HEXAZINONE USE FOR GRASS AND WOODY WEED CONTROL—EFFECTS ON ESTABLISHMENT AND LONG-TERM GROWTH OF *PINUS RADIATA* PLANTATIONS

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ABSTRACT

The herbicide hexazinone was applied in three trials to evaluate the effects of controlling grass, dolly bush (*Cassinia aculeata* R. Br), and woody weeds in *Pinus radiata* D.Don plantations. Control of grass on an ex-pasture site strip-sprayed with hexazinone at 2 kg a.i./ha significantly improved the survival and early height growth of *P. radiata*. Grass control was essential to the commercial viability of plantations on this site. Low tree survival on unsprayed plots resulted in poor stem form and heavy branching, as well as significantly reduced volume at age 16 years. On a dolly bush site, strip-spraying with hexazinone at 4 kg a.i./ha resulted in reduced weed growth and significantly higher tree volume growth at age 14 years compared with unsprayed or 2 kg treatments. On a series of sites with various woody and herbaceous weeds including eucalypts and acacias, strip-spraying with hexazinone at 3 kg a.i./ha prior to planting gave good control of weeds and provided significantly increased early tree height growth. In this trial, control of woody weeds resulted in a significant increase (about 30%) in volume of *P. radiata* at age 14 years. This increased volume growth meant that commercial thinning to release final-crop stems could be carried out at least 2 years earlier than on untreated stands.

Economic projections of the growth gains to the end of rotation indicate that the initial cost of herbicide treatment was economically justified on these sites.

Keywords: hexazinone; herbicide; grass; woody weeds; forest growth; weed competition; *Pinus radiata*.

INTRODUCTION

Vegetation such as grass and woody weeds may cause low survival and poor early growth of *Pinus radiata* owing to competition for light, water, and nutrients (Richardson 1991).

Broad-spectrum herbicides can be used to control weeds effectively in *P. radiata* plantations (Jack 1971; Flinn & Minko 1980) with little damage to *P. radiata* (Cromer 1973).

Various foliar and residual herbicides are used operationally in Australia to control a variety of weed species. On many sites effective weed control is provided by relatively low-cost applications of atrazine or mixtures of atrazine with amitrole or glyphosate (Neilsen 1990). For sites with more vigorous weed growth, hexazinone offers better knockdown and residual activity, but at a higher cost. Hexazinone is a water-soluble compound and is predominantly root-absorbed, with some foliar absorption. The concentration of hexazinone in the soil solution is reduced on heavy-textured soils because of increased adsorption on to soil colloids (Rhodes 1980) and higher rates of application are necessary to achieve good weed control (Baker *et al.* 1988). *Pinus radiata* is tolerant of hexazinone although lower application rates may be required to avoid toxicity to plants under moisture stress (Davis 1977) or on light-textured soils. Hexazinone requires moist soil at application, or rain following, and is most effective if plant growth is active and temperatures are warm. It has low mammalian toxicity.

Efficacy of hexazinone varies for sites, for weed species, with quantity applied, with the carrier medium, and with time of application (Eilert 1979; Fagg & Flinn 1983; Baker *et al.* 1988). Eilert (1979) obtained good control of grass, both before and after planting of *P. radiata*, resulting in increased survival and growth of trees. Fagg & Flinn (1983) found that a rate* of 3 kg was considerably more effective than 1.5 kg and that using oil improved effectiveness against *Acacia dealbata* Link but not against eucalypts. Baker *et al.* (1988) found that 2 kg gave good weed control and improved growth of *P. radiata* on two sites. However, on a sandy soil in a low rainfall zone, weed control did not improve with more than 4 kg while on a heavier soil in a moderate rainfall area weed control improved with up to 8 kg. Growth of *P. radiata* was related to the level of weed control.

Preliminary trials in Tasmania showed hexazinone at 3 kg gave good grass control and resulted in improved early growth of *P. radiata* (van Schie 1978). Balneaves & Christie (1988) presented data from four sites in New Zealand showing substantial increases in volume production of up to 71 m^3/ha in sprayed stands at ages 8 to 11 years. Projection of growth indicated an advantage of 100 m^3/ha for sprayed plots at harvest, and calculations showed that strip-spraying improved economic return. Because of high cost, plots with broadcast spraying gave a poorer economic return than unsprayed plots (Glass 1985).

Data on growth response beyond 11 years are limited. After a review of Australian and New Zealand studies, Richardson (1991) extrapolated growth gains of 10–115% at age 25 years and 8–107% at age 30 years. However, Zabkiewicz & Richardson (1990) concluded that, although economic returns can be very high, many operational strategies would not be cost-effective because of high treatment costs and insufficient growth gains.

In the current study, three trials were established to evaluate the effect of hexazinone on weed control and growth of *P. radiata* on sites dominated by either grass, dolly bush, or other woody weeds. Results for *P. radiata* survival and growth are presented up to time of first thinning at ages 14 to 16 years. These results were projected to the end of the rotation to evaluate the cost-effectiveness of using hexazinone on various sites.

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* All herbicide application rates are active ingredient per hectare

METHODS

General Methodology for all Trials

In all three trials hexazinone, as 90% water-soluble powder formulation, was mixed for spraying at a rate of 800 *l*/ha using a hand-pump Berchmeier knapsack. Plots were strip-sprayed with a spray width of 1.5 m centred on tree rows.

Tree growth of each plot was projected (Candy 1989) to rotation length of between 24 and 28 years and the economics of growing the plantation with and without weed control were determined. A discount rate of 5% was used and costs and returns for the economic study were those used in previous studies (Neilsen & Wilkinson 1990). Specific costs for hexazinone treatment including application were A$110/ha, $160/ha, and $210/ha for the 2, 3, and 4 kg rates respectively.

Analysis of variance was used to determine least significant differences for comparison of treatments where appropriate. Tukey's test for cross classification was used to analyse survival.

Trial 1: Effects of Hexazinone on Grass Control

The study area was an improved pasture site at Wilmot in north-west Tasmania. The soil was a kraznozem formed on Tertiary basalt. Annual rainfall of 1400 mm is evenly distributed throughout the year. Grass species present were perennial ryegrass (*Lolium perenne* L.), annual ryegrass (*L. rigidum* Gaud.), and couch grass (*Cynodon dactylon* (L.) Pers.).

The site was disced and mound-ploughed prior to planting with bare-root *P. radiata.* Shortly after planting, 235 g of fertiliser (11:5:0—N:P:K) was applied around each tree. Grass seeds germinated very soon after ploughing and the fertiliser promoted rapid grass growth. Treatments (0, 2, and 4 kg hexazinone) were applied 3 months after tree planting, by which time the grass was 10 to 30 cm tall and overtopping some pines.

There were three replicates of the three treatments. Plots were 12 × 18 m (0.022 ha) with about 25 trees per plot. Weed control was assessed and tree height measured for the first 2 years, and volume growth was measured at age 16 years, prior to thinning.

Trial 2: Effects of Hexazinone on the Control of Dolly Bush

The woody shrub dolly bush is a major problem in *P. radiata* plantations in many areas of northern Tasmania. The study area at China Bush in north-west Tasmania was an ex-native forest site with moderate annual rainfall of 1000 mm. The soil was a heavy podsol formed on Permian argillaceous sediments.

The site was ripped and mound-ploughed prior to planting with bare-root *P. radiata.* Treatments (0, 2, and 4 kg hexazinone) were applied before tree planting. Shortly after planting, 235 g of fertiliser (11:5:0—N:P:K) was applied around each tree.

There were three replicates of the three treatments. Plots were 12 × 12 m (0.015 ha) with about 20 trees per plot. Weed control was assessed and tree height measured for the first 3 years, and volume growth was assessed at age 15 years. After operational thinning at age 15 years, the volumes of thinned trees were estimated from stump measurements. During thinning every fifth row was removed and the remaining stand was thinned to leave a uniform

crop of trees. This regime did not optimise the silvicultural gain from weed control. Nevertheless, economic projection for this trial was carried out on the actual thinned plots.

Trial 3: Effects of Hexazinone on the Control of Woody Weeds

Eight study sites were selected on ex-native forest sites within four plantation areas. Weeds present in the four plantations are listed in Table 1. The sites were all of moderate annual rainfall (1000–1200 mm). Soils were yellow podsolics formed on Devonian-Silurian sediments.

TABLE 1–Weeds present at planting or growing after planting in the four plantation areas used in Trial 3

Site	Weeds	Cover and control
Retreat	*Leptospermum scoparium* *Haloragis* spp. *Acacia botrycephala* Desf. *Pultenaea gunnii* Benth. *Eucalyptus amygdalina* Labill.	Excellent control of weeds for 1 year with hexazinone. Heavy *Leptospermum* on the unsprayed areas.
Evercreech	*Senecio* spp. *Acacia dealbata* *Daviesia latifolia* *Lomatia tinctoria* R.Br. *Epacris* spp. *Pteridium esculentum* *Eucalyptus amygdalina*	Sparse cover at time of planting. Excellent early weed control with hexazinone.
Nicholas	*Poa* spp *Pultenaea juniperina* Labill. *Epacris* spp *Lomatia tinctoria* *Eucalyptus amygdalina*	Scattered cover of grass. Good early weed control with hexazinone.
Saddleback	*Lomatia* spp. *Pteridium esculentum* *Acacia dealbata* *Eucalyptus amygdalina*	Sparse cover at planting. Good weed control with hexazinone.

Productivity of these soils is low to moderate. After clearing, six of the sites were mound-ploughed and the other two, on a heavier soil, were ripped and mounded. Hexazinone at 0 and 3 kg was applied prior to planting of bare-root *P. radiata* seedlings. Fertiliser was applied shortly after planting (235 g of 11:5:0—N:P:K per tree), and again at about age 8 years (a 50:50 mixture of rock- and super-phosphate at 700 kg/ha).

There were two blocks of two replicates of the two treatments in each of four plantations, giving 32 plots in all. Plots were 12 × 12 m (0.015 ha) with about 20 trees per plot. Weed control was assessed and tree height measured for the first 3 years and volume growth was measured before plots were thinned to 300 stems/ha at age 14 years.

RESULTS

Trial 1: Effects of Hexazinone on Grass Control

Survival of pine seedlings

At age 2 years, survival of the unsprayed seedlings was an unacceptable 35% whereas for the sprayed plots it was significantly better at over 90% (Table 2).

TABLE 2–Survival at age 2 years of *P. radiata* seedlings planted on Trial 1, an ex-pasture site, with or without spraying with hexazinone

Treatment	Survival (%)
Unsprayed	35.3 a
Hexazinone 2 kg	97.3 b
Hexazinone 4 kg	90.7 b

Columns of identical letters indicate non-significant subsets

Weed control

Spraying with hexazinone, at 2 or 4 kg, effectively controlled the grass for 2 years, while the unsprayed plots continued to be overgrown by grass.

Early tree growth

At age 1 year, height of trees in plots sprayed with hexazinone at 2 kg was significantly greater than in 0 or 4 kg treatments. The poor height growth at the higher spray rate may indicate some phytotoxicity on this site, although any detrimental effect was short lived (Fig. 1a).

By age 2 years, tree height in both spray treatments was significantly ahead of that in the unsprayed treatment (Fig. 1a). Growth in the second year was significantly greater (covariate analysis) indicating a prolonged response to grass control.

Growth of trees at age 16 years

At age 16 years volume of trees in the plots treated with hexazinone at 2 or 4 kg was significantly greater ($p>0.01$) than in the unsprayed plots (465, 534, and 236 m^3/ha, respectively) (Table 3, Fig. 2a). Differences in volume were due almost entirely to poor survival on the unsprayed plots. On this productive site, form was generally poor and branches large, and this was exacerbated in the unsprayed plots by the low stocking. In selection for thinning to 250 final-crop trees/ha, large trees with poor branching in the sprayed plots would be removed to provide the best stand based on form and branch characteristics. In the unsprayed plots, low stocking necessitated the retention of some large, poor-quality trees but even so the plots were only 60% stocked. As a result, the mean diameter of retained crop trees in the unsprayed plots was higher than that in sprayed plots (Table 3) although potential sawlog quality would be substantially lower.

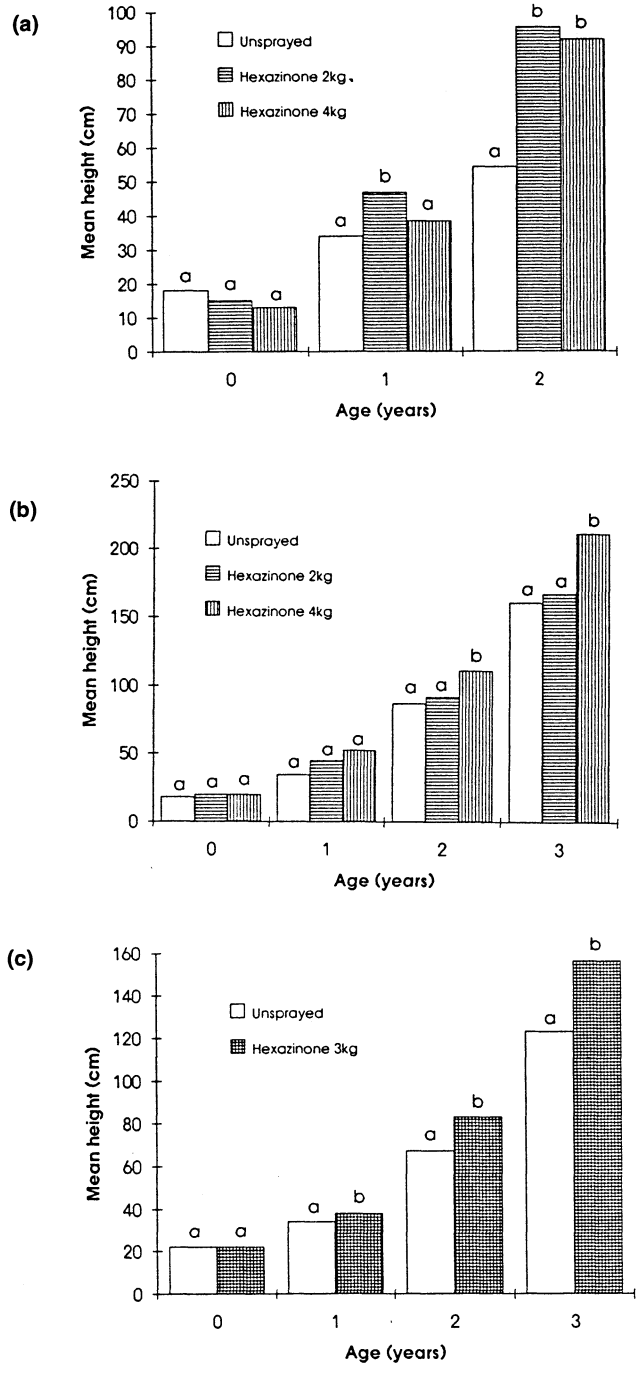

FIG. 1–Height growth (cm) to age 2 or 3 years for *P. radiata* seedlings planted on (a) ex-pasture site, (b) dolly bush site, or (c) woody weed site with or without spraying with hexazinone at planting (identical letters indicate non-significant subsets within each age class)

TABLE 3–Mean dominant height (MDH), volume, and mean diameter of trees retained as final-crop trees, at age 14 or 16 years for *P.radiata* untreated or treated with hexazinone at planting

Treatment	MDH (m)	Total volume (m^3/ha)	Thinning volume (m^3/ha)	Volume retained as final-crop trees (m^3/ha)	Mean diameter of retained trees (cm)
Ex-pasture site					
Unsprayed	22.3 a	236 a	142 a	94 a	34.1 a*
Hexazinone 2 kg	20.9 a	465 b	344 b	121 ab	30.0 a
Hexazinone 4 kg	23.5 a	534 b	394 b	141 b	31.6 a
Dolly bush site					
Unsprayed	20.5 a	205 a	123 a	82 a	26.1 a
Hexazinone 2 kg	19.9 a	171 a	103 a	68 a	24.2 a
Hexazinone 4 kg	22.3 a	271 b	184 b	87 a	26.9 a
Woody weed site†					
Unsprayed	18.0 a	148 a	84 a	64 a	20.9 a
Hexazinone	18.9 b	194 b	117 b	77 b	22.6 b

Columns of identical letters indicate non-significant subsets

* Unsprayed treatment plots are only 60% stocked after thinning

† For MDH, LSD = 0.6 m for this site

Trial 2: Effects of Hexazinone on the Control of Dolly Bush

Survival of pine seedlings

There was no effect of treatment on survival which averaged 95%.

Weed control

Hexazinone at 2 kg substantially reduced the amount of dolly bush and at 4 kg totally removed it from the planting area (Table 4). A reduction in bracken (*Pteridium esculentum* (Forst.f.) Cockayne) cover from 20% to 10% on the hexazinone-treated areas was not significant.

TABLE 4–Weed cover at age 1 year on plots of *P.radiata* seedlings with or without hexazinone applied for dolly bush control

Treatment	Weed cover
Unsprayed	30% dolly bush, 20% bracken, 5% flat weeds
Hexazinone 2 kg	10% dolly bush, 15% bracken, 5% flat weeds
Hexazinone 4 kg	10% bracken

Early tree growth

Hexazinone at 4 kg resulted in significantly greater tree height at age 3 years; height in plots treated with 2 kg was not significantly different from the unsprayed treatment (Fig. 1b).

Growth of trees at age 14 years

At age 14 years, the plots treated with hexazinone at 4 kg had significantly greater volume ($p>0.05$) than the unsprayed plots or plots treated with 2 kg (271, 205, and 171 m^3/ha respectively) (Table 3, Fig. 2b).

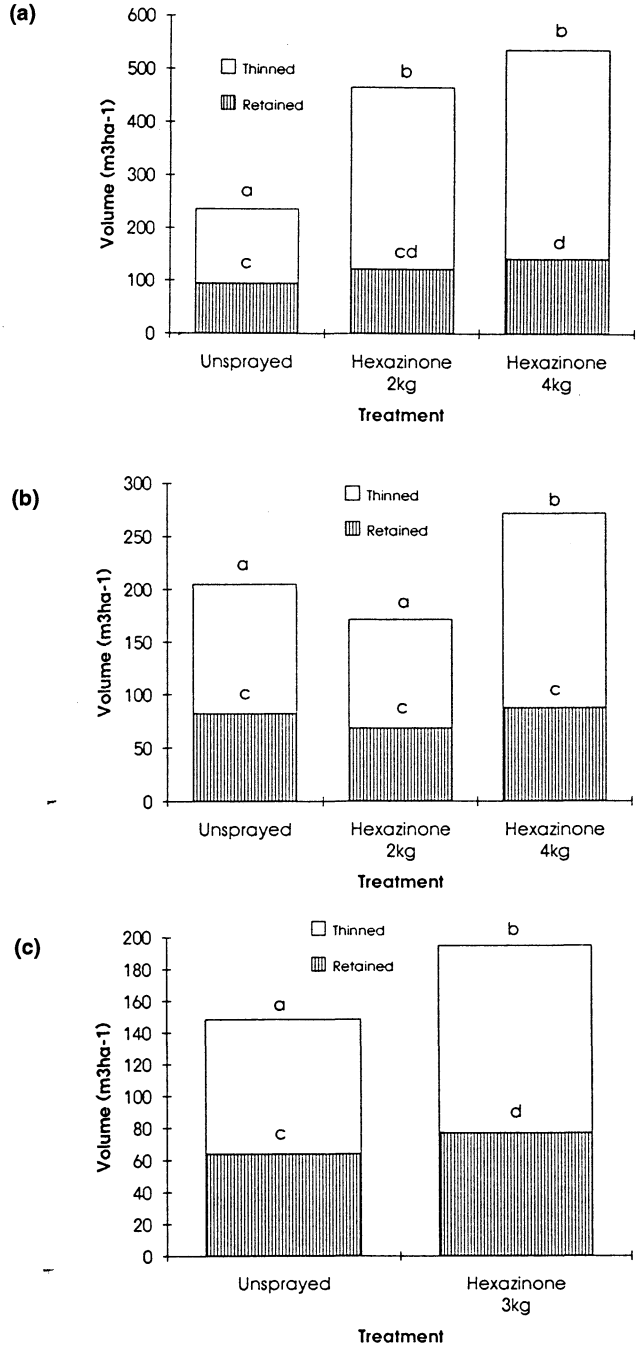

FIG. 2–Total, thinned and retained volume (m^3/ha) of *P. radiata* at time of thinning for *P. radiata* planted on (a) ex-pasture site (age 16 years), (b) dolly bush site (age 14 years), or (c) woody weed site (age 14 years) with or without spraying with hexazinone at planting (identical letters indicate non-significant subsets within each volume class)

Trial 3: Effects of Hexazinone on the Control of Woody Weeds

Although growth varied between sites, there were consistent treatment effects.

Survival of pine seedlings

There was no effect of treatment on survival which averaged 95%.

Weed control

Few weeds were present on hexazinone-treated plots at age 1 year, but weed cover had re-established in untreated plots (Table 1). Hexazinone gave good control of weeds such as tea-tree (*Leptospermum scoparium* Forst.), *Acacia* spp., and *Davesia latifolia* R.Br. which are difficult to control with other herbicides.

Early tree growth

In the first 3 years there was a significant response to herbicide treatment. Over this period, height growth differences continued to increase (Fig. 1c).

Growth of trees at age 14 years

At age 14 years the hexazinone-treated plots had significantly greater volume ($p>0.001$) than the unsprayed plots (194.6 m^3/ha compared to 148.4 m^3/ha) (Table 3, Fig. 2c). Mean Dominant Height was also significantly greater for the hexazinone treatment, indicating a continuation of the early height advantage.

Projection of Tree Growth and Economics of Weed Control

The growth advantage provided by the appropriate hexazinone treatment was substantial in all three trials at tree ages 14 and 16 years.

In Trial 1, improved survival in sprayed plots resulted in greater thinning volume and a fully stocked final stand after thinning. Projection of volume growth to rotation length (24 years for the treated and 27 years for the unsprayed plots) gave a substantially higher volume production for the sprayed plots. Economic evaluation showed improved performance with hexazinone treatment (Table 5).

TABLE 5–Change in economic parameters, nett present value (NPV), and return on investment at rotation age, for plots of *P.radiata* sprayed with hexazinone at planting compared with unsprayed plots*

Trial	Strip spraying NPV (A$)	Broadcast spraying NPV (A$)†	Strip spraying Return on investment (%)
Ex-pasture site	+840	+730	+43
Dolly bush site	+67	–57	+10
Woody weed site	+300	+177	+15

* Projected to final-crop felling, at ages 25 to 27 years, from data at thinning at age 14 or 16 years

† Calculated for extra herbicide cost and assuming equivalent growth gains for strip-spraying

In Trial 2, the growth advantage due to the 4 kg hexazinone treatment was just over 3 years at tree age 14 years. Poor tree selection during routine thinning of these stands resulted in much of this advantage being lost through the removal of large trees from the sprayed plots. Economic advantage was due largely to increased thinning volume, with some advantage of a slight reduction in rotation on the plots sprayed with 4 kg hexazinone (Table 5).

In Trial 3, the growth advantage was just over 2 years at tree age 14 years. Projection of volume growth to rotation length indicated that this would increase to more than 3 years (Candy 1989). Economic evaluation indicated improved performance with hexazinone treatment (Table 5).

DISCUSSION

Poor survival and suppression of growth of *P. radiata* in unsprayed plots at Wilmot were due to heavy competition from grass. Survival rate without spraying was unacceptable at 35%. With post-planting hexazinone spraying at 2 kg, survival and early growth were good and the plantation was successfully established. Achievement of 100% greater volume at age 16 years in sprayed plots on this highly productive site resulted in a substantial economic advantage. Trees in the unsprayed plots had very large branches and poorer form which would further reduce the economic return.

Woody shrubs such as dolly bush are more difficult to control. At 1 year after spraying with hexazinone at 2 kg, the density of dolly bush and other weeds was reduced from 55% ground cover to 30% (Table 4) but this level of control did not improve the growth of *P. radiata.* Hexazinone at 4 kg reduced weed cover to 10% and resulted in significantly increased early seedling growth. These results confirm that a moderate increase in weed cover can have a substantial effect on tree growth. Nambiar & Zed (1980) found that on dry sites even a 5–10% increase in weed cover resulted in reduction of *P. radiata* growth through water stress. By age 14 years the plots sprayed with 4 kg had 30% more volume than the unsprayed plots, resulting in a projection of reasonable economic advantage. The full advantage of weed control was not realised in practice because of poor selection of final-crop trees in the routine operation. As the final crop provides the major economic return, removal of large trees of good form at thinning will result in a prolonged rotation and substantially reduced economic return.

Use of hexazinone at 3 kg on the woody weed sites resulted in good weed control and improved early tree growth. In these trials weed control using hexazinone at planting resulted in a 30% increase in volume at age 14 years. Commercially viable thinning was feasible for the treated plots, yielding 117.6 m^3/ha, while for the unsprayed plots at least 2 more years of growth were required (Fig. 2c). Final-crop trees in the treated plot had an advantage of about 1.7 cm in diameter (Table 3) and a total of 13 m^3/ha more volume. After thinning, the advantage of 2 years over trees from the unsprayed plots is projected to increase to more than 3 years by clearfelling age.

In all three trials, hexazinone treatments which controlled weeds gave a clear economic advantage. The results indicate that growth gains from weed control persist to at least first thinning age of 14 to 16 years, particularly where initial survival without weed control is very low. Where survival is not a problem, weed control can still provide significant growth gains, although the economic advantage must be off-set against the cost of herbicide treatment.

In the current trials the control of dolly bush was economically justified with strip-spraying of hexazinone at 4 kg, but the additional cost for broadcast-spraying would not have been economic. In contrast, the control of woody weeds with hexazinone at 3 kg was economic using costs for either strip or broadcast application, although the economic return calculated for broadcast-spraying would be lower. These analyses assume that an equivalent growth gain will be obtained from either strip- or broadcast-application but this may not be so. For grasses and herbaceous weeds, spot application is much more cost-effective than more extensive treatments (Davenhill *et al.* 1991). For woody weeds a larger initial control area may be required to restrict growth until tree canopies have gained reasonable control of the site. Wilkinson & Neilsen (1990) found that strip-spraying with atrazine allowed vigorous, large-crowned species such as *Eucalyptus nitens* (Dean & Maiden) Maiden to rapidly dominate the site and suppress weed growth. *Pinus radiata,* with slower initial growth and different crown architecture, may be more sensitive to early competition from woody weeds. Experience in Tasmania indicates that *P. radiata* is severely retarded by prolific regrowth of *Acacia* spp. Broadcast-spraying with hexazinone is routine for such sites (Neilsen 1990).

On sites with woody weeds, weed control may provide further financial benefits in the form of improved access for silvicultural operations and reduced fire hazard. Without weed control, costs for thinning and pruning may be up to 67% higher (Zabkiewicz & Richardson 1990). In Tasmania, inter-row clearing of woody weeds with small bulldozers has been necessary on some sites to provide access for pruning operations at about age 5 years. This increases costs by A$120/ha. It is clear that weed control regimes will vary from site to site, depending upon expected weed growth, cost of treatment, and likely benefits in terms of increased tree survival, increased growth, reduced rotation length, or reduced costs of subsequent silvicultural treatments.

CONCLUSIONS

Hexazinone at rates between 2 and 4 kg effectively controlled grass, dolly bush, and woody weeds on a number of sites planted with *P. radiata.* On a grass site, poor survival of tree seedlings in the absence of weed control made herbicide application essential. For sites dominated by woody weeds, significant tree growth gains were obtained with the use of hexazinone at 3 kg.

Volume growth gains from weed control treatments persisted to at least age 14 to 16 years, resulting in substantial economic advantage.

The current study indicates that strip application of hexazinone is economically justified at rates of 2 kg on grass sites, 3 kg on woody weed sites, and 4 kg on dolly bush sites.

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