WEED CONTROL AND LARGE BARE-ROOT STOCK IMPROVE EARLY GROWTH OF *PINUS RADIATA* IN SOUTH AFRICA

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ABSTRACT

Survival and early growth of two grades of bare-root *Pinus radiata* D. Don seedlings were studied in response to soil cultivation (augering, disking, pitting, or ripping) combined with standard or intensive weed control. Soil tillage after clearfelling did not improve volume yields but did increase establishment costs. Overall, intensive weed control improved fourth-year volume per hectare by 108%. Planting Grade A seedlings (4.1 mm average root-collar diameter) instead of Grade B seedlings (2.8 mm average root-collar diameter) brought about a 36% increase in volume per hectare. For the pitting treatment, the unit cost of the additional volume produced by planting Grade A stock was approximately US\$7/m^3 compared to \$10/m^3 for the additional volume resulting from intensive weed control. This study suggests that planting larger diameter seedlings and allowing 1500 kg competing biomass/ha (1 year after planting) may be ecologically more advantageous and economically equivalent to planting small grade seedlings and total eradication of vegetation cover.

Keywords: seedling quality; seedling grade; site preparation; soil cultivation; herbicides; costs.

INTRODUCTION

Pinus radiata is used for timber production in South Africa but planting of this species has been restricted due to diplodia (*Sphaeropsis sapinea* (Fries) Dyko & Sutton) attacks after hail damage (Swart *et al.* 1985; Lindquist 1987) and adverse soil properties of some sites (Grey 1989). *Pinus radiata* is planted mainly in the Cape forest regions, where competing vegetation consists of fynbos (1–3 m tall sclerophyllous shrubland).

For a long time it was believed that *P. radiata* would give good growth and timber yield when planted amongst fynbos vegetation (Donald 1971). More recent studies, however, revealed that reducing fynbos vegetation can increase survival and early growth (Zwolinski, Donald & Groenewald 1993; Zwolinski *et al.* 1994). After harvesting, re-establishment of exotic plantations is usually impeded by fast natural regeneration of competing vegetation. Immediate regeneration goals can be achieved by vegetation control or planting large-diameter stock (Stubbings 1958; McMinn 1982; Albert *et al.* 1980; Balneaves 1989; Baker & Ledgard 1991; South, Mitchell, Zutter, Balneaves, Barber, Nelson & Zwolinski 1993). Suppression of vegetation for maximum tree growth can be costly (Miller *et al.* 1995; South *et al.* 1995). In some areas, nursery production of large-diameter seedlings is increasing as herbicide use declines (Perreault *et al.* 1993). Apart from implications for the preservation of indigenous vegetation, the prolonged suppression of plant cover can have a harmful ecological impact on long-term site quality (e.g., losses of soil and nutrients). Therefore, allowing a moderate level of weed cover and planting large-diameter seedlings may be an attractive alternative.

In South Africa, size recommendations for bare-root stock have traditionally been restricted to seedling height and have generally ignored root collar diameter (RCD). Planting of seedlings shorter than 30 cm has been recommended (Denison 1981; Wessels 1987; Hinze 1994). It was believed that small planting stock can yield maximum growth, provided the seedlings survive and are not suppressed by adjacent plants (Donald 1986). Recently, intensive weed control and planting seedlings thicker than 4 mm at root collar have proved cost effective (South, Zwolinski & Donald 1993).

The objectives of this study were to (i) determine tree performance at 4 years of age for 16 regeneration treatments, (ii) compare the cost-effectiveness of these establishment methods, and (iii) evaluate the optimal vegetation cover for two seedling grades based on the relationships between vegetation cover, tree performance, and regeneration costs.

METHODS

In 1989, a study was established at Blueliliesbush State Forest (34°01'S, 24°01E', 200 m above sea level) in South Africa after the first rotation of *P. pinaster* Ait. was clearfelled. The experimental area has uniform topography with 0.5° southern slope. The hydromorphic "duplex" soils are poorly drained and highly leached, with low phosphorus content. The topsoils are very fine-textured silt loam, grading into loam or silt loam at 40 cm depth and with abrupt transition to a gleyed yellow clay at approximately 80 cm depth. The soils were classified as a Kroonstad-Oakleaf intergrade which is equivalent to ochric planosol in the Food and Agricultural Organisation of the United Nations classification (MacVicar *et al.* 1977). A detailed description of the geomorphology and pedology of the region has been provided by Grey *et al.* (1987). The competing vegetation of the area consisted mainly of fynbos species. This vegetation changed rapidly in response to the clearfelling and site preparation (Zwolinski & Donald 1995). The number of species recorded 6 months after harvesting increased by 72%, i.e., from 46 under the pine canopy to 79 in the harvested field. Before treatment application, the vegetation was relatively uniform.

In November 1988, seeds were sown in four drills which were spaced 15 cm apart. Final bed density was 160 seedlings/m^2 so seedlings were spaced about 4.2 cm apart within the row. In September 1989, seedlings appeared healthy and had well-established mycorrhizas. Numerous *Rhizopogon* sp. fruiting bodies were present in the seedbed.

A split-split-plot design was used to compare four methods of soil cultivation (augering, disking, pitting, and ripping) applied to whole plots, two levels of weed control (subplots), and two morphological grades of bare-root seedlings (sub-subplots). Planting pits (45 cm diameter) were either made by hand to 20 cm depth (pitting) or were made with a two-man earth auger (augering) to 40 cm depth. Ripping, to a depth of 60 cm, was done with a one-tooth subsoiler after the post-harvest slash had been removed. The most intensive treatment involved slash removal, mechanical destumping, ripping, and 25-cm-deep disk-plowing with a three-disk plough followed by a disk harrow (both mounted on a 4×4 tractor). Weed control treatments involved either slashing and pulling of weeds to prevent overtopping of the planted trees (standard weed control) or repetitive use of glyphosate and hexazinone supplemented by hand weeding (intensive weed control). The morphological grades of the planting stock included seedlings 25 to 31 cm in height (Grade A seedlings; mean height = 27.2 cm, SD = 0.18; mean RCD = 4.1 mm, SD = 0.08) and 14 to 20 cm in height (Grade B seedlings; mean height = 18.4 cm, SD=0.22; mean RCD = 2.8 mm, SD = 0.06). On 26 September 1989, each of the 62 plots was planted with 10 × 10 trees (49 measurement trees) spaced 2.7 m apart (1372 trees/ha). Each tree was treated with 208 g superphosphate (10.5% P) at planting (30 kg P/ha). In total, four replications were established on 4.67 ha.

The following costs (US$/ha) were estimated for specific treatment combinations: $270 for augering and standard weed control, $481 for augering and intensive weed control, $534 for disking and standard weed control, $673 for disking and intensive weed control, $236 for pitting and standard weed control, $447 for pitting and intensive weed control, $322 for ripping and standard weed control, and $533 for ripping and intensive weed control. The costs of seedlings and planting (assuming 9% higher planting costs for Grade A seedlings) were $71/ha for the small grade and $132/ha for the larger grade. Cost estimates of specific operations have been discussed by South, Zwolinski & Donald (1993).

Ground line diameters (GLD) and heights (H) were measured 4 years after planting. The following conic volume index (tree volume) was calculated on each tree:

$$\text{conic volume} = 0.2618 \times \text{GLD}^2 \times \text{H}$$

Total volume (m^3) per hectare was calculated as

$$1372 \times \text{survival \%} \times \text{average conic volume.}$$

The competing vegetation was assessed at five random points in each subplot before site preparation, at planting, and 1 year after planting. Percentage vegetation cover and height were estimated within the 1-m^2 circular plots, and dry biomass was defined by harvesting all above-ground vegetation from 0.25-m^2 sampling plots. Details regarding establishment of the experiment and sampling schedules have been provided by Zwolinski (1992).

The data were subjected to an analysis of variance. Means for specific treatment levels were separated with Tukey's HSD. Relationships between different amounts of vegetation cover and tree growth or regeneration costs were studied with linear regression analysis (SAS 1985).

RESULTS AND DISCUSSION

Survival of Trees

Survival was improved only by using a higher grade of planting stock (Table 1). The 12% improvement in survival of Grade A seedlings (Table 2) was important because 68% survival of the Grade B plants would require follow-up treatments according to regional practice. Supplemental planting (blanking or beating up) can occur when survival is less than 80%

TABLE 1–ANOVA table for *Pinus radiata* performance 4 years after planting.

Factor	df	Survival	Height	GLD	Conic volume per tree	Conic volume per ha
		F-value				
Blocks	3	1.6	0.9	0.6	0.8	1.7
Cultivation (C)	3	2.5	2.6	0.6	1.2	1.6
[Error mean square	9	0.02	3164.7	1.3	29.1	62.8]
Weed control (W)	1	0.2	170.9***	330.3***	485.4***	202.3***
C × W	3	1.9	7.7**	8.3**	16.4***	2.4
[Error mean square	12	0.004	952.7	0.7	10.5	23.4]
Seedling grade (S)	1	16.1***	25.8***	8.3**	6.2*	39.7***
C × S	3	0.7	0.7	0.1	0.1	1.2
W × S	1	0.1	2.2	1.2	0.3	0.3
C × W × S	3	0.7	0.3	0.3	0.2	0.2
[Error mean square	24	0.02	886.3	1.0	26.2	21.5]

* significant at the 5% level
** significant at the 1% level
*** significant at the 0.1% level.

TABLE 2–Performance of *Pinus radiata* at 4 years after planting for the main effects and the interaction between soil cultivation and weed control.

Treatment	Survival (%)	Height (cm)	GLD† (cm)	Conic volume dm³/tree	Conic volume m³/ha
Soil cultivation					
Augering	69	499	11.7	21.6	20.4
Disking	78	530	12.2	23.2	24.8
Pitting	70	515	12.3	25.0	23.9
Ripping	78	555	12.3	24.5	26.4
Weed control					
Standard	75	477	10.3	15.0	15.5
Intensive	73	576	14.0	32.3	32.3
Seedling grade					
A (4.1 mm)	80	545	12.5	25.1	27.5
B (2.8 mm)	68	504	11.7	21.8	20.3
Interactions					
Augering*standard	72	436	9.5	11.3	11.1
Augering*intensive	67	567	14.1	32.7	29.9
Disking*standard	76	502	10.7	17.3	18.1
Disking*intensive	77	557	13.5	28.8	30.2
Pitting*standard	73	447	9.9	13.3	13.7
Pitting*intensive	68	587	14.9	37.5	34.7
Ripping*standard	79	518	10.8	17.8	19.2
Ripping*intensive	81	593	13.7	31.1	34.5

† GLD = ground-line diameter

(even though Donald and others (1988) have suggested that this practice has no economic justification). In addition, inadequate stocking may result in rapid spread of certain invasive weed species, causing depreciation in site quality and accessibility (De Ronde & Bredenkamp

1984). In contrast to the initial results (Zwolinski 1992; South, Zwolinski & Donald 1993), there was no significant soil cultivation–weed control interaction for fourth-year survival.

Growth of Trees

There was an interaction between weed control and soil cultivation (Table 1). Where intensive weed control was applied, growth was not improved with any mechanical soil cultivation treatment (Table 2). Unexpectedly, augering yielded lowest height, ground-line diameter, and survival (Table 2). This can be explained by an alteration of physical soil properties. The soil structure was disrupted with the mechanical auger, and this caused a dramatic decrease in soil pressure resistance (Zwolinski, Donald & van Laar 1993). The amplitude of this change was higher for augering than for any other soil treatment. We assume that the rapid reduction in soil resistance created unfavourable conditions for initial root growth.

Overall, intensive weed control more than doubled conic tree volume or volume per hectare. The difference was most evident for augering and pitting because disking or ripping resulted in some mechanical suppression of vegetation. Ripping with intensive weed control yielded the best height growth, but pitting with intensive weed control produced the greatest ground-line diameter and conic volume.

Seedling grade affected all of the tree characteristics studied. After 4 years in the field, Grade A seedlings were 8% taller and 7% thicker than Grade B seedlings. Planting Grade A seedlings improved the per tree and per hectare volumes by 15% and 36%, respectively.

Cost-benefit Comparison

Regeneration costs for various treatment combinations were plotted against fourth-year volume per hectare (Fig. 1). Mechanical soil cultivation treatments (augering, pitting, or disking) simply increased costs without improving volume growth, and only investing in intensive weed control or higher grade seedlings resulted in significantly higher volumes (Table 1). If the direct effects from augering, disking, or ripping are only short-term (4 years or less), then for this site, it appears these mechanical treatments would not be economically justified. This supports the general belief in South Africa that complete site preparation (ploughing and disking to a depth of 25 cm) is seldom required for pines, especially on second-rotation sites (Hinze 1994).

Ripping and disking cause some suppression of vegetation, and so any growth gains from these mechanical treatments may have been due to a reduction in competition instead of soil amelioration. Therefore, an economic comparison was done exclusively for hand pitting where the effects of soil cultivation were limited (Table 3). At 4 years of age, the volume gain from intensive weed control was 20 to 23 m^3/ha. In contrast, there was an 8 to 11 m^3/ha gain for planting Grade A seedlings rather than smaller seedlings. Although the fourth-year volume gain was doubled, the additional cost of applying intensive weed control was 3.4 times that of growing and planting larger diameter seedlings (i.e., \$211/ha more for weed control *v.* \$61/ha more for Grade A seedlings). Therefore, a gain of 1m^3 at year 4 cost an additional \$6 to\$8 when using larger grade seedlings, compared with an additional \$9 to \$11 for applying intensive weed control. As the stand ages, there is no doubt these relationships will also change. However, to be equally cost-effective, the additional harvested value from

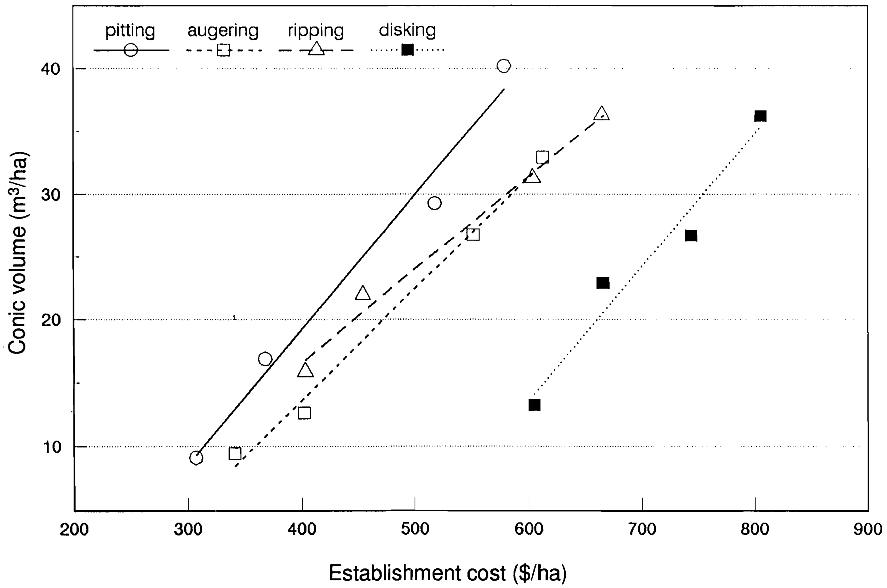

FIG. 1–The relationship between establishment costs ($/ha) of various weed control and seedling grade combinations and conic volume per hectare at year 4 for different soil cultivation treatments. Each point represents a seedling grade/weed control treatment combination (for each line, the combination of grade A seedlings with extra weeding is the highest cost; grade B seedlings with extra weeding is next highest cost; and grade B seedlings with no extra weeding is the lowest cost).

TABLE 3–Conic volume, regeneration costs (7% interest rate), and unit costs when planting Grade A or B seedlings with or without intensive weed control (pitting treatment only).

Treatment	Volume (m^3/ha)	Costs ($/ha) at age 0 yr	Costs ($/ha) at age 4 yr	Unit cost at 4 yrs ($/$m^3$)
Pitting + Grade B seedlings	9.1	307	402	44.17
Pitting + Grade A seedlings	16.9	368	482	28.54
Pitting + intensive weed control + Grade B seedlings	29.3	518	679	23.17
Pitting + intensive weed control + Grade A seedlings	40.2	579	759	18.88

the intensive weed control treatment will need to be 3.4 times that of the gain from planting larger diameter seedlings.

Weed Cover—Tree Growth Relationship

Although the experimental site was relatively homogeneous, some micro-site differences in vegetation existed prior to treatment. One year after planting, the above-ground dry biomass of the vegetation ranged from 56 to 2641 kg/ha depending on site preparation. The range in vegetation increased after treatment due to both chemical and mechanical suppression of the vegetation. An attempt was made to model the relationship between vegetation cover and tree performance. In addition, the cost of suppressing vegetation was also examined in hopes of defining an economic optimal level of vegetation cover.

As expected, the slopes of the relationships between vegetation cover and tree performance or regeneration costs were negative for both seedling grades (Table 4). This indicates that both tree growth and regeneration costs increased as competing vegetation was decreased. However, Grade A seedlings outperformed Grade B seedlings under any weed cover (within the tested biomass range). When total volume per hectare was examined for the pitting treatment (Fig. 2A), the largest difference between the two grades was observed for low vegetation cover. Therefore, even if effective weed control greatly improved growth of smaller stock, the total volume production of large seedlings was substantially improved. To achieve an equivalent cost of $20/m^3, Grade A seedlings could compete with 1500 kg weed biomass/ha while Grade B seedlings would require almost complete weed suppression (Fig. 2B).

TABLE 4—Parameter estimates and summary statistics for linear relationships between vegetation dry mass (tons/ha) 1 year after planting (independent variable) and tree performance at 4 years of age or regeneration costs, separately for large and small planting stock (32 observations for each seedling grade)

Seedling grade	Dependent variable (unit)	Parameter estimate		R^2	Probability level
		Intercept	Slope		
A	Height (cm)	584	–47	0.56	0.0001
	GLD* (cm)	13.9	–1.6	0.57	0.0001
	Tree volume (dm^3)	32.1	–7.5	0.57	0.0001
	Total volume (m^3/ha)	35.2	–8.4	0.57	0.0001
	Costs ($/ha)	673	–114	0.64	0.0001
B	Height (cm)	548	–49	0.45	0.0001
	GLD (cm)	13.3	–1.7	0.49	0.0001
	Tree volume (dm^3)	28.8	–7.4	0.46	0.0001
	Total volume (m^3/ha)	26.2	–6.5	0.41	0.0001
	Costs ($/ha)	612	–114	0.64	0.0001

* GLD = ground-line diameter

CONCLUSIONS

Intensive weed control and planting Grade A seedlings improved fourth-year volume per hectare. Over a half of the volume improvement from planting larger diameter seedlings resulted from better survival. The cost per unit volume gain from additional weed control was slightly higher than for an investment made on purchase and planting of large diameter seedlings. The per unit costs for volume production by planting Grade B seedlings at no competition (100 kg vegetation mass/ha) were the same as growing Grade A seedlings at 1500 kg vegetation cover/ha. This site-specific study suggested that Grade A seedlings require less early weed control to achieve the same level of volume production (age 4).

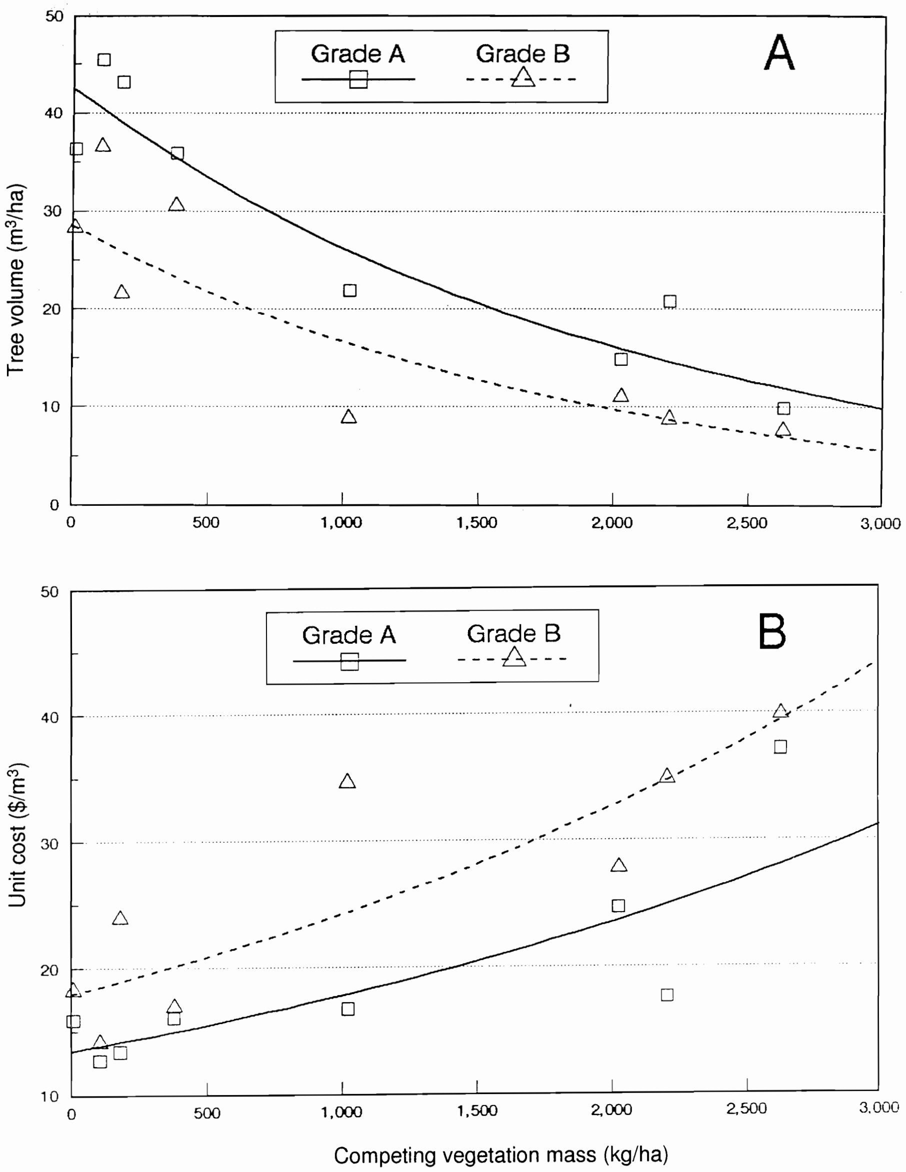

FIG. 2–The relationship between competing vegetation cover and seedling grade for (A) conic tree volume per hectare, and (B) production cost per cubic metre at age 4 (each point represents a plot mean).

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