The effect of seasonal and climatic factors on *Eucalyptus obliqua* mortality in response to stem injection of glyphosate

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Abstract

A year-long study investigated the effect of season on tree mortality following glyphosate injection in eucalypt regeneration at a wet sclerophyll and a dry sclerophyll site in Tasmania. Trees of a range of sizes were injected at each site on a monthly basis, and their decline and death monitored using a canopy rating system. Generally, the larger the diameter class, the longer it took for 90% of trees in that diameter class to die, regardless of the season of injection or site. Season of injection affected the speed of kill at both sites; trees were generally killed more quickly at the drier site following winter injections, and at the wetter site following summer injections. Ninety per cent of trees injected in all months were dead within three months at the wetter site and within 12 months at the drier site. Available moisture and metabolic activity are important factors in the efficacy of glyphosate injection and vary from site to site. At the dry forest site, available moisture may limit metabolic activity and growth in summer which may explain the slower mortality from summer injections. The findings are used to make recommendations concerning the scheduling and monitoring of pre-commercial thinning.

Introduction

In Tasmania, 600 ha / yr of 10–25-year-old eucalypt regrowth are currently being pre-commercially thinned by stem injection of glyphosate herbicide. The aim of this pre-commercial thinning (PCT) program is to concentrate growth onto retained stems and to prepare stands for commercial thinning in the future. With the practice costing $330–400 / ha, a reliable method for monitoring its effectiveness is needed. A 90% mortality target has been set by Forestry Tasmania as a minimum standard for contractor performance.

The first visible signs of tree death following injection of glyphosate are crown wilting and browning, but the length of time between injection and these visible effects varies. This variability is due in part to the mode of action. Glyphosate acts as a systemic herbicide which, after injection, is translocated throughout the tree in its conductive tissue (Carlisle and Trevors 1988). Under conditions of drought stress, the rate of translocation is reduced, and the effectiveness of the herbicide is diminished. Several workers in reports from mainland Australia indicated seasonal differences in the effectiveness of glyphosate for killing unwanted trees (e.g. Minko 1981; Whitford *et al.* 1995).

This study investigated how long it took for the crowns of *Eucalyptus obliqua* to brown off completely following stem injection in each month of the year at two climatically different sites in Tasmania. It also attempted to identify any seasonal or climatic conditions

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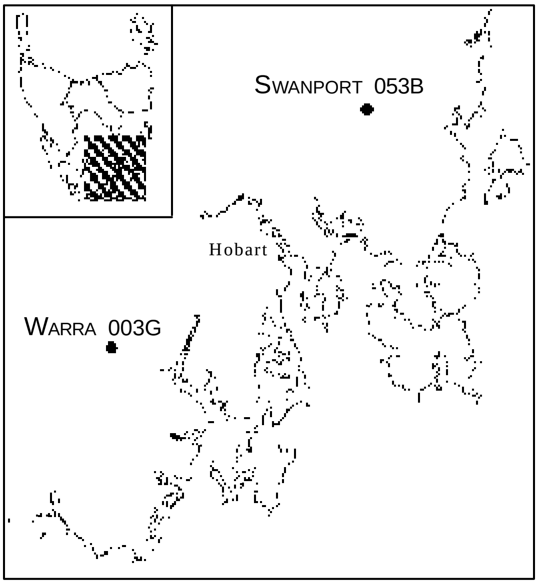

Figure 1. Location of the two study sites, Warra 003G and Swanport 053B, in southern Tasmania.

which resulted in less than 90% mortality within a stand. The findings are used to make recommendations concerning the scheduling and monitoring of PCT in Tasmania.

Methods

Site descriptions

The two sites used in the study were Warra 003G, a highly productive site in wet sclerophyll forest in southern Tasmania, and Swanport 053B, a less productive site in dry sclerophyll forest in eastern Tasmania (Figure 1). Both sites carried predominantly *E. obliqua* regrowth, with some *E. amygdalina* and *E. globulus* present at Swanport 053B. Site characteristics are summarised in Table 1.

Weather

Long-term averages based on the ANUCLIM climate prediction program were used (Table 2) (McMahon *et al.* 1997). Climate means were predicted for the 10 km x 10 km square in which each site lies. The two areas experience similar mean temperatures throughout the year, with the slightly lower mean monthly temperatures at Swanport 053B, probably reflecting its higher altitude. Warra 003G receives more rain and experiences less evaporation, with least rainfall occurring in summer at both sites. Swanport 053B has two more frost-free months each year and receives approximately 2500 hours of sunshine, compared to 1750 hours at Warra 003G (Davies 1965).

Sampling method

At each site, 240 trees were numbered, tagged and measured for diameter (cm) at 1.3 m above ground level in winter 1998. The diameter ranges of trees initially

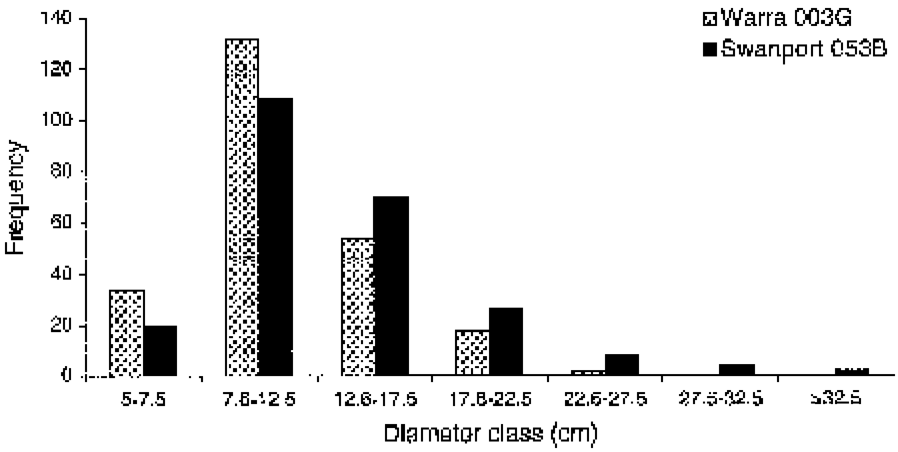

Figure 2. Diameter distribution of injected trees by diameter class and site.

Table 1. Site characteristics at Warra 003G and Swanport 053B.

	Warra 003G	Swanport 053B
Age at injection (yrs)	16	26
Parent material	dolerite	quartz sandstone
Altitude (m asl)	80	400
Site index[1]	41	20
Mean height of dominants (m)	21	13
Density at thinning (stems / ha)	3000	2000

[1] Calculated as the mean height of the tallest 30 trees / ha at age 50 years.

Table 2. Mean daily temperatures (°C) and total rainfall (mm) for the two study sites, by season, as predicted by ANUCLIM.

		Max °C	Min °C	Rainfall (mm)	Evaporation (mm)	Rain days
Summer	Warra 003G	20.7	9.4	261	12.3	37.9
	Swanport 053B	19.1	9.0	172	13.8	29.4
Autumn	Warra 003G	16.3	6.7	302	5.7	47.9
	Swanport 053B	14.9	6.1	181	6.1	36.3
Winter	Warra 003G	11.2	2.8	401	2.7	54.9
	Swanport 053B	9.6	2.3	189	2.6	42.1
Spring	Warra 003G	15.6	5.4	407	7.4	53.6
	Swanport 053B	13.8	4.5	188	8.7	41
Annual	**Warra 003G**	**16.0**	**6.1**	**1371**	**851**	**194.3**
	Swanport 053B	**14.4**	**5.5**	**730**	**945**	**148.8**

included in the experiment are shown in Figure 2. Trees for injection were chosen on the basis of form, size and spacing as in a standard PCT operation. A block of 20 trees with a range of diameters representative of the site was allocated to each month.

Stem-injection equipment

The stem-injection equipment used in this study, the ‘Steminjector’ by Stem Injection Systems, ACT, is identical to that currently being used by contractors in Tasmania (Cunningham and Peña 2000; Cunningham 1995; Figure 3). The unit consists of a small backpack container for the herbicide, connected with plastic tubing to the injection hammer. The claw of the hammer has been modified, and is used to strike the tree,

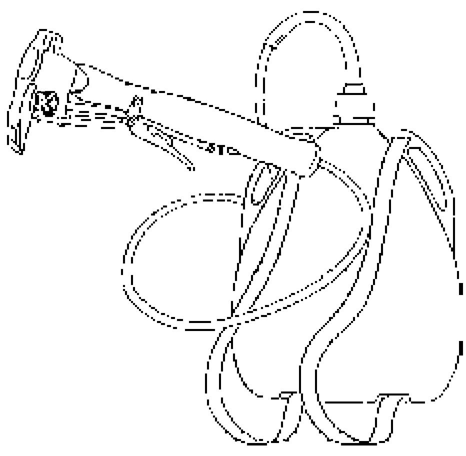

Figure 3. Stem-injection equipment comprising a backpack container and an injection hammer connected by plastic tubing.

penetrate the bark and lodge in the sapwood. A lever is then squeezed to compress the plastic tubing and inject the chemical into the small 'well' created. No gas is used as a propellant. Too shallow or too deep a cut will result in ineffective dosing. The Steminjector is calibrated to release 1 ml of undiluted herbicide per compression. Roundup 360® (360 g.a.i./l) was used in this study. Injections, or 'hits', are spaced evenly around the stem at about shoulder height.

Stem injection

Injection took place in the third week of each month. The diameters of trees due for injection were re-measured to ensure correct dosing, the injections were performed, and the diameters and the dose received were recorded. Dose rates currently used by contractors performing PCT were used for this study (Table 3). Diameter classes 1 and 5 were not included in the later analysis, as they comprised so few trees.

Table 3. Dose rates of glyphosate (ml) used in this study for different diameter classes.

Diameter class	Diameter (cm)	Dose (ml)
1	5–7.5	1
2	7.6–12.5	2
3	12.6–17.5	3
4	17.6–22.5	4
5	22.6–27.5	5

Table 4. Canopy rating system used to monitor tree decline and death.

Canopy rating	Symptoms
0	Healthy crown
1	Wilting of leaves
2	Some browning of crown
2.5	> 75% of crown browned off
3	Entire crown dead
4	Leaves dropped off

Canopy monitoring

Each month, trees injected in previous months were assessed using the canopy rating system in Table 4. Trees were considered 'dead' when they reached canopy rating 3, but continued to be monitored until they reached canopy rating 4. For each month of injection, the number of months until 90% of trees injected in that month reached a canopy rating of 3 was calculated. Upon conclusion of the study, these monthly results were pooled into seasons, with December to February comprising summer, March to May autumn, June to August winter, and September to November spring.

Results

Warra 003G

The 90% stand mortality target (canopy rating 3) was achieved three months after injection for trees injected in all seasons. Virtually all trees were dead within four months of injection (Figure 4a). None of the trees injected in winter was dead after one month, whereas 68% of trees injected in summer and 44% and 38% of trees injected in spring and autumn, respectively, were recorded dead after one month. For trees in diameter classes 2 and 3, the mean number of months required for trees to achieve a canopy rating 3 was greater in the winter than in all other seasons (Figure 4b). For trees in diameter class 4, season appeared to have affected the speed of kill to a lesser extent; trees injected in all seasons required a similar length of time to reach canopy rating 3, and this period was longer than for all other diameter classes.

Swanport 053B

The 90% stand mortality target was achieved within 12 months after injection for trees injected in all seasons. This occurred in the fourth month after injection for trees injected in winter, and in the seventh, eleventh and twelfth month after injection for trees injected

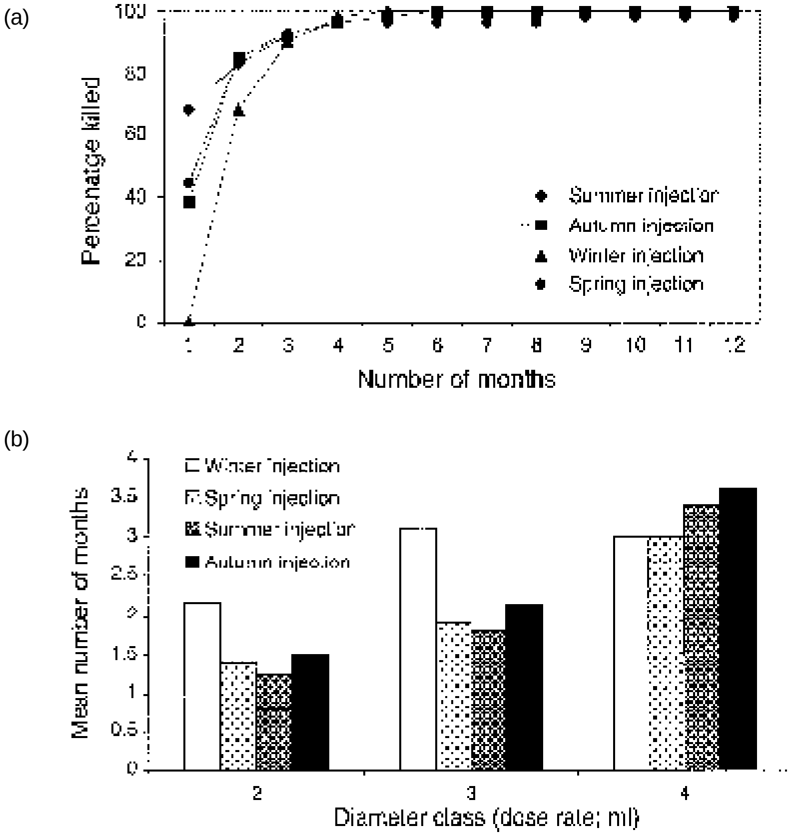

Figure 4. Warra 003G. (a) Percentage of trees with canopy rating 3 after a given number of months. (b) Mean number of months taken to kill trees in various diameter classes (see Table 3), by season of injection.

in spring, summer and autumn respectively (Figure 5a). For trees in diameter class 2, the mean number of months required to achieve a canopy rating 3 was similar for all seasons, whereas trees in diameter class 3 which had been injected in winter died more quickly than in all other seasons (Figure 5b). Trees in diameter class 4 died almost twice as quickly when injected in winter or spring than when injected in summer or autumn.

A single green branch persisted in a limited number of trees in diameter classes 2 and 3 for 6–12 months after the rest of the crown had died, regardless of the season of injection. In all cases, these branches eventually died. On several trees in diameter classes 4 and 5, the growing tip of the crown browned off but the remainder of the crown was unaffected. These trees received a revised canopy rating of 0 after the affected leaves dropped off. Both these phenomena have been observed occasionally in the operational context.

No clear relationship was found at either site between individual tree size and the number of months after injection before that tree reached canopy rating 3. However, the mean number of months after injection before trees in a given diameter class reached canopy rating 3 increased with increasing diameter class when data from all seasons were pooled. Furthermore, at both sites, a greater percentage of trees in the smaller diameter classes were recorded dead in the early months following injection, whereas in the larger diameter classes a

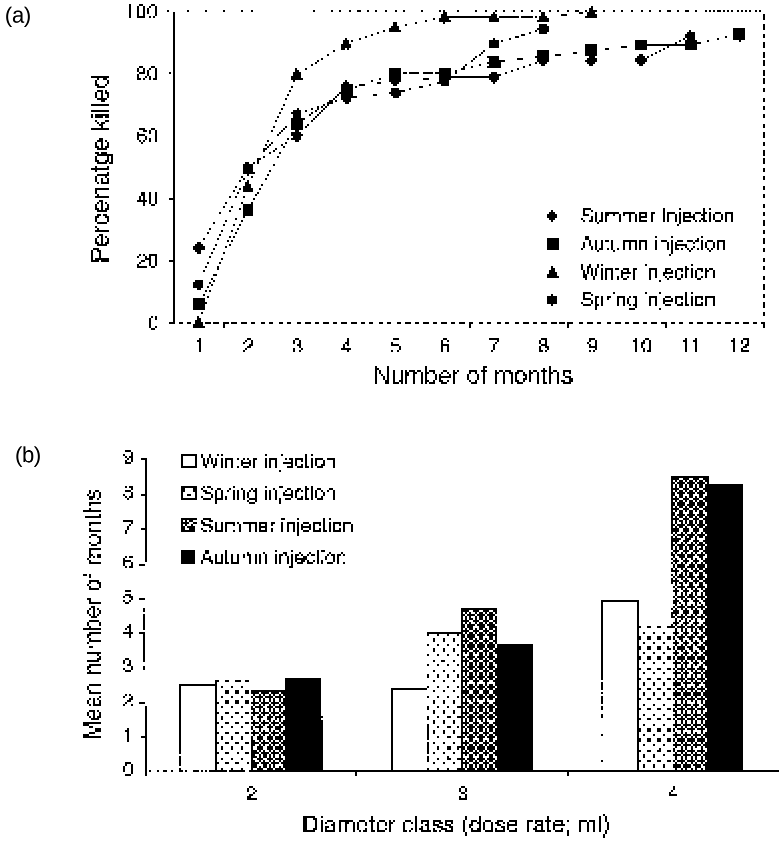

Figure 5. Swanport 053B. (a) Percentage of trees with canopy rating 3 after a given number of months. (b) Mean number of months taken to kill trees in various diameter classes (see Table 3), by season of injection.

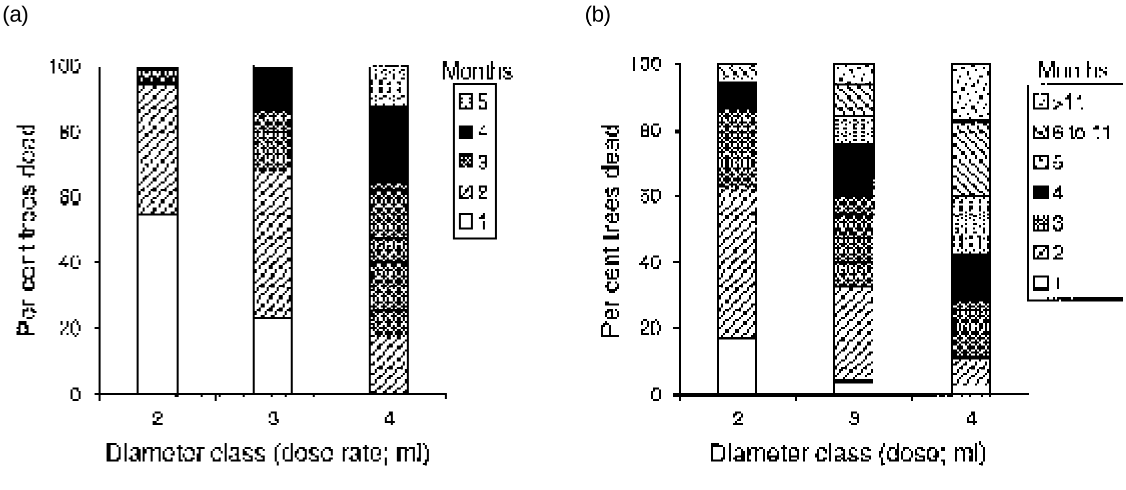

Figure 6. Percentage of trees dead within a given number of months by diameter class (see Table 3) at (a) Warra 003G and (b) Swanport 053B.

greater percentage of trees were recorded dead when more time had elapsed since injection (Figure 6a, 6b). In general, the larger the diameter class, the longer it took for 90% of trees in that diameter class to die, regardless of the season of injection.

Discussion

Season of injection affected herbicide efficacy at both sites; trees were generally killed more quickly at the drier site (Swanport 053B) following winter injections, and at the wetter site (Warra 003G) following summer injections. Importantly, injection in all months eventually achieved 90% mortality. Differences in the speed of kill can partly be explained by the mode of action of glyphosate, its relationship to weather conditions, and site-specific stand characteristics.

Mode of action of glyphosate

Glyphosate is transported within injected trees in the conductive tissue, in a similar manner to photoassimilates. Within the plant, the herbicide inhibits growth by interfering with the creation of certain amino acids, interrupting metabolism. Under conditions of drought stress, the transport of glyphosate, and thus its potential effectiveness, is reduced to an even greater extent than is that of photoassimilates (Carlisle and Trevors 1988). The label of one common formulation, Nufarm Weedmaster 360, cautions against treating weeds (using a spray application) under poor growing or dormant conditions, and states that 'visible effects of control may be delayed by cool or cloudy weather at and following treatment'. In short, whatever method of application is used, glyphosate is most efficient at killing plants when they are actively growing.

Factors which affect efficacy of herbicide

Several workers in Victoria and Western Australia have reported seasonal differences in the effectiveness of injected glyphosate for killing various *Eucalyptus* spp. (e.g. Dooley *et al.* 2000; Fagg *et al.* 1990). Injection in seasons other than summer has generally been found to be most effective (Whitford *et al.*1995), and a relationship to high photosynthetic rates (Meyer *et al.* 1983) and high humidity (Jordon 1977) implicated in glyphosate efficacy.

Whitford *et al.* (1995) reported that eucalypt mortality declined linearly with vapour pressure deficit[1] (v.p.d.; kPa), suggesting that high v.p.d. (low humidity) reduced translocation of herbicides, as high v.p.d. is known to reduce stomatal conductance (Turner *et al.* 1984). They recommended that stem injection only be done when v.p.d. has been less than 1.5 kPa on the day prior to injection. This threshold was also used by Dooley *et al.* (2000). V.p.d. was calculated for each of the two study sites using mean monthly wet and dry bulb temperatures at 3 p.m. Values were consistent within season across sites, averaging 9.3 millibars (mb) for summer, 6.3 mb for spring and autumn, and 3.6 mb for winter. V.p.d. is therefore an unlikely limiting factor to herbicide effectiveness in Tasmania, where v.p.d. would exceed 15 mb at these sites only for periods when temperatures rise above 25°C (C.L. Beadle, pers. comm). This may explain why injection in all months eventually resulted in 90% mortality, with the speed of kill dependent on other factors.

Differences in herbicide efficacy between sites

Cremer (1972) found the active growth period for *E. regnans* at Maydena, 25 km north of the Warra 003G site, to be restricted to the seven warmest months of the year. Given this, the relatively short frost-free period, and the amount of sunshine received in south-western Tasmania (Davies 1965), it is reasonable to state that the most active

[1] Vapour pressure deficit is defined as the difference between saturation vapour pressure at the dry bulb temperature, and ambient vapour pressure.

growing season at the Warra 003G site is generally spring and summer.

The climate regime for south-eastern Tasmania, where Swanport 053B is located, is quite different. Rainfall sufficient to compensate for evaporation, to stimulate germination and to maintain plant growth above the wilting point is adequate in the midsummer months in only one year in two in this region (Davies 1965). Growth in irrigated and rain-fed eucalypt plantations at Lewisham, a warm, dry site 30 km south of the Swanport 053B site, continued throughout the winter months (Honeysett *et al.* 1996). However, growth of irrigated trees was greater throughout the year than that of rain-fed trees, and this difference was more pronounced during summer, when less rain fell. Low rainfall in combination with high termperature may limit metabolic activity and thus reduce the efficacy of glyphosate at the Swanport site over the summer months.

It is suggested that injection is most efficient for a given site during periods with adequate moisture and temperatures which do not severely restrict metabolic processes. This period is normally spring to summer in the wet sclerophyll forests. In the dry sclerophyll forests, available moisture may be more important than metabolic activity in promoting the efficacy of glyphosate, making winter the more effective period. However, winter death at Swanport was more protracted than at Warra, presumably because of lower temperatures associated with the higher altitude of the dry sclerophyll study site chosen.

The principle that injected herbicide is less effective in less optimal growth conditions can be extended to explain its reduced effectiveness on harsher sites (Fagg *et al.* 1990; Sterrett 1969). This may partly explain the slower kill rates observed year-round at Swanport 053B, and the cases of persistent green branches or death of only the growing tip.

Tree size and herbicide dose rate

On average, the crowns of larger trees at both sites took longer to brown off, but no clear relationship was found at either site between individual tree size and speed of kill. Similar results have been reported for *E. sieberi* overwood (Dooley *et al.* 2000). In that study, the dose rates used had been assigned on the basis of diameter, resulting in a declining dose rate per unit basal area. Other authors have field-tested glyphosate dose rates calculated as grams of active ingredient per m^2 of tree basal area (g.a.i./m^2). Roberts and McCormack (1991) recommended 40 g.a.i./m^2 basal area for young *E. obliqua* and *E. regnans*, citing a 95% mortality rate. The dose rates used in this study correspond to 91.6, 61.1 and 45.8 g.a.i./m^2 basal area for diameter classes 2, 3 and 4 respectively. The two populations of *E. obliqua* discussed here displayed some site-specific morphological differences; it is possible that there have been physiological adaptations as well, necessitating different dose rates for a given species in different forest types.

Conclusions and recommendations

The best time for injecting eucalypt regrowth is in its most active growing season provided there is adequate moisture available. This is generally summer for wet sclerophyll forests and winter for dry sclerophyll forests in Tasmania. Ideally, injection should also be done at a time which allows the stand to enter its next growing season released from competition to the full extent intended by the PCT treatment (i.e. with all injected trees completely dead). Recommended seasons for injection are spring and summer for wet sclerophyll forests, and autumn and winter for dry sclerophyll forests. This introduces the herbicide into the tree's system during or just prior to the season in which it is most effective.

The lower efficacy of glyphosate at the lower rainfall site suggests that rates used should probably be increased by at least one hit per diameter class for injections done in any season but winter. Monitoring of stem-injection work for target mortalities should not take place until three months after the work has been completed. Earlier checks of contractor performance can be made, and include visual checks for sapwood penetration by the injection hammer and to ensure that the correct number and even spacing of hits have been used for the tree size in question.

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