frost event has not been described. We discuss the impact of a spring freeze event at budburst on the shoot yield of *Vitis vinifera* L. Chardonnay ‘Mendoza’.

**Materials and methods**

An experiment was established to evaluate the effectiveness of delayed winter spur pruning and sodium alginate gel application to modify the timing of grapevine budburst; however, on 25/26 September 2000, a radiation frost occurred, causing damage to a proportion of the developing buds. The budburst delay experiment was laid out in a split-plot factorial design, with nine, three-vine replicates, blocked across three rows (n = 27). The vines used for experimentation were 10-year-old, non-grafted, *Vitis vinifera* L. Chardonnay clone ‘Mendoza’, growing in the Lincoln University vineyard in Canterbury, New Zealand (43°38′52″S, 172°27′21″E). The vines exhibited millerandage, which, for the Mendoza clone in New Zealand, is typically associated with Grapevine leafroll-associated virus, type 1 (GLRaV-1) [ICTVDB virus 00.017.0.03.002] (Cohen 2000). Vines were pruned to 32 buds on 16 spurs; shoots were trained vertically. Vines in each replicate were pruned on one of three dates: 28 July (Early; typical time of pruning), 18 August (Mid; late winter pruning) or 8 September 2000 (Late; very late winter pruning). Sodium alginate gel was applied on three occasions to pre- and post-pruned vines on bud positions suitable for spurs, according to treatment. Groups of four spurs were randomly allocated along the cordon of each vine, as either a non-treated control (Control), a single application on 28 July (Early), or 18 August (Mid), or a multiple application on 28 July, 18 August and 8 September 2000 (Repeat). The alginate was applied using a paintbrush as a gel, containing 4% sodium salt anhydro-β-D-mannurononic acid (Sigma, St Louis, Missouri, USA) dissolved in a 0.75-M solution of sucrose. Spurs were sprayed with a 0.2-M calcium chloride solution before a liberal application of the gel. The gel was immediately and thoroughly sprayed with a 0.2-M calcium chloride solution. The divalent cation solution of calcium chloride stabilised the viscous liquid gel to form a cross-linked gel/sucrose matrix.

Bud and shoot development were assessed using the modified Eichhorn and Lorenz (E-L) system (Coombes 1999) on 26 September 2000. The apical and basal buds of two randomly selected spurs from within each alginate treatment on each vine were tagged and rated. An assessment of primary shoot death was made on 5 October 2000 from tagged spurs, and the subsequent development of secondary shoots from nodes from tagged spurs was recorded on 1 November 2000.

Vines were harvested on 10 April 2001, and vine yield and yield components were recorded. Air temperature during the spring freeze event on 25 September 2000 was collected from the Lincoln University weather station (43°38′41″S, 172°27′23″E). The weather station was located approximately 200 m north of the experimental site across flat land, separated by two 10-m-high *Populus nigra* ‘Italica’ shelterbelts.

Data analysis was completed using GenStat version 10.1 (Lawes Agricultural Trust, Rothamsted, UK). Analysis of variance was used to identify treatment effects on shoot phenology, spring freeze incidence and secondary shoot development. The data were analysed as a split plot design with the ‘Pruning’ treatment stratum containing 16 degrees of freedom and at the ‘Pruning.Gel’ stratum, 72 degrees of freedom. A t-test was used to assess differences in yield components between primary and secondary shoots; except for the number of bunches per shoot where the Chi-square test was used, because of the categorical nature of the data. The relationship between the incidence of shoot death and phenological stage was tested via regression, and any potential confounding effect of the pruning and gel treatments was tested for via the general linear model.

**Results**

The phenological development of buds was delayed by later winter spur pruning and application of sodium alginate gel (Table 1). In general, late pruning and multiple applications of gel were more effective in delaying budburst.

A spring freeze event occurred during budburst. Air temperatures at 1.2-m height dropped below 0°C after 2200 h on 25 September 2000, reaching a minimum temperature of −1.7°C at 0300 h on 26 September. The freeze event lasted for approximately 5 h (Figure 1).

Treatments applied to delay the normal development of primary shoots tended to have a lower incidence of spring freeze damage (Table 1). The incidence of primary shoot damage was higher in treatments with advanced bud development; however, buds at E-L stage five suffered no damage (Figure 2).

The subsequent development of secondary shoots after the freeze event was lower where treatments had been applied to delay the normal development of shoots (Table 2). No nodes

**Table 1.** The effect of delayed winter spur pruning and alginate gel application on the phenological development of Chardonnay grape primary shoots and the percentage incidence of death of primary shoots.

<table>
<thead>
<tr>
<th>Alginite treatment</th>
<th>Control</th>
<th>Early</th>
<th>Mid</th>
<th>Repeat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phenological development of primary shoots</td>
<td>Pruning treatment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Early</td>
<td>3.2</td>
<td>3.9</td>
<td>2.8</td>
<td>3.2</td>
</tr>
<tr>
<td>Mid</td>
<td>2.8</td>
<td>2.7</td>
<td>2.7</td>
<td>2.3</td>
</tr>
<tr>
<td>Late</td>
<td>2.6</td>
<td>2.2</td>
<td>2.1</td>
<td>1.8</td>
</tr>
<tr>
<td>Percent death of primary shoots</td>
<td>Pruning treatment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Early</td>
<td>63.9</td>
<td>61.1</td>
<td>58.3</td>
<td>2.8</td>
</tr>
<tr>
<td>Mid</td>
<td>58.3</td>
<td>36.1</td>
<td>47.2</td>
<td>0.0</td>
</tr>
<tr>
<td>Late</td>
<td>38.9</td>
<td>11.1</td>
<td>16.7</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Phenology data were collected on 26 September 2000, the morning after a −1.7°C spring freeze event, using the modified Eichhorn and Lorenz (E-L) stage phenology scale, from buds on tagged spurs. Treatment effects (P = 0.003) are separated using a least significant difference (LSD) (Fisher’s LSD; P = 0.05) of 0.007, except at the same level of pruning, where 0.510 should be used. Primary shoot death data were collected on 5 October 2000, from buds on tagged spurs. Significance (P = 0.018) is demonstrated using a LSD (Fisher’s LSD; P = 0.05) of 19.6, except at the same level of pruning, where 19.5 should be used.
were found to have both primary and secondary shoots growing in combination. Secondary shoot development was positively related with the incidence of primary shoot death (Figure 3).

Yield per node was almost three times greater on primary shoots than secondary shoots as a consequence of the mean number of bunches per shoots (Table 3). Neither the average bunch weight, number of berries per bunch, average berry weight, nor the number of flowers on the first branch of the inflorescence were different between primary and secondary shoots.

Comparing the fruitfulness of primary shoots with that of secondary shoots revealed that 63% of primary shoots possessed two bunches, 26% possessed one bunch and 11% no bunches, whereas 11, 28 and 61% of secondary shoots possessed two, one or no bunches, respectively (Figure 4).

Table 2. The effect of delayed winter spur pruning and alginate gel application on the percentage incidence of secondary shoot development in Chardonnay grape.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Application time</th>
<th>P value</th>
<th>LSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pruning</td>
<td>Early Mid Late</td>
<td>0.008</td>
<td>16.4</td>
</tr>
<tr>
<td>Alginate Control</td>
<td>Early Mid Repeat</td>
<td>&lt;0.001</td>
<td>11.7</td>
</tr>
</tbody>
</table>

Data collected on 1 November 2000, from buds on tagged spurs; means were separated using Fisher’s least significant difference (LSD) test (P = 0.05).

Figure 1. Air temperature over the evening of 25 September to the morning of 26 September 2000, showing the minimum temperature and duration of the freeze event. Data were collected from the Lincoln University weather station (43°38′41″S, 172°27′23″E), approximately 200 m north of the experiment site.

Figure 2. Incidence of primary shoot death in Chardonnay grape at different stages of phenological development. Figures indicate the number of buds at each stage of development; modified Eichhorn and Lorenz stage data collected on 26 September 2000, the morning of the spring freeze event; error bars represent 95% confidence intervals.

Figure 3. The relationship between the incidence of primary shoot death in Chardonnay grape and the development of secondary shoots. Symbol area is relative to the number of values at each point (range = 1–4); plotted values are vine means (n = 27); primary shoot death was recorded on 5 October 2000, and secondary shoot development was recorded on 1 November 2000. y = 0.899 + 1.03x, P = < 0.001 R² = 0.88.

Figure 4. Comparison of the proportion of primary (black bars) and secondary (white bars) Chardonnay grape shoots bearing zero, one or two bunches (n = 826); χ² = 133, P = < 0.001.
Table 3. Yield components of primary and secondary shoots of Chardonnay grapes.

<table>
<thead>
<tr>
<th>Yield component</th>
<th>Primary shoots</th>
<th>Secondary shoots</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield per node (g)</td>
<td>57.9 (2.8)</td>
<td>19.1 (3.4)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Average bunch weight (g)</td>
<td>38.2 (1.25)</td>
<td>37.9 (4.09)</td>
<td>0.97</td>
</tr>
<tr>
<td>Number of berries per bunch</td>
<td>58 (1.52)</td>
<td>50 (4.48)</td>
<td>0.068</td>
</tr>
<tr>
<td>Average berry weight (g)</td>
<td>0.89 (0.009)</td>
<td>0.89 (0.028)</td>
<td>0.88</td>
</tr>
<tr>
<td>Number of bunches per shoot</td>
<td>1.5 —</td>
<td>0.5 —</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Number of flowers on the first branch of the inflorescence</td>
<td>28 (0.83)</td>
<td>26 (1.63)</td>
<td>0.36</td>
</tr>
</tbody>
</table>

P values were calculated from t-tests except for the number of bunches per shoot, where Chi-square was used; numbers in brackets represent the standard errors of the mean.

Discussion

Differences in bud development (Table 1) associated with delayed winter spur pruning and application of alginate gel were similar to those reported in the literature (Antcliff et al. 1957, Dami et al. 1996, Friend and Trought 2007). Treatments with delayed phenology also had a reduced incidence of primary shoot death (Table 1) after the spring freeze event of 25/26 September 2000, demonstrating the effectiveness of such treatments in reducing damage from early spring freeze events.

The modes of action of the two treatments applied are not clear. Delayed winter spur pruning appears to take advantage of the natural cumulative inhibition of proximal buds resulting from acrotory. Acrotony is the increase in vigour of vegetative proleptic branches (from dormant buds) from basal to the apical positions of the parent growth unit (Lauri 2007). The distribution of shoot growth along canes pruned after budburst presented by Friend and Trought (2007) suggests a hierarchy between buds along a cane, with buds at apical node positions possessing greater vigour than buds at basal node positions. Howell and Wolpert (1978) also found growth suppression of basal nodes when longer canes with additional buds were left at pruning. The mode of action of alginate gel could have multiple causes: Dami et al. (1996) found canes treated with alginate gel had lower water content and postulated this could slow bud metabolic activity, but also suggested that the low gas permeability of alginate may allow an oxygen deficiency and a carbon dioxide accumulation potentially slowing bud metabolic activity. A physical restriction, from encasing a bud with the dry non-flexible matrix of the alginate, may physically hinder the development of buds. The temporary placement of a spring-loaded peg around a bud will delay budburst (Huglin and Schneider 1998).

As bud development became more advanced, the incidence of primary shoot death was greater (Figure 2), in agreement with the findings of Gardea (1987). buds at modified E-L stage 1 (dormant winter bud) had a 2% death rate, whereas those at modified E-L stage 4 (green tip, first leaf tissue visible) had a 68% death rate. The survival of the seven buds at modified E-L stage 5 (Figure 2) should be interpreted with caution. The small number of buds contributes to a large standard error and casts doubt as to the validity of this result. An analysis for a confounding effect of pruning and gel treatments on the incidence of primary shoot death with stage of development found no treatment effect.

The extent of the damage suffered in the spring freeze event reported here was higher than might be expected based on the data of Gardea (1987), which suggest that most of the buds should have been capable of surviving the −1.7°C event. Mean bud development was at modified E-L stage 2.7, a stage capable of surviving temperature conditions of approximately −3°C. The temperatures quoted by Gardea (1987) are tissue temperatures, and Trought et al. (1999) and Ireland (2005) highlight that thermal radiation from plant tissues may result in buds being 2 to 3° below air temperatures during freeze events. Tissue temperatures, therefore, may have dropped between −2.7 and −3.7°C, matching the T∞ value reported for buds at the swollen/woolly stage of development, conceivably explaining the mean incidence of 33% primary shoot death across the experiment.

A strong treatment effect of delayed pruning and gel application on the development of secondary shoots was evident (Table 2); however, only main effects existed. The development of secondary shoots appeared to be a response to the death of the primary shoot, rather than a response to treatments that delay budburst (Figure 3). Secondary shoots and quiescent buds from perennial wood often grow on vines where inadequate numbers of nodes were left at pruning (May and Bessis 1985). The signal for secondary shoot development in our situation appears to be localised, as in this trial, secondary shoots were only present where the primary shoot had been killed, suggesting that winter pruning levels (node numbers) were appropriate.

Spring freeze events can have a profound effect on the productivity of a vineyard, and the event reported here was no exception. Yield loss after an early spring freeze event is proportional to the number of primary shoots that are killed, the number of secondary shoots that replace those primary shoots and the fruitfulness of the secondary shoots. Based on the mean incidence of primary shoot death and the measured yield per node, we estimate that secondary shoots contributed on average 200 g of yield per vine, and reduced the estimated yield loss from primary shoot death from 34 to 23%. The extent of yield compensation from secondary shoots is likely to be cultivar dependent, as Kasimatis and Kissler (1974) found the proportion of yield from primary, secondary and latent buds varied greatly between Tokay and Carignane grapevines.

The average yield per node of secondary shoots was approximately 30% that of primary shoots (Table 1). The differences in yield per node were principally caused by the lower bunch number per shoot compared with the primary shoots (Figure 4), although the data suggest that a small reduction in berry number per bunch may also contribute to differences in yield (Table 3). In this vineyard, during the 2000–2001 season, a secondary shoot was less likely to possess two bunches and more likely be unfruitful (Figure 4). Presumably, the quiescent nature of the secondary shoots at the time of the spring freeze...
event meant that fruitfulness of these shoots was unaffected by the freezing temperature conditions.

Although fewer bunches were present on secondary shoots, the number of flowers on the first branch of the inflorescence and bunch yield components were no different from those of primary shoots. Inflorescence number per shoot appears to be driving the yield contribution of secondary shoots. Little information exists on whether the differences in fruitfulness of primary and secondary shoots are consistent between seasons, or on the temperature requirements and timing of inflorescence induction and initiation on secondary shoots.

Conclusions
In response to an early spring freeze event, ‘Mendoza’ Chardonnay vines produced secondary shoots from nodes where primary shoots were killed. The incidence of primary shoot death was related to the extent of shoot development, with less advanced stages of phenology better able to survive sub-zero temperatures. Therefore, treatments that delay budburst will reduce the risk of frost damage early in the season. The development of secondary shoots counters potential yield losses associated with a spring freeze event. However, secondary shoots are only partially able to compensate for the loss of primary shoots because of their lower number of bunches.

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References

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