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Cost-effectiveness of three methods of applying glyphosate herbicide to jarrah (*Eucalyptus marginata*) standing trees and cut stumps

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ABSTRACT

In the jarrah (*Eucalyptus marginata* Donn ex Smith) forests of south-western Australia the Department of Conservation and Land management (CALM) uses stem injections of glyphosate, and the spraying of glyphosate onto cut stumps, to poison unwanted and non-commercial trees. These treatments are applied to create gaps where adequate regeneration exists and promote the growth of this regeneration, or to thin and increase growth of the trees remaining in a stand.

We compared the cost and effectiveness of Ecoplug capsules containing glyphosate, with the notch and inject method currently used by CALM to treat standing trees, and found that the notch and inject method was cheaper ($4 per square metre of basal area treated (m^{-2}) versus $44 m^{-2} for Ecoplug capsules), and produced a higher mortality (80% versus 45%). We recommend the notch and inject technique for poisoning standing trees.

We also compared the cost of three cut stump treatments: Ecoplug capsules, commercially produced pressure packs of glyphosate, and the backpack method currently used by CALM. The Ecoplug capsule treatment was most expensive (\$72 m^{-2}), approximately 4 times the total cost of using a backpack (\$16 m^{-2}) or pressure pack (\$21 m^{-2}) per square metre. When these costs were corrected to account for the different doses applied in the treatments, the total cost of the pressure pack treatment (\$16 m^{-2}) was less than the cost of the backpack treatment (\$17 m^{-2}). The mortalities observed in the three cut stump treatments (96%, 93%, and 95%) were not significantly different at $p > 0.25$.

Pressure packs of glyphosate are recommended for treating cut stumps where the convenience and flexibility of a prepared and packaged product are of benefit.
Problems with this product need to be resolved. The cans corroded after 6 months of storage. Operators using this product must wear a glove to protect the hand holding the can from spray bounce.

INTRODUCTION

Following logging in the jarrah forest, CALM conducts a program of Jarrah Stand Improvement (JSI). This is the mechanical removal or poisoning of unwanted and non-commercial trees, either to create gaps where adequate regeneration exists and promote the growth of this regeneration, or to thin, and increase growth of the trees remaining in a stand. CALM annually thins approximately 3000 ha and creates gaps on approximately 5000 ha of jarrah forest (CALM 1991, 1992, 1993, 1994). Of these areas approximately 4000 ha is poisoned by stem injection of liquid glyphosate (A. Seymour, pers. comm., Sil Rec Database). Whitford et al. (1996) have shown that, for jarrah (*Eucalyptus marginata* Donn ex Smith) a mortality of approximately 80% can be achieved in all seasons except summer, with a dose of 20 grams of active ingredient (g.a.i.) m^{-2} of stem basal area. CALM's current prescription for the poisoning of jarrah is based on this work, and uses the notch and inject method of applying liquid glyphosate.

A small portion of the area receiving JSI is given a cut-stump treatment. Here the tree is felled, and the stump sprayed with a glyphosate solution. This procedure is more costly than the notch and inject treatment but is used where the commercial extraction of small thinned trees occurs. The cut-stump treatment will become more common as markets develop for the currently unwanted stems.

These treatments, which are important silvicultural tools applied to large areas of the jarrah forest, are costly to apply, and their application is physically demanding and at times unpleasant. CALM is seeking treatments that are effective, efficient and inexpensive, and maximise worker safety. In this trial we examine alternative methods of treating standing trees and cut stumps and compare the costs and effectiveness of these methods with those currently used by CALM.

The specific aims of these trials are:

Stem injection of standing trees;

To compare the costs and effectiveness of the two methods of application of glyphosate herbicide to standing jarrah trees in spring at a dose of 20 g.a.i. m^{-2}. These methods were: a) notching the sapwood and injecting a liquid mixture into the notch, and b) hammering out a hole in the sapwood, and inserting and breaking a capsule of powdered glyphosate in the hole.

Cut stumps;

To compare the costs and effectiveness of the three methods of applying glyphosate herbicide to jarrah tree stumps in autumn at a dose of 20 g.a.i. m^{-2}. These methods were; a) spraying the cut stump with a liquid mixture from a backpack, b) spraying the cut stump with a liquid mixture from a pressure pack, and c) hammering out a hole and inserting and breaking a capsule of powdered glyphosate in the hole.

METHODS

Stem injection and capsule treatments of standing trees.

This experiment used a randomised complete block design with two treatments (notch and inject with a liquid mixture, and hammer hole and insert and break a capsule of dry powder) and 5 replicates, randomly assigned to ten, 1 ha plots (fig.1). These plots were located in an area of Holyoake Block which was logged in March 1994 under a thinning prescription (CALM 1995) which aims to achieve a retained basal area over bark of 15 m^{-2} ha^{-1}. Trees selected to retain were marked. Logging contractors then removed any commercially valuable unmarked trees. The remaining competing stems within 1 to 4 metres of the marked trees would then be poisoned using the notch and inject treatment. These trees were used in this trial.

For the stem injection treatment, trees were notched at waist height by striking downward with a tomahawk at approximately 45° from the horizontal, and injected the notch with glyphosate using a Phillips automatic vaccinator (model 74). Notches were spaced approximately 15 cm apart about the stem. The amount of glyphosate mixture (concentration 180 g.a.i. l^{-1}) injected into the notches increased with trunk diameter following a prescription that was designed to deliver a mean dose of 20 g.a.i. m^{-2}. The herbicide dose was administered within 5 seconds of the notching. For the capsule treatment, trees were hit with an Ecoplug hammer creating a small hole in the sapwood. An Ecoplug capsule containing 352.5 mg of glyphosate was inserted into the hole, and the head of the capsule hit to break the capsule inside the sapwood. The dose administered was controlled by varying the capsule spacing. Capsule spacing decreased with increasing tree diameter following a prescription that matched doses delivered with the Ecoplug capsules to those delivered under the stem injection prescription. All treatments were applied in fine weather. Standing trees were treated over 3 days in November and December of 1994 by employees experienced in the notch and inject technique. Following the recommendation of Whitford et al. (1995), the vapour pressure deficit (v.p.d.) at 1500 hrs on the day prior to treatment was less than 15 mb (range, 12 to 13 mb).

The time taken to treat each plot was recorded. For each tree on the plot, we measured diameter over bark at 1.3 m (DBHOB), the number of notches or capsules applied, and assessed mortality. Mortality was assessed in September 1995, nine months after treatment, and again in April 1997, 28 months after treatment. Results presented here are those of the 1997 assessment.

Cut stumps

This experiment has a randomised complete block design considering three treatments of the cut stumps (spraying the cut stump with a liquid mixture from a backpack, spraying the cut stump with a liquid mixture from a pressure pack, and hammering a hole and inserting a capsule of dry powder) and 5 replicates, randomly assigned to fifteen, 0.25 ha plots (fig.1). These plots were located adjacent to the plots of standing trees treated using the stem injection techniques, and were logged in the same thinning operation.

In the capsule treatment, one operator felled the trees and the second operator applied the capsules using the same prescription used with the standing trees. In the back-pack sprayed treatment, one operator felled each tree and a second operator sprayed the stump with glyphosate solution of 1 part glyphosate (at 360 g.a.i. l^{-1}) to 10 parts water (32.2 g.a.i. kg^{-1}, or 32.7 g.a.i. l^{-1}), completely covering the exposed sapwood. In the pressure pack treatment, a single operator felled the trees and sprayed the exposed sapwood with a glyphosate solution. Two concentrations of glyphosate were used in the pressure pack treatment (273g kg^{-1} and 33g kg^{-1}) when the supply of 273g kg^{-1} pressure packs was consumed before all the plots were treated. For the backpack and pressure pack treatments the time delay was measured between commencement of falling, and commencement of application of the glyphosate solution to the exposed sapwood. The time taken to treat each plot was recorded as was the number of capsules used, or the weight of chemical applied to each plot. All treatments were applied in fine weather. These treatments were applied over 3 days in May 1995, five months after the standing trees were treated.

We assessed mortality in September 1995, four months after treatment, and in April 1997, 23 months after treatment. The results presented here are those of the 1997 assessment. We measured the diameter over bark of each stump on each plot, and on capsule treated plots, counted the number of capsules in each stump. We developed a relationship between stump diameter and DBHOB from a random sample of 61 fallen trees. We applied this relationship to all stumps to estimate DBHOB.

Costs

In calculating the total costs of the treatments the following chemical costs were used: liquid glyphosate (360 g.a.i. l^{-1}), \$4.95 l^{-1}, Ecoplug capsules, \$0.48 each, pressure packs \$37 (273g kg^{-1}) and \$4.65 (33g kg^{-1}). The hourly labour cost used was \$13 per hour.

RESULTS

Standing Trees

The standing treated trees ranged in size from a DBHOB of 1 cm to 125 cm. The mean DBHOB was 15.7 cm.

The mean basal area poisoned in the capsule treatment was slightly higher than in the notching treatment (6.25 m^2 ha^{-1} versus 5.90 m^2 ha^{-1})(Table 1).

Mortality and Dose

Mortality in the capsule treatment (45%) was lower than in the notching treatment (80%) (Table 2).

The prescription used with the capsule treatment was designed to produce doses that matched the doses administered to standing trees under the notching prescription and this achieved satisfactory results. The mean dose administered to standing trees using capsules was 28.2 g.a.i. m^{-2}, only slightly higher than the mean dose of 27.4 g.a.i. m^{-2} administered in the notching treatment (Table 1.).

Cost

The total cost of the capsule treatment was 12 times the cost of notching on a per ha and per m^2 treated basis. The total cost of the capsule treatment was \$44 m^{-2} versus \$3.60 m^{-2} for notching standing trees (Table 1).

The cost of glyphosate supplied in the capsules (\$1.36/g.a.i) is 99 times that of liquid glyphosate (\$0.01375/g.a.i.). On a square metre basis, the capsules cost 101 times that of liquid glyphosate (Table 1) indicating close matching of the doses applied in the two treatments.

The labour cost when using capsules (\$5.52 m^{-2}) was 1.7 times the labour cost of notching (\$3.25).

Cut-stump

DBHOB from stump diameter

The mean stump height from a random sample of 61 stumps was 48.1 ± 1.58 cm (s.e.). We developed a regression relationship between stump height and DBHOB.

$$\text{DBHOB} = 0.873 * \text{Stump Diameter} + 0.327 \qquad r^2 = 0.968 \qquad n = 61$$

Mortality and Dose

The three cut stump treatments produced similar mortalities; 96% for the backpack treatment, 93% for the capsule treatment, and 95% for the pressure pack treatment. These mortalities were not significantly different at $p > 0.25$ (ANOVA, n.s. at $p > 0.25$).

In this trial, the doses administered in the capsule and the pressure pack treatments ($\bar{x} = 36.3$ and 34.1 g.a.i. m^{-2} respectively) were more than 3 times the dose administered in the backpack treatment ($\bar{x} = 10.0$ g.a.i. m^{-2}) (Table 1). The target dose was 20 g.a.i. m^{-2}.

Costs

At \$72 m^{-2}, the total cost of poisoning cut-stumps with capsules was approximately 4 times the total cost of using a backpack or pressure pack per square metre (Table 1). The total cost of the pressure pack treatment (\$21 m^{-2}) was slightly higher than the backpack treatment (\$16 m^{-2}) (Table 1).

In this trial, the cost of the glyphosate used in capsules (\$49 m^{-2}) was approximately 350 times that of liquid glyphosate (\$0.14 m^{-2}). This large difference occurred partly because the mean dose applied in the capsule treatment (36.3 g.a.i. m^{-2}) was more than 3 times the mean dose administered in the backpack treatment (9.9 g.a.i. m^{-2}) (Table 1). The pressure pack glyphosate (\$11 m^{-2}), was cheaper than the capsules but still notably more than the liquid glyphosate used in the backpack treatment (Table 1).

The labour cost in the pressure pack treatment was lower than in the backpack or capsule treatments. At \$10 m^{-2}, pressure pack labour costs were 37% less than the backpack treatment, at \$16 m^{-2}, and 56% less than the capsule treatment, at \$23 m^{-2}. (Table 1). The labour cost of using capsules (\$23 m^{-2}) was only slightly higher than the labour cost of using a backpack (\$16 m^{-2}).

DISCUSSION

Standing Trees

Poisoning standing trees with capsules is clearly more expensive than the notch and inject method currently used by CALM (Table 1). This is mainly due to the cost of the capsules, but also to the higher labour cost of applying capsules. The lower labour cost of notching is due to the fluid natural movements that are possible with the notch and inject technique, and the single tomahawk blow required for each notch, compared with two hammer blows for each capsule. The movements necessary to hammer and remove a wad of wood from the tree, grasp and insert a capsule, and then hit the capsule head, lack rhythm and are unlikely to improve with practice. The regular jarring that occurs when trees are hit with the Ecoplug hammer, and the jerking that occurs as the hammer is removed from the tree, contrasts with the comparatively gentle cutting of a sharp tomahawk into green bark and sapwood. The repetitive jarring that would occur with continuous use of the Ecoplug hammer may lead to injuries.

When notching standing trees with liquid glyphosate, the chemical cost is 10% of the total cost, while labour is 90%. Whitford et al. (1995) observed a plateau in mortality beyond a dose of 20 g.a.i. m^{-2}. For doses lower than 20 g.a.i. m^{-2}, mortality declined sharply. Operational prescriptions designed for broadscale use must be simple and inevitably over-dose and/or under-dose some tree sizes. The low cost of glyphosate relative to the labour cost, and the decline in mortality below a dose of 20 g.a.i. m^{-2}, mean that it is justifiable to use a prescription that overdoses some trees. With prescriptions that produce overdoses, the effective cost (cost per m^2 killed) may remain the same (an increase in mortality with a proportional increase in cost) or even decrease (an increase in mortality greater than the proportional increase in cost).

Cut Stumps

The back-pack treatment is the cheapest method of treating cut stumps, followed by the pressure pack method. Both of these application techniques provide little control over the applied dose.

The backpack treatments received a mean dose of 10 g.a.i. m^{-2} (using a glyphosate solution of 1 part glyphosate, at 360 g l^{-1}, to 10 parts water). This is half the target dose of 20 g.a.i. m^{-2} and is a result of the uncontrolled nature of the application system. Despite this low mean dose the mortalities achieved in these treatments were very high (96%). However this dose is marginal and the high mortality observed with this treatment may have been fortuitous. A decrease in the glyphosate dilution to 1 part glyphosate (at 360 g l^{-1}) to 4 parts water would increase the applied dose to approximately 22 g.a.i. m^{-2}, reduce the risk of low mortalities, while increasing the total cost of this treatment by only 4% (to \$17 m^{-2}). The cost of glyphosate is very low relative to the labour cost and it is preferable to accept occasional over-dosing in this treatment than reduced mortality due to doses below the target 20 g.a.i. m^{-2}.

The pressure pack treatment received a mean dose of approximately 34 g.a.i. m^{-2}. This is higher than the target dose of 20 g.a.i. m^{-2}. In this treatment the packaged glyphosate was expensive, approximately half of the total cost. Labour costs, the remaining half of the total costs, were low. For these reasons, and because the cost of this packaged product is proportional to the concentration of the glyphosate purchased, it is important that the appropriate concentration is identified. Two concentrations of glyphosate were trialed in pressure packs (33 g kg^{-1} and 273 g kg^{-1}). From these trials, a pressure pack concentration of 104 g kg^{-1} , at a cost of approximately $6.40 m^{-2}, would provide a dose of 20 g.a.i. m^{-2}. This would yield a total cost of $16 m^{-2} to use pressure packs. This cost is equivalent to the cost of the backpack treatment.

The uncontrolled dose applied in the pressure pack treatment depends on the work practices of the operator, and will probably be affected by the diameter of the stumps being treated. Trials or monitoring of application rates need to be undertaken to determine if this concentration is correct for a range of operators working in forests with varying diameter structures.

The pressure packs used in this trial must be used with a gloved hand, because liquid splatters onto the users hand. This may be due to the short nozzle on the cans. At the concentration recommended, using these pressure packs without a glove is dangerous and unacceptable.

The lower concentration pressure packs used in this trial (33 g kg^{-1}) corroded from the inside after storage for approximately 6 months. Storage of these cans with operational use is likely to exceed 6 months and this problem needs to be solved before pressure-packs are used regularly.

The capsules and the pressure pack, unlike the glyphosate used in the backpack, are packaged ready to use. This convenience, and the associated cost saving, was not considered in calculating costs. In the pressure pack treatment (which would have a total cost equivalent to that of the backpack treatment if the correct doses were applied) the pre-mixed packaging provides efficiency, flexibility in how this work is done, and the potential for fallers to poison stumps in a variety of forest operations where such treatment does not occur presently. This is potentially the most significant improvement in work practices indicated by this trial.

Estimation of DBHOB from stump diameter

Our regression for estimating the DBHOB of the trees from stump diameter was based on measurements of 61 trees. The stump height of these trees ranged from 25 to 75 cm, with a mean of 48.1 cm. We did not use stump height to develop this predictive relationship as it did not contribute significantly to the linear regression equation. Khatry Chhetri and Fowler (1996) used both stump diameter and height in a non-linear regression using data from 163 trees. Their expression for small diameter trees (mixed species broad-leaved trees in Nepal) is remarkably similar to our simple linear regression for jarrah once a mean stump height of 48.1 cm is substituted into their equation. This expression of Khatry Chhetri and Fowler (1996) may be generally applicable where no relevant site or species data is available. However for our data at this single site the regression of Khatry Chhetri and Fowler (1996) underestimated DBHOB by 2%.

Equation from this work

DBHOB = 0.873 * Stump Diameter + 0.327

Khatry Chhetri and Fowler (1996)

DBHOB = 0.5039 * $(\text{Stump Diameter})^{1.0177}$ x $(\text{Stump height})^{0.1252}$

Khatry Chhetri and Fowler (1996) using a mean stump height of 48.1 cm

DBHOB = 0.8184 * $(\text{Stump Diameter})^{1.0177}$

CONCLUSIONS

Standing Trees

- Ecoplug capsules containing glyphosate are not recommended to replace the current notch and inject technique employed by CALM to poison standing trees. Ecoplug capsules cost considerably more than liquid glyphosate, are more expensive to apply, yield a lower mortality than the notch and inject method currently used, and the application technique may produce injuries in the operators.

Cut-Stump

- Although Ecoplug capsules containing glyphosate produced mortalities similar to those found with other methods this treatment is not recommended for use in cut-stump operations because the capsules cost considerably more than liquid glyphosate.
- The labour cost when using Ecoplug capsules in cut-stump operations was equivalent to the labour cost of the backpack treatment currently used by CALM, and the mortality was equivalent to that of the backpack treatment. If the cost of the Ecoplug capsules is reduced, Ecoplug capsules containing glyphosate could be considered as an alternative treatment for cut-stumps.
- Pressure pack sprays of glyphosate are a convenient alternative method of treating cut-stumps at a cost equivalent to the cost of the backpack treatment currently used by CALM.
- A pressure pack concentration of 104 g kg^{-1} is recommended. Trials or operational monitoring need to be undertaken to determine if this concentration is correct for a range of operators working in forests with varying diameter structures.
- The pressure pack treatment has a low labour cost because only one operator is required. Pressure pack sprays provide flexibility in managing stand basal area because treatment can be undertaken by the faller, during the logging operation. This is potentially the most significant improvement in work practices indicated by this trial.
- Chemical costs in cut-stump operations using liquid glyphosate (ie. backpack spray applications) are much less than labour costs (1/30 of the cost if a dose of 20 g.a.i. m^{-2} is used). As there is poor control over the applied dose in these operations, a higher concentration of glyphosate (ie., a lower dilution) is recommended to ensure high mortality. A dilution of 1 part glyphosate (at 360 g l^{-1}) to 4 parts water is suggested by this work.

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Figure 1. Layout of plots used in comparison of two methods of poisoning standing jarrah trees and three methods of poisoning cut-stumps. Plots located in Holyoake Block, Dwellingup District. See table 2 for treatments assigned to each plot.

<table>
<tr><td colspan="2">20</td><td>19a</td><td>19b</td><td>18a</td><td>18b</td><td>17a</td><td>17b</td><td>16a</td><td>16b</td></tr>
<tr><td colspan="2">11</td><td>12a</td><td>12b</td><td>13a</td><td>13b</td><td>14a</td><td>14b</td><td>15a</td><td>15b</td></tr>
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Notch</td></tr>
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Table 1. Summary of costs comparing two methods of poisoning standing jarrah trees, and three methods of poisoning cut-stumps. Values are means ± standard errors. Costs used were; liquid glyphosate (360 g.a.i./l), $4.95/l, Ecoplug capsules, $0.48 each, pressure packs $37 (273g/kg) and $4.65 (33g/kg), and labour $13 per hour.

Treatment	**Basal area treated**	**Mean dose**	**Mortality**	**Cost per hectare**			**Cost per square metre**			**Cost per square metre killed**
				Glyphosate	Labour	Total	Glyphosate	Labour	Total	Total
	m^2 ha^{-1}	gai m^{-2}	%	($)	($)	($)	($)	($)	($)	($)
Standing trees										
Capsule	6.25 ± 0.61	28.23 ± 1.84	45.20 ± 4.95	235.20 ± 12.27	33.67 ± 2.29	268.87 ± 12.47	38.44 ± 2.50	5.52 ± 0.50	43.96 ± 2.67	100.84 ± 8.93
Notch	5.90 ± 0.79	27.40 ± 1.59	79.57 ± 4.43	2.24 ± 0.38	19.24 ± 3.67	21.48 ± 4.03	0.38 ± 0.02	3.25 ± 0.34	3.63 ± 0.36	4.60 ± 0.51
Cut stump										
Capsule	5.44 ± 2.05	36.33 ± 2.15	92.88 ± 3.38	264.96 ± 104.73	110.59 ± 42.51	375.55 ± 146.76	49.47 ± 2.92	22.57 ± 2.70	72.04 ± 5.34	77.84 ± 5.86
Backpack	6.13 ± 0.97	9.97 ± 0.42	96.43 ± 1.46	0.84 ± 0.14	105.04 ± 32.77	105.88 ± 32.89	0.14 ± 0.01	15.93 ± 2.11	16.07 ± 2.11	16.71 ± 2.29
Pressure pack	6.11 ± 1.06	34.10 ± 12.41	94.69 ± 1.77	54.36 ± 17.81	60.49 ± 11.81	114.85 ± 20.89	10.77 ± 3.98	9.76 ± 0.36	20.53 ± 3.83	21.68 ± 4.08

Table 2. A comparison of mortalities achieved with two methods of poisoning standing jarrah trees, and three methods of poisoning cut stumps. Plot number and treatment, basal area treated, and mortality for individual plots.

Treatment	Plot	BA treated $m^2 ha^{-1}$	Dose gai m^{-2}	Mortality %
Standing Capsules	2	7.94	23.57	29.0
	3	5.28	27.51	41.0
	4	6.94	27.65	46.0
	8	6.59	27.54	58.0
	10	4.53	34.90	52.0
Mean		6.25 ± 1.21	28.23 ± 3.68	45.2 ± 9.9
Standing Notched	1	8.80	30.37	93.0
	5	4.05	26.56	70.0
	6	5.82	21.79	70.8
	7	5.51	27.80	86.0
	9	5.29	30.47	78.0
Mean		5.90 ± 1.76	27.40 ± 3.56	79.6 ± 8.9
Cut stump Backpack	14b	4.94	8.78	100.0
	15a	4.57	10.77	100.0
	16a	4.74	9.57	94.1
	17b	6.73	11.07	93.8
	18a	9.70	9.65	94.3
Mean		6.13 ± 2.18	9.97 ± 0.94	96.4 ± 2.9
Cut stump Capsules	12b	11.71	38.29	90.1
	13a	8.71	33.84	82.0
	13b	3.77	29.14	100.0
	14a	1.89	39.62	100.0
	15b	1.11	40.74	92.3
Mean		5.44 ± 4.59	36.33 ± 4.80	92.9 ± 6.8
Cut stump Pressure pack	16b	3.40	59.45	91.3
	17a	4.10	63.95	96.0
	18b	6.39	6.82	90.2
	19a	7.67	5.82	95.9
	19b	9.00	34.45	100.0
Mean		6.11 ± 2.36	34.10 ± 27.74	94.7 ± 4.0