OPTIMISING SPOT WEED CONTROL: FIRST APPROXIMATION OF THE MOST COST-EFFECTIVE SPOT SIZE

BRIAN RICHARDSON, NOEL DAVENHILL, GRAHAM COKER, JOHN RAY, ARTHUR VANNER, and MARK KIMBERLEY

New Zealand Forest Research Institute,
Private Bag 3020, Rotorua, New Zealand

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ABSTRACT

Spot spraying, where only the area around individual trees is treated, is becoming an increasingly important method of herbicide application during establishment of *Pinus radiata* D. Don plantations in New Zealand. Minimising the spot size reduces costs and has perceived environmental benefits from reduced herbicide use. Trials were undertaken at two sites to determine the effect of area and duration of spot weed control on *P. radiata* growth. One year after planting, crop growth benefits from weed control were proportionally greater on the more productive site. Here, crop diameter growth continued to increase, albeit at a declining rate, as spot size was increased to the point of complete weed control. A similar trend was apparent with height growth up to spot diameters of about 1.5 m. With larger spot sizes, further gains in height growth were minimal. On the less productive site, significant growth benefits were apparent only from the smallest spot size treatment. At both sites, diameter growth was more sensitive to weed control than height growth.

Keywords: weed control; competition; spot spraying; herbicide; *Pinus radiata*.

INTRODUCTION

Many studies have demonstrated that the survival and growth rates of *Pinus radiata* crop trees can be reduced by competition with other plant species for water, light, and nutrients (Richardson 1993; Richardson *et al.* 1993). Consequently, weed control is normally undertaken during the period of crop establishment. Although herbicide application is the standard method of weed control, these chemicals are expensive and there is public pressure against their use. Hence, it is important to use the minimum quantity of herbicide to greatest effect. Spot applications, where only the ground area around individual trees is treated, are becoming increasingly popular, partly because of the reduction in the quantity of herbicides used. For example, with a 1.5-m-diameter spot and 833 stems/ha, only about 15% of the area is treated with herbicide compared with broadcast treatment; this provides large cost reductions and perceived environmental benefits. Spot spraying is most appropriate on sites covered predominantly with herbaceous vegetation (defined as annual or perennial grasses or broadleaves without a woody stem). A significant proportion of cutover sites can be placed in this category because of the practice of oversowing with mixtures of legumes and grasses. In addition, much of the new forest planting is on to fertile pasture sites.

Two important management issues related to spot spraying are (1) the optimal spot size and (2) the duration of weed control. These two factors dictate the proportion of a site that has to be treated, the number of applications, and thus the amount of herbicide required. To select the ideal spot diameter and duration of weed control, the cost of treatment must be balanced against its benefits in terms of growth, survival, and quality of the crop. Although some of these factors have received limited study, there has been no conclusive definition of the optimum area and duration of herbaceous weed control for *P. radiata* growth and survival in New Zealand (Balneaves 1987; Balneaves & Henley 1992; Clinton & Mead 1990; West 1984). It is clear that these parameters will vary with soil type, climate, and competitor species (Richardson *et al.* 1993). It has been suggested that on moist sites in the Bay of Plenty, 1 year weed-free is most cost-effective for growth (West 1984). However, this conclusion may not be valid because it was based on a maximum spot size of 1 m diameter which may not be sufficient to eliminate competition and maximise growth, even within the first year after planting. Research in dry areas in South Australia suggests that sites should be maintained competition-free for a period of 2 years if maximum growth potential is to be realised (Sands & Nambiar 1984). These findings may relate to some sites in New Zealand, but certainly not all. On a site at Rangiora, Clinton & Mead (1990) demonstrated that release of 4-year-old *P. radiata* from herbaceous competition for 12 months resulted in increased diameter growth. Competition for water was thought to be the primary cause of growth suppression although competition for nutrients was also implicated.

This paper presents first-year growth data from two trials designed to define the optimal area and duration of weed control. Both sites were located in the central North Island region of New Zealand.

METHODS

Site Location and History

Trials were laid out in Kaingaroa and Kinleith Forests on light pumice soils. The sites were 460 and 584 m above sea level, with mean annual rainfall of 1483 mm at Kaingaroa and 1585 mm at Kinleith.

Kaingaroa

Two trials were located in Compartment 1135 (next to Northern Boundary Road). This compartment was first planted with *P. radiata* in 1965 and was clearfelled in November 1989. After harvesting, the site was V-bladed and replanted with *P. radiata* which was both aerially and spot-released using herbicides. By 1993, however, a decision was made to replant because of severe competition from broom (*Cytisus scoparius* L.) and bracken fern (*Pteridium esculentum* (Forst. f.) Cockayne). Vegetation was desiccated with an aerial application of glyphosate (5.4 kg a.i./ha) in February 1993, and was roller-crushed in March 1993. The trial site was oversown in April 1993 with a mixture containing Yorkshire fog (*Holcus lanatus* L.) at 10 kg/ha and lotus (*Lotus uliginosus* Schk.) at 5 kg/ha. During the following August, *P. radiata* seedlings were planted on top of the V-blade mounds at a spacing of approximately 3 m within rows and 3–4 m between rows (depending on location of mounds).

Kinleith

The trial was located adjacent to Pelican Road in an area from which *P. radiata* had been harvested in 1992. In January 1993 the site was sprayed using a mixture of glyphosate (3.2 kg a.i./ha); metsulfuron (0.1 kg a.i./ha); Silwet L-77, an organosilicone surfactant (0.3 ℓ/ha); and Delfoam (Yates NZ Ltd), a foaming agent (0.35 ℓ/ha). Foaming agents are often used in New Zealand in combination with "foaming" nozzles, to reduce the spray drift associated with conventional disc and core nozzles (Clack 1972; Rowe & Albert 1976). After *P. radiata* tree planting at a 6 × 6 m spacing in August 1993, the site was oversown in October using a mixture of 10 kg annual ryegrass (*Lolium multiflorum* L.)/ha, 3 kg lotus (*L. uliginosus*)/ha, 1.5 kg browntop *(Agrostis capillaris* L.)/ha, and 1.5 kg cocksfoot (*Dactylis glomerata* L.)/ha.

Experimental Design

At Kaingaroa, both a short-term (less than 7 years) and a long-term (a complete rotation) trial were installed, but at Kinleith, only a short-term trial was installed.

The short-term trial at Kinleith consisted of single-tree plots in a randomised complete block design. There were 30 blocks, each containing 14 plots allocated to different combinations of spot diameter and of weed control duration. Results described here are based on measurements made 1 year after tree planting, at which time no repeat spray applications had been made. The five treatment combinations available for comparison at this stage were: 0-, 1-, 1.5-, and 2-m-diameter spots and complete weed control (>3-m-diameter spots), each with a duration of 1 year.

The short-term trial at Kaingaroa had a split-plot design. There were 20 blocks, each with two main plots (with and without fertiliser). Main plots contained four-tree subplots, each allocated to a different combination of spot diameter/weed control duration. Treatment comparisons at this stage were confined to the effects of five spot diameters: 0, 1, 1.5, 2, and >3 m (complete weed control), each with and without fertiliser, after 1 year.

The long-term experiment at Kaingaroa consisted of five treatments, each replicated five times in a randomised complete block design:

(1) Untreated (no weed control);
(2) Complete weed control (maintained throughout the rotation by repeated herbicide application);
(3) Two-year weed control with a 2-m-diameter spot;
(4) Two-year weed control with a 1-m-diameter spot;
(5) Complete weed control (maintained throughout the rotation by repeated herbicide application) plus additional nutrient supply.

Plot size was 45 × 45 m with a 10-m buffer, giving an inner measurement plot of 25 × 25 m containing approximately 18–19 trees at 300 stems/ha final stocking.

Fertiliser Application

A fertiliser regime was designed by Dr M. F. Skinner (Forest Research Institute) for the Kaingaroa trials, to ensure that tree growth was not limited by nutrient supply. The following elements were applied in the spring after planting.

- nitrogen, 50 kg/ha as urea;
- phosphorus, 50 kg/ha as long-life super;
- magnesium, 100 kg/ha as calcined magnesite;
- boron, 6 kg/ha as ulexite.

This mixture was applied in Treatment (5) of the long-term trial, and to the plus-fertiliser main plots of the short-term trial.

Weed Control

Herbicides were applied by forestry spraying contractors using modified drench guns and standard full-cone nozzles (e.g., Full Jet GG4.3W, Spraying Systems Co.). Spots were centred on individual trees and spot size was varied by changing the height of application. Complete weed control was achieved using either knapsacks and fan nozzles, or a small boom sprayer with fan nozzles. In September 1993 herbicide treatments were applied at both Kaingaroa trials using a mixture of terbuthylazine (7.5 kg a.i./ha), haloxyfop (0.5 kg a.i./ha), and clopyralid (0.6 kg a.i./ha). At Kinleith, herbicides were applied in December 1993 using a mixture of haloxyfop (0.5 kg a.i./ha), clopyralid (0.6 kg a.i./ha), and simazine (10 kg a.i./ha).

Measurements

The heights and root collar diameters of all trees were measured and tree health was assessed shortly after planting and again at the end of the first year (i.e., the winter after planting). Six months after spraying, actual spot diameter was assessed by measuring the longest axis of the spot and the axis at 90° to it. Mean spot diameters were calculated. The distance from the centre of the spot to each tree was also measured. In the few places where herbaceous plants (weeds) in the target area were not killed, the percentage of ground covered by weeds within 0.5 m of each tree was estimated. This approach was chosen in preference to an estimate of weed survival over the whole target area because it was assumed that at this stage, weed growth close to the tree would be most important. In addition, where some weeds did survive in the target area, they tended to be very close to the tree, possibly because of a deficiency in herbicide application technique. Above-ground weed biomass in untreated areas was estimated during summer by harvesting all herbaceous material in 20 randomly located quadrats (0.3 × 0.3 m at Kaingaroa and 0.5 × 0.5 m at Kinleith) and obtaining the mean oven-dry weight per sample.

Statistical Analysis

The long-term Kaingaroa trial was assessed using analysis of variance (ANOVA) and a least significant difference (LSD) test to assess the effect of experimental treatments on tree survival and growth. The analysis was performed using plot means. Initial tree diameter or height, percentage weed ground cover, and tree position within the spot were tested as possible covariates.

For the two short-term trials, the original intention was to analyse the effect of nominal spot diameter on growth and survival. However, it was found that spot diameters had not always been accurately applied to the correct trees (Table 1). In particular, some control trees actually had herbicide applications. Trees were therefore grouped into the following spot diameter classes: 0 m (no weed control), 0.1–1 m, 1.1–2 m, 2.1–3 m, and >3 m. These classes were then regarded as treatments and assessed using ANOVA and LSD tests. The analysis of the Kinleith trial was applied to individual trees (i.e., a single-tree plot analysis was used). For the Kaingaroa trial, subplot means were analysed, and the effect of fertiliser was tested against the block × fertiliser interaction (i.e., a split-plot analysis was used). Block effects were removed in the analysis and initial tree diameter or height, percentage weed ground cover, and tree position within the spot were tested as possible covariates.

In addition to the ANOVAs, regression equations relating tree growth to spot diameter were derived. Tree diameter was found to be modelled adequately as a function of spot diameter using an exponential equation with planting diameter as a covariate:

$$\text{dia 1} = (a + b.\text{dia 0}) \,.\, (1 + c.e^{d.(\text{spot diameter})})$$

where a, b, c, and d are the regression coefficients,

dia 1 and dia 0 are the measured tree diameter at 1 year and at planting, respectively.

To test the hypothesis that the relative effect of weed control on tree growth is greater for the smaller diameter trees, an additional interaction term was added to the model, and tested for significance:

$$\text{dia 1} = (a + b.\text{dia 0}) \,.\, (1 + (c1 + c2.\text{dia 0}).e^{d.(\text{spot diameter})})$$

Equivalent models were used for height growth. For the short-term trials, the curves were fitted to individual tree measurements, while plot means were used for the long-term trial. These analyses were undertaken using the NLIN procedure in the SAS statistical package (SAS Institute Inc. 1987).

For both Kaingaroa trials, a few trees planted between the V-blade mounds on areas devoid of topsoil showed clearly inferior growth and were omitted from the analysis.

RESULTS

Spot Size

The accuracy of the spot applications is described in terms of comparisons of requested and measured spot diameters in Table 1. In theory there should have been no spot sizes

TABLE 1–Comparison of requested and actual spot diameters for each treatment and location.

Trial	Requested spot diameter (m)	Measured mean spot diameter (m)	Distribution of spot diameters (m) by actual diameter class (%) 0	0.1–1	1.1–1.5	1.6–2	2.1–3	>3
Kaingaroa long-term	0	0	100	0	0	0	0	0
	1	1.4	1	0	81	17	0	0
	2	1.9	3	0	2	86	9	0
	>3	3.0	0	0	0	0	100	0
Kaingaroa short-term	0	0.4	75	0	9	11	4	0
	1	1.2	3	13	76	6	1	0
	1.5	1.5	2	1	49	44	4	0
	2	1.5	7	8	44	27	14	0
	>3	2.0	8	2	12	40	37	1
Kinleith short-term	0	0.4	83	1	4	7	2	2
	1	0.6	41	30	19	8	2	0
	1.5	1.2	19	11	33	29	7	1
	2	1.9	7	1	4	44	42	1
	6	5.4	5	0	0	1	2	93

recorded for the no weed control treatments, but this was not so (Table 1). This discrepancy arose because: (1) there were application errors; (2) in some areas there was no growth of non-crop vegetation, even though there was no weed control, and so a nominal spot size equivalent to the tree spacing was used. Overall, there were substantial discrepancies between requested and mean measured spot diameters, especially in the short-term trials (Table 1). The source of this error was probably variability in the height of the spot gun nozzle.

A second consideration in terms of application accuracy is the position of the tree within the spot. In this respect performance was satisfactory. The distance between the tree and the spot centre was, on average, less than 20% of the spot radius length. This factor was not significant ($p > 0.05$) as a covariate in analyses of variance with tree height and diameter as dependent variables. Therefore, variation in the position of the tree within the spot was unlikely to have contributed to the treatment effects on tree growth.

Tree Growth and Survival

The analyses of variance indicated highly significant differences in diameter for the various weed control treatments at both Kaingaroa and Kinleith ($p<0.001$ for all three trials). At Kaingaroa, gains of approximately 200% were observed for the first-year diameter growth (after accounting for diameter at planting) when comparing the no weed control and complete weed control treatments (Tables 2 and 3). Absolute tree diameter growth and differences were much smaller at Kinleith but there was still a 63% increase in growth between the same extreme treatments.

At both sites, the effects of spot weed control on height growth were less marked than on diameter growth. At Kaingaroa the differences were highly significant ($p<0.001$ for both trials) but at Kinleith there were no significant differences ($p=0.5$). The gain in height growth between the no weed control and complete weed control treatments was approximately 60% at Kaingaroa.

The only significant covariate in any of the analyses was initial tree size (either diameter or height). Neither percentage weed cover nor position of tree within the spot was significant.

TABLE 2–Effect of spot diameter on 1-year tree diameter, height, and mortality, in short-term trials

Trial location	Spot diameter class (m)	Tree diameter (mm)		Tree height (cm)		Tree mortality (%)
		At planting	At age 1	At planting	At age 1	
Kaingaroa	0	3.6	8.3 a	20.3	50.7 a	5.8 a
	0.1–1	3.5	11.0 b	20.7	59.4 b	7.9 a
	1.1–2	3.7	14.1 c	21.3	67.6 c	9.6 a
	2.1–3	3.5	16.5 d	20.1	70.5 c	10.1 a
	>3 (complete)	3.6	16.4 d	19.9	67.5 c	10.4 a
Kinleith	0	5.8	7.4 a	28.1	36.9 a	7.8 a
	0.1–1	5.8	8.5 bc	29.2	38.5 a	0.8 b
	1.1–2	5.9	8.1 b	29.3	39.5 a	1.0 b
	2.1–3	5.9	8.4 bc	28.9	39.9 a	2.6 ab
	>3 (complete)	6.0	8.6 c	29.7	39.5 a	0.8 b

Means followed by the same letter do not differ significantly ($p = 0.05$).

TABLE 3—Effect of spot diameter on 1-year tree diameter, height, and mortality, Kaingaroa long-term trial

Requested spot diameter (m)	Tree diameter (mm)		Tree height (cm)		Tree mortality (%)
	At planting	At age 1	At planting	At age 1	
0	4.9	8.9 a	26.2	56.4 a	4.7 a
1	4.7	15.0 b	24.4	70.0 b	7.4 a
2	4.6	15.5 b	24.9	69.7 b	7.1 a
>3 (complete)	4.8	17.8 c	25.8	71.4 b	1.2 a
>3 with fertiliser (complete)	4.7	17.7 c	24.4	71.5 b	6.8 a

Means followed by the same letter do not differ significantly (p = 0.05).

Therefore, some measure of initial tree size should be used when interpreting treatment effects.

There was little or no tree growth response to fertiliser at Kaingaroa. The only significant response was to height growth in the short-term trial where the trees with fertiliser were marginally taller (64.3 cm *v.* 62.1 cm) (p = 0.042).

The regression analysis showed a strong trend for increased tree height growth up to a spot diameter of about 1.5 m at Kaingaroa (Fig. 1a). With larger spot sizes, further gains in height growth were minimal. Diameter growth showed a similar trend but continued to increase, albeit at a declining rate, to the point of complete weed control (Fig. 1b). At Kinleith, height and diameter growth gains from weed control were very small, irrespective of spot size.

There was no evidence to indicate significant interaction between diameter growth and initial tree size, although the range of tree sizes used was very small. In other words, the relative benefit from weed control was the same whatever the initial tree size.

The amount of variation in *P. radiata* height and diameter growth that was associated with weed control and initial tree size in each trial is indicated in Table 4. In the short-term trials (both Kaingaroa and Kinleith), where the regression model was based on individual-tree growth data, 35–27% of all variation in diameter growth and 25–43% of the variation in height growth was accounted for in this way. As expected, the percentage variation associated with weed control and initial tree size in the long-term trial was much greater because each data point represented a mean of approximately 40–50 trees. Even so, the very high value of 93% for diameter variation indicates that micro-environmental, fertility, and other factors were not causing large differences in tree growth across the site.

At Kaingaroa, mortality at the end of the first year ranged from 1.2% to 10.4% but there were no significant differences among spot size treatments (p = 0.32) (Tables 2 and 3). At

TABLE 4—Percentage of variation in tree growth after 1 year, associated with weed control and initial tree size.

Location	Variation in tree growth associated with weed control and initial tree size (%)	
	Height growth	Diameter growth
Kaingaroa short-term	25	37
Kaingaroa long-term	76	93
Kinleith	43	39

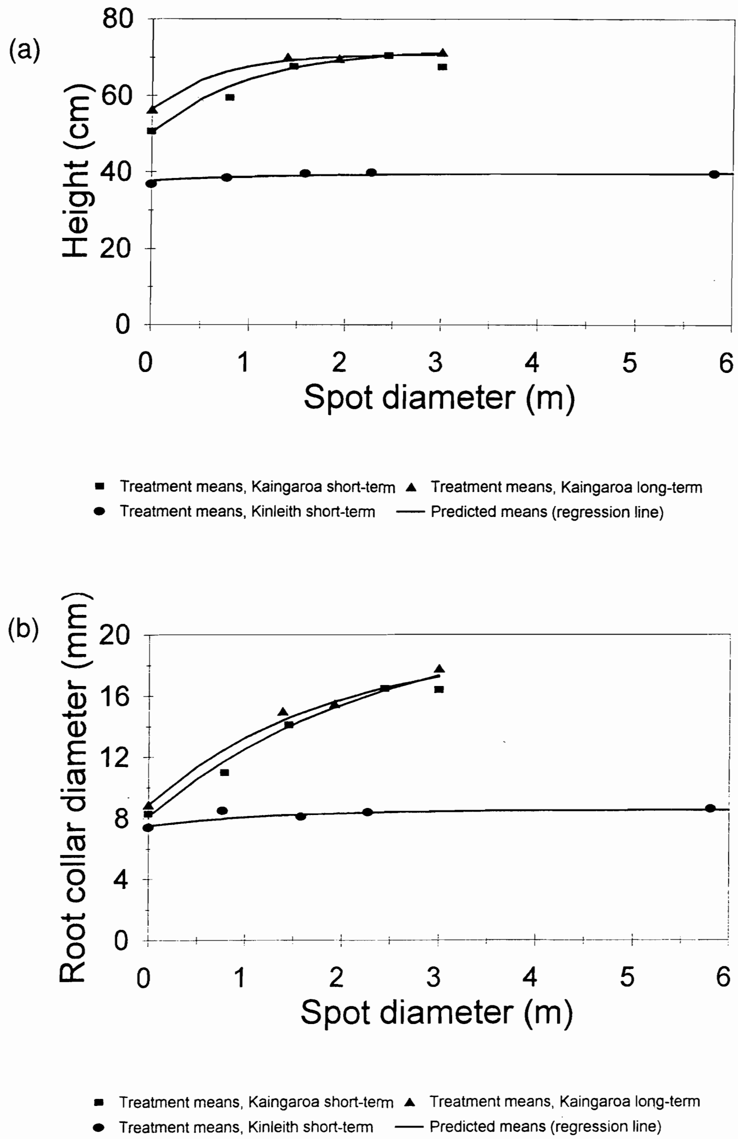

FIG. 1–Predicted and treatment means for *P. radiata* (a) height and (b) diameter growth 1 year after planting, as a function of weed-free spot size.

Kinleith, mortality was generally low except in the untreated plots where it was approximately 8% and significantly higher than in weed control treatments ($p = 0.002$). Although less than 5% of trees in any one treatment at Kaingaroa showed browsing damage, significantly more trees were damaged where there was complete weed control than where there was no weed control ($p = 0.005$). This may help to explain why mortality levels, which might have been expected to be highest in unsprayed plots, did not appear to be influenced by spray treatments at Kaingaroa.

Weed Growth

The untreated ground cover at each site was composed predominantly of oversown species, but included a range of other grasses and herbaceous broadleaves. At Kaingaroa, only sparse scattered patches of bracken and broom were present. Biomass on unsprayed areas at Kaingaroa was more than twice that at Kinleith (6890 ± 865 kg and 3015 ± 294 kg oven-dry weight/ha, respectively). Within the herbicide-treated areas, weed cover was very low to non-existent, and inclusion of this variable in the analyses showed no significant effects on growth data.

Experimental Precision

The long-term and short-term trials at Kaingaroa provided an interesting comparison of relative precision in a large-plot trial (45 × 45-m plots including buffers) and a small-plot trial (four-tree plots of 8 × 6 m). The root mean square errors (RMSE, a measure of the unexplained variation) for the analysis of plot means from the long-term trial were 0.98 mm for diameter and 4.24 cm for height. The corresponding RMSEs in the short-term trial were 2.17 mm and 8.87 cm. After mortality was accounted for, the large-plot trial averaged 41.5 trees per plot while the small-plot trial averaged 3.37 trees per plot. Using these figures, it can be seen that the smaller plots would have achieved precision equivalent to that of the larger plots if only 40% as many trees had been measured for diameter, and 36% as many trees for height. This demonstrates the advantage of using small plots for short-term trials. Long-term trials require large buffered plots to eliminate edge and competition effects.

DISCUSSION

Despite careful calibration prior to applying the spot herbicide treatments, there was a large discrepancy between requested and measured spot diameters. The fact that applications were made by experienced contractors who knew that their performance was to be carefully measured, suggests that standards for operational application may need some attention.

Absolute tree growth and herbaceous weed biomass production during the first year after tree planting was much greater at Kaingaroa than Kinleith. Mean annual rainfall at each site was similar, so the most probable reasons for productivity differences were less favourable temperature and/or soil fertility at Kinleith. There was no growth response to fertiliser application in combination with total weed control at Kaingaroa. Unfortunately, the effect of fertiliser was not assessed at Kinleith. The 120-m-lower elevation at Kaingaroa would probably be associated with less extreme temperatures and that could have contributed to greater overall growth. Mason & Whyte (1992) have shown the importance of altitude in predicting *P. radiata* growth up to age 5 in the central North Island.

The tree response to weed control was also much greater at Kaingaroa than at Kinleith, possibly because weed growth was more vigorous and competition for shared resources was more intense at Kaingaroa. At Kinleith, factors other than competition from weeds probably limit tree growth so weed control is not critical during the first year. However, weed competition was often associated with a significant increase in tree mortality at Kinleith. Mason & Whyte (1992) demonstrated a significant interaction between growth response to weed control and altitude, weed control having a greater effect at lower elevations. The large degree of site variability in terms of response to weed control demonstrated in this and other studies (Richardson *et al.* 1993) highlights the importance of careful site selection for experimental design. It also demonstrates that results should not be extrapolated to other sites.

In order to define the optimal area and duration for weed control, treatment costs must be balanced against value gains at the end of the rotation. Where rotation-age data are not available, there are at least two ways of calculating cost-benefit. Probably the most appropriate method for projecting rotation age growth gains from short-term data is to express the growth gain in terms of a time change (Richardson & West 1993; Wilkinson *et al.* 1992). The time difference between treated and untreated stands is the difference between the current age of the untreated stand and the age of the treated stand at which the volume was identical. With assumptions as to likely future growth trends (Mason 1991; Richardson & West 1993), existing growth models can be used to calculate the economic impact of such time changes. However, this method cannot reliably be used with only first-year data.

A second method that has been used to calculate cost-benefit is to calculate the growth gain at a point in time and compare this to treatment cost to give growth per unit of cost for each treatment (Balneaves 1987; Balneaves & Henley 1992). Using this method, Balneaves (1987) concluded that on a dry South Island site, the optimal spot size per unit of cost was the smallest spot size treatment used (1.0 m diameter) even though maximum growth was obtained only with complete weed control. A similar calculation leads to an identical conclusion for the experiments reported here. However, there are problems with this method. Firstly, no consideration is given to future growth trends on the various treatments. Secondly, although the growth gain per unit of cost decreased with spot sizes greater than 1 m, the amount of wood produced continued to increase. As long as the value of this extra growth is greater than additional treatment cost, overall profit continues to increase. This technique fails to account for the value of increased wood production and is not appropriate for ranking treatments according to economic return.

With only 1 year of data there is no reliable basis for quantitatively assessing the optimal spot size. At this stage, tree growth trend data can be used to make subjective but practical recommendations based on "threshold" spot sizes, i.e., those beyond which only slight gains in growth or a rapid decrease in the rate of growth gain can be expected. At Kinleith it is clear that a spot size between 0.5 and 1 m diameter is all that is required to maximise growth and minimise mortality. At Kaingaroa, there is a threshold spot size for maximising height growth at around 1 m. However, with diameter growth, a much more important variable in terms of crop biomass production, there is no clear threshold. It would appear that any spot size between 1.5 and 2.0 m diameter would give a substantial growth benefit. Although significant growth gains continue beyond this spot size range, other benefits resulting from maintaining a herbaceous ground cover, such as exclusion of shrub species, reduced erosion, and addition of nitrogen to the site if a legume is present (West & Dean 1995), would be lost if spot size was increased much beyond this point.

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