PINUS RADIATA GROWTH RESPONSE TO SPOT WEED CONTROL

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ABSTRACT

Spot spraying, where only the area around individual trees is treated, is an important method of herbicide application during establishment of radiata pine (*Pinus radiata* D. Don) plantations in New Zealand. Minimising the spot size reduces costs and has perceived environmental benefits from reduced overall herbicide use. This report presents an integrated analysis of nine recently undertaken experiments at six separate sites. The trials were designed to determine the radiata pine growth response to spot weed control. Experimental sites were located on both the North and South Islands. Each trial was analysed using the age-shift (or time-shift) approach, which compares treatments on the basis of tree age at a fixed size rather than tree volume at a fixed age. In this method, treatment effects are quantified as age shifts, effectively the reductions in time taken to reach a standard tree volume by treated trees compared with the untreated control trees. The method of implementing the age-shift model, for spot treatments on pasture or oversown sites, and subsequent economic analysis into VMAN was demonstrated.

The analysis showed that:

- The reduction in rotation length achieved by total weed control was as follows: 0.5 years at East Coast and Southland, 0.9 years at Kaingaroa, approximately 1.2 years at Tokoroa, and 1.8 years at Tokoiti.
- A spot diameter of 1 m achieved half the benefit of total weed control, while a spot diameter of 2 m achieved 75% the benefit of total weed control.
- Generally, there was little benefit in maintaining spots beyond 1 year. Tokoiti was an exception to this where a second year of control proved beneficial.
- Once trees reached 2 m height, weed control gave little additional benefit (with the exception of Tokoiti where threshold of 4 m was required).
- A 1.5 m diameter spot maintained for 1 year in Kaingaroa increased the present value of the stand by $180/ha (this assumes a value of $40K/ha at felling and an 8% discount rate).

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

INTRODUCTION

Many studies have demonstrated that the survival and growth rates of *Pinus radiata* D. Don crop trees can be reduced by competition with other plant species for water, light, and nutrients (Richardson, 1993; Richardson et al., 1996b; 1999). 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. With a high proportion of forestry companies in New Zealand obtaining or seeking Forest Stewardship Council (FSC) certification, there is also a commitment to reducing chemical use wherever possible. Hence, it is important to use the minimum quantity of herbicide to greatest effect.

Spot herbicide applications, where only the ground area around individual trees is treated, reduce the quantity of chemical used compared with broadcast applications. For example, with a 1.5 m diameter spot and 833 stems per hectare, only about 15% of the area is treated with herbicide compared with broadcast treatment. Compared with aerial herbicide applications, spot treatments also reduce the potential for spray drift. Spot treatments therefore provide large cost reductions and perceived environmental benefits. This technique is most appropriate on sites dominated by herbaceous vegetation (defined as annual or perennial grasses or broadleaves without a woody stem) either naturally or from oversowing.

Two important management issues related to spot spraying are the definition of the optimal spot size and the duration of weed control. These two factors dictate the proportion of a site that has to be treated, the number of spray 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. Prior to the work described in this report, these factors received limited study (Balneaves, 1987; Balneaves and Henley 1992; Clinton and Mead, 1990; West, 1984; Richardson et al., 1996a, 1997a). All published New Zealand studies on spot weed control have reported tree growth benefits but it is clear that factors such as area and duration of weed control, soil type, climate, and competitor species influence the size and duration of growth responses.

This paper presents radiata pine growth data from a series of trials designed to define the optimal area and duration of weed control at sites located on both the North and South Islands. The trials were implemented through both the NZ Site Management Cooperative (NZSMC) and individual forestry companies, as described below. Preliminary results from some of these experiments have been described previously (see previous NZSMC reports; Gous *et* al. (2002); Richardson *et* *al*. (1996a; 1997a). This report presents an integrated analysis of all recent experiments to determine the radiata pine growth response to spot weed control.

METHODS

Location and design of trials

Data from a series of 9 trials located at 6 separate sites (Tables 1 and 2) were collated into a single database. Locations included the Bay of Plenty / Central North Island (5 experiments), East coast of the North Island (1 experiment), Otago (2 experiments) and Southland (1 experiment). While there was variation in site characteristics, none of the sites were especially dry.

The design of individual trials differed slightly across and within sites, but all consisted of some common treatments (Table 3). All experiments included a weed free treatment to estimate potential tree growth in the absence of weeds and, with the exception of the long-term trial at Tokoiti, a no weed control treatment to estimate the maximum effect of weeds. Intermediate treatments consisted of combinations of weed-free spot area and the duration of control. At three locations both long- and short-term experiments were installed. Short terms experiments always had more treatments, smaller plots, and were designed to last for up to 7 years. Long-term experiments had fewer treatments but large plots designed to last for a rotation if required.

Table 1: Spot size trial locations

Trial Code	Forest	Region
AD1S (short-term experiment)	Kaingaroa Compartment 1035	Central North Island
AD1L (long-term experiment)	Kaingaroa Compartment 1035	Central North Island
AD2S (short-term experiment)	Tokoiti Forest	Milton – South Otago
AD2L (long-term experiment)	Tokoiti Forest	Milton – South Otago
AD3S (short-term experiment)	Slopedown, Compartement 16	Invercargil - Southland
AD4S (short-term experiment)	Kinleith Forest – Tokoroa	Central North Island
AD5S (short-term experiment)	Kaingaroa Compartment 1161	Central North Island
AD5L (long-term experiment)	Kaingaroa Compartment 1161	Central North Island
AD6S (short-term experiment)	Mungatu Compartment 34	East Cape

Table 2: Spot size trial site characteristics

Trial code	Altitude (m)	Slope (°)	Rainfall (mm/yr)	Soil
AD1S	460	0	1483	Yellowbrown Pumice soils
AD1L	460	0	1483	Yellowbrown Pumice soils
AD2S	55	15	800	Mixture of Raurekau silt loam and Taratu Hill gravel
AD2L	55	15	800	Mixture of Raurekau silt loam and Taratu Hill gravel
AD3S	260	15	1000	Lowland yellow brown earths
AD4S	584	7	1585	Yellowbrown Pumice soils
AD5S	380	10	1483	Yellowbrown Pumice soils
AD5L	380	10	1483	Yellowbrown Pumice soils
AD6S	260	15	1362	Pareora greymuddy siltter cacegravel

Table 3: Treatments applied at different site locations

	Treatment Specification							
Site code	No weed control	1.0 m, 1 yr[1]	1.5 m, 1 yr	2.0 m, 1 yr	1 m, 2 yr	1.5 m, 2 yr	2.0 m, 2 yr	Total weed control
AD1S	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
AD1L	Yes						Yes	Yes
AD2S	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
AD2L					Yes		Yes	Yes
AD3S	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
AD4S	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
AD5S	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
AD5L	Yes	Yes					Yes	Yes
AD6S	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

[1]Treatments specified in terms of spot diameter (e.g. 1.0 m) and time that the spot is maintained weed-free (e.g. 1 year)

A brief summary of the different experiments follows:

- A short-term (AD1S) and a long-term experiment (AD1L) were installed in Compartment 1135 in Kaingaroa forest. After broadcast spraying in February 1993, the radiata pine cutover was oversown in April 1993 with a mixture of Yorkshire fog (10 kg/ha) and *Lotus uliginosus* (5 kg/ha). abandoned after 1 year because entire area was sprayed - appear to provide little useful information.
- AD2L - Long-term trial, Tokoiti. 4 treatments (but no control treatment), 5 reps, 60 trees per plot. All treatments appear to have been applied correctly. Treatments were analysed according to design using plot means.

- AD2S - Short-term trial, Tokoiti. 8 treatments, 5 reps, 10 trees per plot. All treatments appear to have been applied correctly. Treatments were analysed according to design using plot means.
- AD3S - Short-term trial, Slopedown, Southland. 8 treatments, 4 reps, ~18 trees per plot. Some initial sprays were missed (about 60 trees in total) and these trees were eliminated from the analysis. Apart from this, treatments appear to have been applied correctly. Treatments were analysed according to design using plot means.
- AD4S - Short-term trial, Tokoroa. 16 treatments, 30 reps, 1 tree per plot. Treatments were often applied incorrectly. Trees were therefore reclassified into 5 treatments on the basis of the 3 spot size assessments, which appear to have been carried out accurately on all trees. This trial was only monitored for 3 years.
- AD5L - Long-term trial, Kaingaroa. 5 treatments, 5 reps, 34 trees per plot. Approximately 70 trees were incompletely treated in the 'total weed control' treatment and were eliminated from the analysis. Apart from this, treatments appear to have been applied correctly. Treatments were analysed according to design using plot means.
- AD5S - Short-term trial, Kaingaroa. 9 treatments, 4 reps, ~12 trees per plot. Treatments appear to have been applied correctly. Treatments were analysed according to design using plot means.
- AD6S - Short-term trial, Rayonier, East Cape. 8 treatments, 5 reps, 14 tree per plot. Approximately 50 trees were missed in the initial spray and were eliminated from the analysis. The second spot assessment is incomplete and was ignored. Treatments were analysed according to design using plot means.

All trials were established on cutover sites that were oversown except Tokoiti, which was an ex-pasture site. Measurements taken at regular intervals included tree height and diameter, ground cover within the spot, actual spot diameter, the degree of multi-leadering, and tree health status. Diameter measurements were based on ground level measurements (GLD) early in the trials. When the trees were tall enough diameter was measured at 1.4 m height (DBH).

Analysis methods

Each trial was analysed using the age-shift (or time-shift) approach, which compares treatments on the basis of tree age at a fixed size rather than tree volume at a fixed age. In this method, treatment effects are quantified as age shifts, effectively the reductions in time taken to reach a standard tree volume by treated trees compared with the untreated control trees. Note that a simple comparison of growth increments can over or underestimate the longevity of a growth response because of the natural association between tree size and growth rate caused by the nonlinear nature of the growth trajectory. The age-shift method overcomes this problem.

To apply this method, separate non-parametric regression growth curves were fitted for each plot to the mean D^2H over time. Smoothing spline functions fitted using the SAS TPSPLINE procedure (SAS, 1987) were used for this purpose. From these functions, estimates of the time taken for mean tree size to reach a series of specified sizes were obtained for each plot. For each specified size, a separate ANOVA was performed on the time taken to reach that size. Time contrasts between treatments and the control (age shifts) were estimated and tested for significance.

The age shifts between treatments and the control were used to predict the likely economic benefits of the treatments by assuming that the rotation lengths would be reduced by a corresponding amount. The following procedure based on this estimated reduction in rotation length and stand value at harvest was used.

Firstly, the increase in the present value of the stand ignoring costs discounted to the time of treatment was calculated using:

$$\begin{aligned}\Delta PV &= FV\left((1+r)^{-(T-t)} - (1+r)^{-T}\right) \\ &= \frac{FV}{(1+r)^T}\left((1+r)^t - 1\right)\end{aligned}$$

where r is the discount rate, the untreated stand has T years remaining to harvest, the treatment reduces the rotation by t years while producing the same yield, and the future value at harvest of the untreated stand is FV (\$ ha^{-1}). Secondly, the cost saving arising from the reduction in rotation length was calculated using:

$$\begin{aligned}\Delta C &= C\sum_{j=1}^{T} 1/(1+r)^j - C\sum_{j=1}^{T-t} 1/(1+r)^j \\ &= C\frac{(1+r)^t - 1}{(1+r)^T r}\end{aligned}$$

where annual costs are C (\$ ha^{-1}) including, e.g., the cost of land which could be represented as an annual rental cost, along with routine annual management costs.

Ignoring treatment costs, the discounted value of the treatment is $\Delta PV + \Delta C$. Treatment costs should then be subtracted from this amount to obtain the net present worth of the treatment. However, in this study, treatment costs were not considered.

RESULTS

Age shift analysis of D^2H

Appendix 1 summarises data showing how much each treatment lagged behind the weed-free treatment at a range of ages in each of the trials. This age shift is the extra time taken for trees to reach the same size as weed-free trees at a given age. The response variable used in the time shift analysis was diameter squared times height, which can be regarded as a surrogate of stem volume.

Time shifts between weed-free and unsprayed treatments over time are shown in Figures 1 and 2. With the exception of trial AD2S (Tokoiti) the extra time required for trees without weed control to reach the same volume as those with weed control reached an asymptote at around 0.5 to 1 year (Figure 1). The asymptote for the Tokoiti trial would be closer to about 2 years. Although there was a slight suggestion of an increased time shift at AD5S (Kaingaroa, short-term trial), this was an artefact of the small plots sizes and the experiment reaching the end of its useful life.

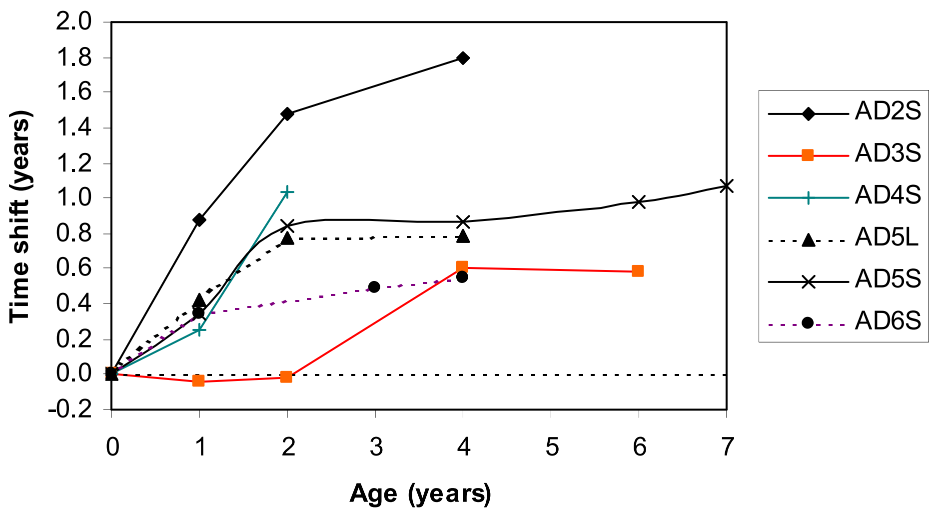

Figure 1: Estimated time lag between weed-free and unsprayed treatments for each trial. This is the extra time taken for trees growing in the presence of weeds to reach the same size as weed-free trees at the specified age.

When the same time shift data are expressed as a function of tree height growth (Figure 2), it can be seen that tree height is a good surrogate to indicate the duration of competition on most sites. In all of the experiments where data were available, but with the exception of Tokoiti, the time shift reached an asymptote by the time trees reach a height of 2 m. When the time shift reaches an asymptote it indicates that competition from the non-crop species is no longer occurring (as the growth curves are not diverging but following parallel trends). At Tokoiti it appeared that the asymptote would not be reached until a tree height of about 4 m.

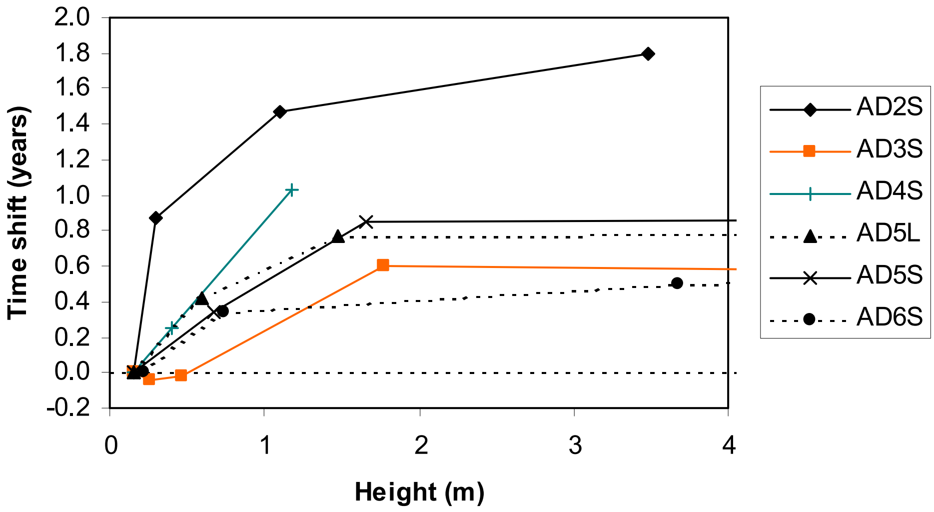

Figure 2: Estimated time shift between weed-free and unsprayed treatments for each trial plotted against mean height.

Two mechansisms can explain the duration of competiton from the oversown herbaceous species. When the trees are small there will be competition for light. However, when the weeds are less than about 50% tree height, this effect becomes insignificant. Therefore tree height should (crudely) be related to the dutration of competition. Previous work has also shown the importance of competition for water when trees grow with herbaceous species on dry sites (Richardson *et al.* 1997b). Studies suggest that the duration of competition in this circumstance is related to the time taken for tree roots to access water in the soil profile below the root zone occupied by herbaceous species (see Richardson 1993 for references). Once again, at a crude level it is likely that tree height gives an indicative measure of root depth.

Figures 1 and 2 represent the maximum effect of weed competition in terms of time shift i.e. a comparison of tree size on plots with no weed control after planting versus tree size on plots given complete weed control. When intermediate levels of weed control are applied (i.e. different area and duration of weed control) the time shift (Figure 3) or percentage tree growth (Figure 4) compared with total weed control varies according to the intensity of control (spot diameter).

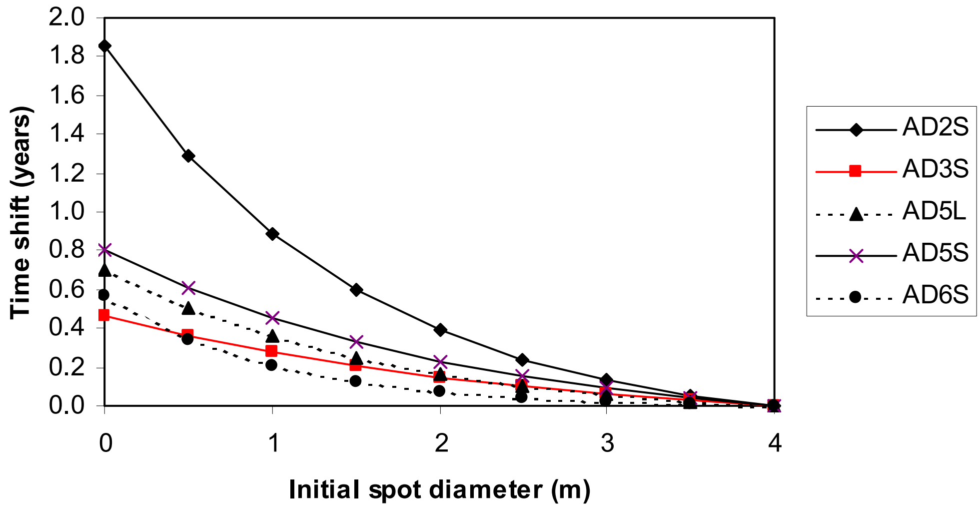

Figure 3: Time shift, based on tree volume, versus initial spot diameter for each trial, 4 years after planting. The time shift represents the additional time required to reach the same size as trees given total weed control.

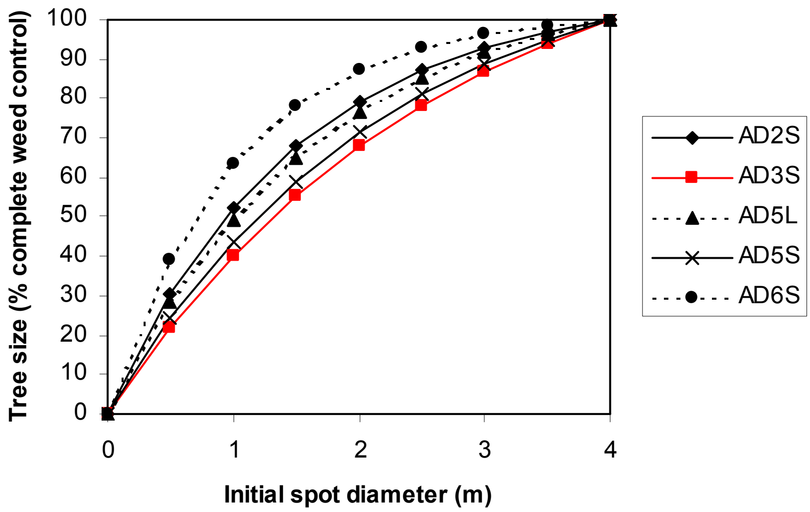

Figure 4: Effect of initial spot diameter on tree size (volume index) expressed as a percentage of tree size given total weed control.

An economic analysis of spot spraying

An economic evaluation of weed control based on the age-shift analysis was performed by applying a discounted cash flow analysis to the assumed reduced rotation length based on the time shift at age 4 years. No account was taken in this analysis of the cost of weed control. However, the calculated NPV (net present value) can be directly compared with costs to determine whether weed control is economically justified. The economic value of total weed control for each trial for a range of assumed future crop values and discount rates is shown in Table 4, and for a range of spot sizes in Figure 5. The values shown represent the amount of money that can be spent on weed control. A more detailed analysis based on the long-term Kaingaroa trial is shown in Figure 6.

Table 4: Reduction in rotation length achievable by total weed control compared with no weed control and the resultant present value of weed control at planting for each trial for a range of discount rates (DR) and per hectare future values at felling (FV). Note that AD2L is not included because of the absence of a control treatment, and AD4S is not included because it was only monitored for 3 years.

Trial	Reduction in rotation (years)		Present value of total weed control ($/ha)			
	mean	95% C.I.	FV=$30K/ha		FV=$50K/ha	
			DR=8 %	DR=10 %	DR=8%	DR=10 %
AD2S	1.79	0.27	540	400	880	640
AD3S	0.60	0.20	140	110	230	170
AD5L	0.78	0.27	210	160	350	260
AD5S	0.86	0.20	240	180	400	290
AD6S	0.54	0.26	170	130	280	210

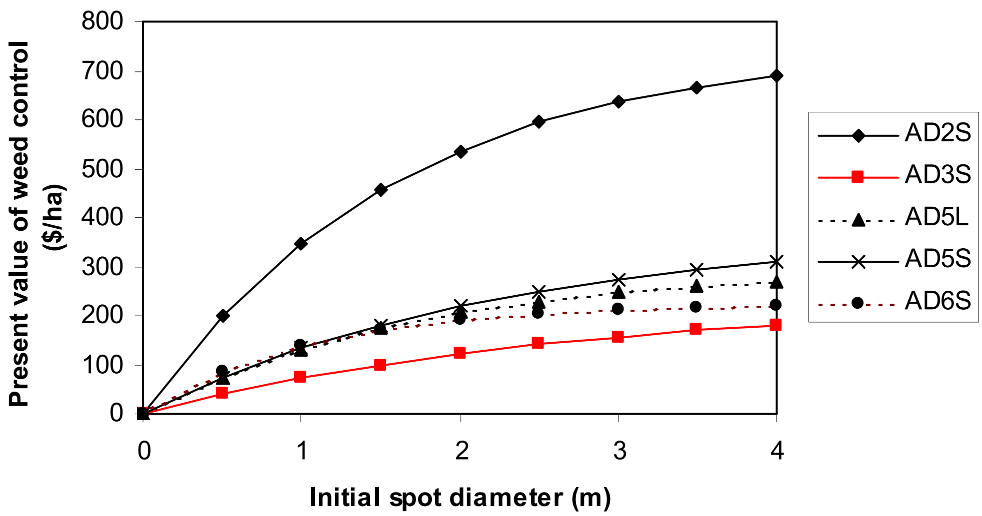

Figure 5: Value of weed control evaluated at planting, excluding the treatment cost (i.e. the amount of money that can be spent on weed control). This analysis uses an 8% discount rate and assumes stand value at felling (27 years age) is $40K/ha and fixed annual costs are $200/ha.

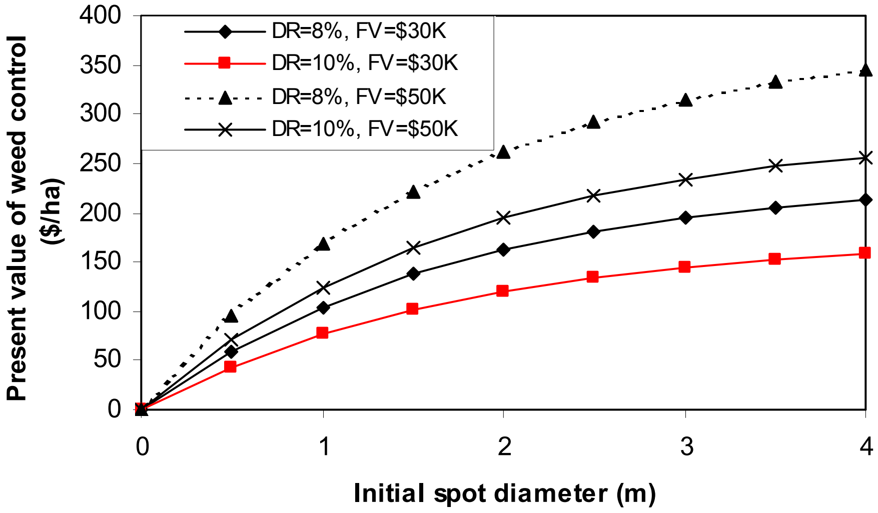

Figure 6: Present value of spot weed control for a range of discount rates (DR) and per hectare future values at felling (FV) for trial AD5L (Kaingaroa). This analysis assumes a felling age of 27 years and fixed annual costs of $200/ha.

The present value of weed control shown in Figures 5 and 6 represents the break-even amount of money that can be spent on weed control. If weed control can be achieved at a cost less than the present value, then the operation will realise a profit.

MODELS FOR USE IN VMAN

The above analysis gives a general overview of the results based on tree volume index (Diameter^2 multiplied by Height). The economic analysis gives some idea of the likely benefit of weed control at typical sites. However, a more comprehensive economic analysis for a particular site is better carried out by implementing the information from these trials into the VMAN (Vegetation Manager) software. This section briefly describes the VMAN models that were developed from these trials. More details are given in Appendix 2.

VMAN requires separate time shift models for height and ground-level diameter (GLD). The time shifts between no-spray and weed-free treatments for height and diameter are shown in Figures 7 and 8. These figures show the extra time taken by the unsprayed trees to achieve the same height or diameter as the weed-free trees, plotted against the mean height of the unsprayed trees. For example in trial AD2S, when unsprayed trees were 2 m in height, they were approximately 1.5 years behind the weed-free trees in height growth (Figure 7), and about 1.8 years behind in diameter growth (Figure 8). Figure 8 includes time shift estimates for both GLD and DBH where these were available, and provides some evidence that the maximum time shift for DBH is somewhat less than for GLD. This appears to have occurred in trials AD3S, AD6S and AD5L but not AD5S, and suggests that weed competition causes a change in tree taper. At present VMAN assumes that taper is unaffected by competition, and that DBH and GLD therefore always have the same time shift.

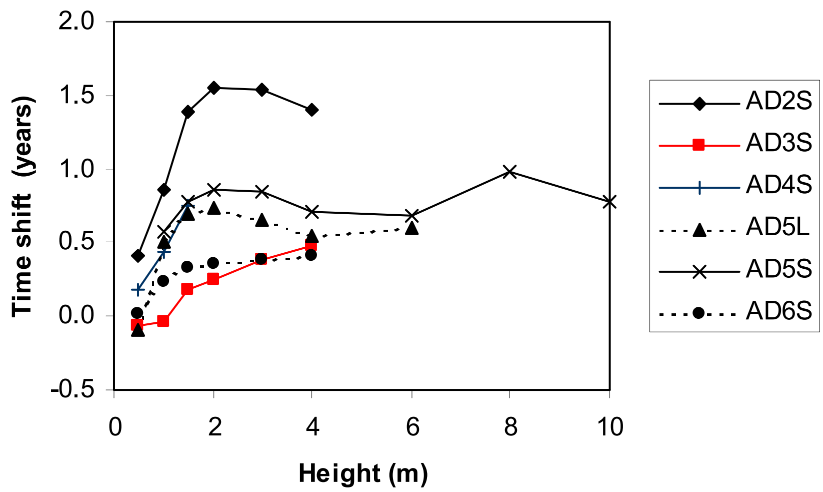

Figure 7: Time shift comparison of height between weed-free and unsprayed trees for each trial.

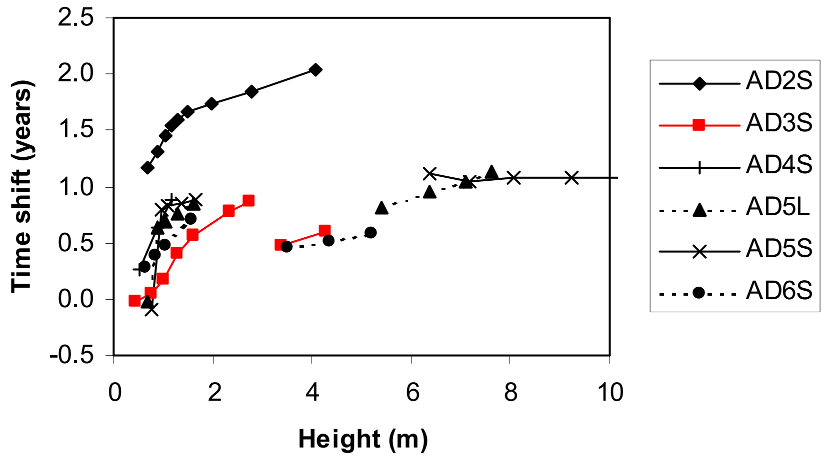

Figure 8: Time shift comparison of diameter between weed-free and unsprayed trees for each trial. Breaks in lines are where measurement of diameter switched from ground level to breast height.

The following exponential model was fitted to the height and GLD time shift data:

(1) $$S = A_{\max}\left(1 - \exp\left(-r\left(h - 0.18\right)\right)\right)$$

where S is the time shift (years), h is height (metres), r is a global model parameter which was assumed to be the same for all trials, and A_{max} is a trial specific parameter representing the maximum time shift for each trial. The mean height at planting in these trials was 0.18 m, and the model therefore requires that the time shift at this height is zero. Parameter estimates obtained by fitting this model using nonlinear regression are given in Table 5. These indicate that the shape of the repsonse (given by the parameter r) is very similar for the height and GLD models. Because of this, VMAN uses a value of 1.22 for both models. The maximum age shift for height is consistently lower than for GLD. This effect is consistent with the fact that tree diameter is more sensitive to competition from weeds than tree height. On average, the A parameter for height is 0.65 times the value for GLD, and this figure is used in VMAN.

Table 5:. Coefficients for the age shift versus height model.

Coefficient	Trial	GLD model	Height model
R	all trials	1.22	1.23
A_{max}	AD2S	2.08	1.56
	AD3S	0.66	0.30
	AD4S	1.13	0.81
	AD5L	0.95	0.67
	AD5S	1.01	0.84
	AD6S	0.77	0.39

To use equation 1 in VMAN, information is required on the maximum age shift, A_{max}, for any site. At present there is limited knowledge about how this should be estimated. Theoretically, the age shift should be higher on drier sites and with oversown species that are either taller or deeper rooted. and there is a suggestion from these trials that A_{max} increases with reducing rainfall (Figure 9). The following model was derived from the GLD coefficients in Table 9:

(2) $$A_{\max} = m + (n - m)\exp(o(R - 500))$$

where R is rainfall (mm/year), and m, n and o are model coefficients. The coefficient n is the time shift corresponding to a 500 mm annual rainfall, and this was arbitrarily set to 6. The other coefficients were fitted by nonlinear regression and estimated to be m = 0.793 and o = -0.00540. This model (shown in Figure 9) is admittedly somewhat crude, but will suffice until more data becomes available to develop a more sophisticated model.

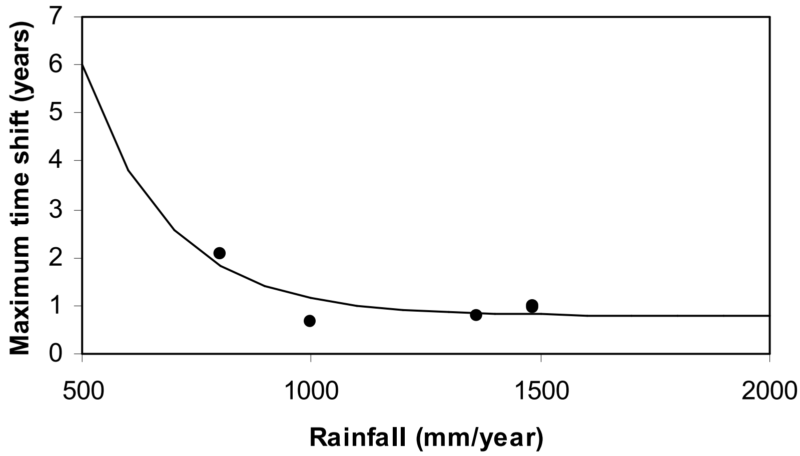

Figure 9: Maximum weed-free versus unsprayed age shift for GLD versus rainfall.

The final component required for VMAN is a model which predicts the effect of spot diameter. The following model (based on Figure 4) is used in VMAN to predict maximum age shift, A, for a given spot diameter D (m):

(3) $$A = A_{\max}(1 - D/4)^{p}$$

where A_{max} is the maximum time shift for weed-free versus unsprayed trees discussed above, and p is a model parameter estimated using nonlinear regression to be $p = 2.2$. This equation assumes that the weed-free condition is equivalenet to a spot diameter of $D = 4$ m.

The above briefly describes the models underlying the new spot spraying function in VMAN, and indicates some of the assumptions that were required when developing these models. The precise manner in which these functions are implemented in VMAN is described in Appendix 2.

CONCLUSIONS

- The reduction in rotation length achieved by total weed control in a series of trials was as follows: 0.5 years at East Coast and Southland, 0.9 years at Kanigaroa, approx. 1.2 years at Tokoroa, and 1.8 years at Tokoiti.
- A spot diameter of 1 m achieved half the benefit of total weed control, while a spot diameter of 2 m achieved 75% the benefit of total weed control.
- Generally, there was little benefit in maintaining spots beyond 1 year. Tokoiti was an exception to this.
- Once trees reached 2 m height, weed control gave little additional benefit (with the exception of Tokoiti).
- A 1.5 m diameter spot maintained for 1 year in Kaingaroa increased the present value of the stand by $180/ha (this assumes a value of $40K/ha at felling and an 8% discount rate).
- Functions based on these trials have been developed and implemented in VMAN.

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APPENDIX 1
SUMMARY OF AGE SHIFT DATA

Tables A1 to A7 summarises data showing how much each treatment lagged behind the weed-free treatment at a range of ages in each of the trials. This age shift is the extra time taken for trees to reach the same size as weed-free trees at a given age. The response variable used in the time shift analysis was diameter squared times height. Ground level diameter (GLD) was used for early estimates and breast height diameter (DBH, indicated by asterisks in the tables) for later estimates. However, in the Tokoiti trials (AD2L and AD2S), ground-level diameters were used for all estimates because the high level of multi-leadering (caused by browsing?) especially in the treatments with greater weed control, made breast-height measurement difficult. The LSD indicates the difference between treatments required for statistical significance (p=0.05). Mean spot diameter and vegetation cover are also given for each treatment. Spot diameter was measured several months after the initial spray. Cover was measured within a diameter of 1 m, also shortly after spraying, and again a year later. The durations given for each treatment are the time spot sizes were maintained by repeat spraying when necessary.

Table A1: Time-lag for each treatment compared with the weed-free treatment in trial AD2L. Note that treatment differences greater than the LSD (least significant difference) are statistically significant (p=0.05).

Treatment	Spot diameter (m)	Duration (years)	Cover (%)	Time lag vs. weed-free (years)		
			1 yr	1 yr	2 yr	4 yr
1	4.0	5	5	0.0	0.0	0.0
2	2.0	2	7	0.0	0.0	0.1
3	1.1	2	13	0.0	0.1	0.4
4	4.0 + fert	5	4	0.0	0.0	0.0
LSD				0.1	0.1	0.2

Table A2: Time-lag for each treatment compared with the weed-free treatment in trial AD2S.

Treatment	Spot diameter (m)	Duration (years)	Cover (%)		Time lag vs. weed-free (years)		
			0 yr	1 yr	1 yr	2 yr	4 yr
1	0.0	0	100	100	0.9	1.5	1.8
2	1.3	1	6	52	0.2	0.6	0.8
3	1.3	2	5	1	0.1	0.2	0.4
4	1.7	1	11	71	0.0	0.3	0.5
5	1.6	2	5	1	0.0	0.0	0.4
6	1.8	1	8	65	0.0	0.3	0.5
7	1.8	2	5	1	0.0	0.0	0.2
8	4.0	5	0	3	0.0	0.0	0.0
LSD					0.2	0.2	0.3

Table A3: Time-lag for each treatment compared with the weed-free treatment in trial AD3S.

Treatment	Spot diameter (m)	Duration (years)	Cover (%)		Time lag vs. weed-free (years)			
			0 yr	1 yr	1 yr	2 yr	4 yr	6 yr*
1	0.0	0	78	91	0.0	0.0	0.6	0.6
2	1.1	1	10	63	0.0	0.0	0.3	0.2
3	1.1	2	11	18	0.0	0.0	0.4	0.2
4	1.7	1	9	43	0.0	0.0	0.3	0.3
5	1.7	2	16	23	0.0	0.0	0.5	0.4
6	2.0	1	10	45	0.0	-0.1	0.2	0.2
7	2.0	2	16	16	0.0	-0.1	0.4	0.4
8	4.0	5	61	12	0.0	0.0	0.0	0.0
LSD					0.1	0.1	0.2	0.3

Table A4: Time-lag for each treatment compared with the weed-free treatment in trial AD4S.

Treatment	Spot diameter (m)	Duration (years)	Cover (%)	Time lag vs. weed-free (years)	
			1 yr	1 yr	2 yr
1	0.0	0	85	0.3	1.0
2	1.0	1	82	0.1	0.7
3	1.9	1	55	0.1	0.5
4	1.9	2	24	0.0	0.3
5	4.0	5	17	0.0	0.0
LSD				0.2	0.2

Table A5: Time-lag for each treatment compared with the weed-free treatment in trial AD5L.

Treatment	Spot diameter (m)	Duration (years)	Cover (%)		Time lag vs. weed-free (years)		
			0 yr	1 yr	1 yr	2 yr	4 yr*
1	0.0	0	64	89	0.4	0.8	0.8
2	1.1	1	6	80	0.1	0.4	0.5
3	2.5	2	3	8	0.1	0.1	0.2
4	4.0	5	14	19	0.0	0.0	0.0
5	4.0 + fert	5	10	27	0.1	-0.1	-0.3
LSD					0.3	0.2	0.3

Table A6: Time-lag for each treatment compared with the weed-free treatment in trial AD5S.

Treatment	Spot diameter (m)	Duration (years)	Cover (%)		Time lag vs. weed-free (years)				
			0 yr	1 yr	1 yr	2 yr	4 yr*	6 yr*	7 yr*
1	0.0	0	56	76	0.3	0.8	0.9	1.0	1.1
3	1.0	1	7	24	0.1	0.7	0.8	0.9	0.9
4	1.0	2	8	23	0.2	0.8	0.9	1.0	1.1
5	1.4	1	2	9	-0.1	0.5	0.5	0.6	0.7
6	1.2	2	3	10	-0.1	0.3	0.3	0.4	0.3
7	3.1	1	1	2	-0.1	0.2	0.2	0.3	0.3
8	3.1	2	1	4	0.0	0.1	0.2	0.2	0.2
9	4.0	5	5	11	0.0	0.0	0.0	0.0	0.0
10	4.0 + fert	5	5	12	0.0	0.0	0.0	0.1	0.1
LSD					0.3	0.2	0.2	0.3	0.4

Table A7: Time-lag for each treatment compared with the weed-free treatment in trial AD6S.

Treatment	Spot diameter (m)	Duration (years)	Cover (%)	Time lag vs. weed-free (years)		
			1 yr	1 yr	3 yr*	4 yr*
1	0.0	0	91	0.3	0.5	0.5
3	0.9	1	62	0.1	0.2	0.3
4	1.0	2	31	0.2	0.2	0.2
5	1.6	1	30	0.1	0.2	0.2
6	1.3	2	26	0.1	0.1	0.1
7	1.8	1	17	-0.1	-0.1	-0.1
8	2.0	2	7	0.0	0.0	0.0
9	4.0	5	26	0.0	0.0	0.0
LSD				0.1	0.2	0.3

APPENDIX 2

IMPLEMENTATION OF SPOT SPRAYING FUNCTIONS IN VMAN

The VMAN functions are based on equations (1), (2) and (3) given in the main text above. The coefficients are given in the following table:

Coefficient	Value
m	0.793
n	5
o	-0.00540
p	2.2
q	0.65
r	1.22
s	0.18

VMAN models growth of individual trees in time steps that can be specified by the user. Equations are used to predict growth of height and diameter for weed-free trees in each time step. Height and diameter growth are reduced to account for weed competition by incorporating competition modifiers into the growth equations. These growth equations are described in an earlier VMAN document and are derived in Kimberley and Richardson (2004)[1].

The competition modifier over time step Δt is, $1-\Delta s/\Delta t$, where Δs is the increase in time shift between the weed-free and competition-affected tree during the time step. In the spot-spray model, Δs is calculated directly from equation (1) above using the heights at the beginning and end of the time step. This is straightforward for diameter growth. However, for height growth, it is complicated by the fact that the height at the end of the time step is itself affected by competition and the time shift cannot therefore be calculated directly. The solution to this problem is to calculate a modifier based on weed-free height growth, and to then adjust this to account for competition. This can be done because the modifier is actually the ratio of competition-affected to weed-free growth over the time step. The derivation of this adjustment is as follows, where Δh_f and Δh_c represent respectively weed-free and competition-affected height growth, and Δs is the time shift assuming weed-free height growth:

[1] Kimberley MO, Richardson B, 2004. Importance of seasonal growth patterns in modelling interactions between radiata pine and some common weed species. *Can. J. For. Res.* **34:** 184-194.

$$\frac{\Delta h_c}{\Delta h_f} = 1 - \frac{\Delta s}{\Delta t}\frac{\Delta h_c}{\Delta h_f}$$
$$\Rightarrow \frac{\Delta h_c}{\Delta h_f} = 1 \Big/ \left(1 + \frac{\Delta s}{\Delta t}\right)$$

The equations as implemented in VMAN are given below. Note that the growth equations giving, e.g., the coefficients c and d, and the seasonal adjustments, s_D and s_H, are defined in the original VMAN specification document. For spot spraying, only the modifiers vary from the original implementation.

Firstly, for each time step beginning at age t, the following calculations are performed to determine the maximum time shift for height (A_H) and diameter (A_D), based on spot diameter (D, metres), spot duration (T, years) and rainfall (R, mm/year):

$$\text{if } T > t \text{ then } A = (1 - D/4)^p \text{ else } A = 1$$
$$A_D = A\left(m + (n - m)\exp\left(o(R - 500)\right)\right)$$
$$A_H = qA_D$$

Then, for each tree, the height modifier (m_H) is calculated, and used to predict height growth using the following equations, where h_t is the current height.

$$H = h_0 + (h_3 - h_0)\left(\frac{1 - \exp(-cs_H\Delta t)}{1 - \exp(-3c)} + \left(\frac{h_t - h_0}{h_3 - h_0}\right)^{1/d}\exp(-cs_H\Delta t)\right)^d$$
$$S_1 = 1 - \exp\left(-r(h_t - 0.18)\right)$$
$$S_2 = 1 - \exp\left(-r(H - 0.18)\right)$$
$$\Delta S_H = A_H(S_2 - S_1)/\Delta t$$
$$m_H = 1/(1 + \Delta S_H)$$
$$h_{t+\Delta t} = h_0 + (h_3 - h_0)\left(\frac{1 - \exp(-cs_H m_H\Delta t)}{1 - \exp(-3c)} + \left(\frac{h_t - h_0}{h_3 - h_0}\right)^{1/d}\exp(-cs_H m_H\Delta t)\right)^d$$

Next, the diameter modifier (m_D) is calculated, and used to predict GLD growth using the following equations, where d_t is the current diameter.

$$S_1 = 1 - \exp\left(-r\left(h_t - 0.18\right)\right)$$
$$S_2 = 1 - \exp\left(-r\left(h_{t+\Delta t} - 0.18\right)\right)$$
$$\Delta S_D = A_D\left(S_2 - S_1\right)/\Delta t$$
$$m_D = \max\left(0, 1 - \Delta S_D\right)$$
$$d_{t+\Delta t} = d_0 + (d_3 - d_0)\left(\frac{1-\exp(-cs_D m_D \Delta t)}{1-\exp(-3c)} + \left(\frac{d_t - d_0}{d_3 - d_0}\right)^{1/d} \exp(-cs_D m_D \Delta t)\right)^d$$

Modifications to the input and output sheets in VMAN to allow for spot spraying are as follows:

Tree sheet

A new input for annual rainfall (in mm) is required. This will only be used for the spot-spray treatment. As a default, we could use, say, 1200 mm.

Weed sheet

In the Weed Input Sheet, the following weed species should be added: "Grass/herbaceous". Perhaps rename "Weed species" to Weed Type" as grass isn't strictly a species? If the user chooses "Grass/herbaceous" as a weed type, this implies that spot spraying is the treatment type, and treatment and results sheets will require modifying. Also, all the other inputs and information on the weed sheet become redundant and should be deactivated.

Treatment sheet

If "Grass/herbaceous" has been selected in the weed sheet, the treatment sheet should be altered as follows. The sheet should be titled "Spot Spray Treatment". For both the test regime and reference regime, the user should be able to specify spot diameter and duration. There should be no other inputs on this sheet and the weed succession and mortality graph options should be removed. The model equations allow spot diameter to range between 0 m (unsprayed) and 4 m (weed-free). However, the best way to enter this may be to give the user several options, such as "Unsprayed", "1 m", "1.5 m", "2 m", and "Weed-free". The user should be able to choose only one of these options per treatment. Similarly, duration should be entered using, say, "0 years", "1 year", "2 years", "3 years", "Indefinite".

Results sheet

These sheets should remain unchanged except that weed height should be removed from the Heights sheet, and the Cover sheet should be removed.