Integration of nursery practices and vegetation management: economic and biological potential for improving regeneration[1]

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Researchers in New Zealand, Scotland, South Africa, Texas, and Alabama provided data on growth responses owing to nursery management practices and weed control after outplanting. Nursery treatments included nitrogen fertilization (0 vs. 168 kg/ha), seedling grades (small-diameter vs. large-diameter seedlings), and a comparison of stock types. Weed-control treatments varied by study and included broadcast and spot applications. Interactions between nursery practices and weed control were examined. Regardless of location, growth (2–8 years after planting) was increased as seedling diameter increased. Practices that increase average seedling diameter in the nursery are typically less costly than silvicultural practices required to obtain similar growth responses from small-diameter stock. Although interactions were observed among sites, stock size, and intensity of weed control, large-diameter stock consistently grew better than small-diameter stock regardless of site or site-preparation method. Thus, increasing the investment of regeneration expenditures at the nursery, relative to that put into site preparation, will substantially improve financial returns on investment. Further research needs in this area are also discussed.

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Des chercheurs de la Nouvelle-Zélande, de l'Écosse, de l'Afrique du Sud, du Texas et de l'Alabama ont fourni des données sur les réactions de croissance associées aux pratiques de gestion en pépinière et de répression de la végétation après transplantation. Les pratiques en pépinière incluent la fertilisation azotée (0 vs. 168 kg/ha), la qualité des semis (semis de petit diamètre vs. de grand diamètre) et une comparaison des types de plants. Les traitements de répression de la végétation variaient selon les études et incluaient des applications locales et des traitements en plein. Les interactions entre les pratiques en pépinière et la répression de la végétation ont été examinées. Peu importe l'endroit, la croissance (2–8 ans après la plantation) a été augmentée lorsque le diamètre des semis augmentait. Les pratiques qui augmentent le diamètre moyen des semis en pépinière sont typiquement moins coûteuses que les pratiques sylvicoles requises pour obtenir des réactions semblables à partir de semis de petites dimensions. Bien que des interactions aient été observées entre les stations, la taille des semis et l'intensité de la répression de la végétation, les semis de fortes dimensions croissaient mieux que les semis de petites dimensions, peu importe la station on le type de préparation de terrain. Ainsi, l'augmentation de l'investissement dans les dépenses de régénération à la pépinière, comparativement à celui effectué dans la préparation du sol, va substantiellement améliorer les retours financiers sur l'investissement. Les besoins de recherches supplémentaires dans ce domaine sont aussi discutés.

[Traduit par la rédaction]

Introduction

Considerable effort has been applied to develop nursery practices that increase seedling performance after outplanting. Likewise, much silvicultural research is aimed at improving plantation establishment and early stand growth. Although the potential gains from optimizing regeneration practices have been discussed (Gordon and Duryea 1985), only a few studies have determined if interactions exist between seedling grade and silvicultural practices. Such studies are needed to determine the benefit:cost ratios of component regeneration practices.

Several researchers have investigated potential interactions among seedling grade and weed control (Albert et al. 1980;

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South and Barnett 1986; Balneaves 1989; Nelson 1990) but few have reported the relative costs of herbicide applications and production of large-diameter seedlings (Mitchell et al. 1988). Woodlands managers require regeneration practices to be cost effective and define successful regeneration in terms of economic returns on the investment. Maximum volume production does not necessarily equate to maximum return on investment. The goal of many woodland managers is to optimize wood production while keeping the unit cost of wood production low (Crutchfield 1991). Efficiently spending a limited regeneration budget requires a basic understanding of important biological interactions. Unfortunately, researchers in the past have usually concentrated on main effects.

This paper reviews studies from Scotland (Nelson 1990) and New Zealand (Balneaves 1989) where interactions between stock size and herbaceous weed control have been examined. Unreported data from similar studies in the United States (Zutter et al. 1986; South and Barnett 1986; Barber et al. 1991) and South Africa (Zwolinski 1992) are also presented. In addition to examining growth gains, this paper examines the relative cost.

Scotland

Materials and methods

The relative importance of stock size, weed control for 5 years, and deer exclosures on survival and height growth of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) was examined on three uncultivated sites in Scotland (Nelson 1990). Although survival and heights at age 6 years were reported, costs of fencing, weed control, and seedlings were not mentioned. Therefore, for the purpose of this paper, herbicide costs are estimated to be: glyphosate, \$11/L; propyzamide, \$96/kg active ingredient (a.i.); and paraquat, \$7/L. The application cost was estimated at \$75/ha. The site at the Kershope Forest had four herbicide applications totaling 6 L/ha of glyphosate and 1.5 kg a.i./ha of propyzamide (total discounted cost of \$468/ha). The site on the Huntly Forest had three herbicide applications and used a total of 2 L/ha of glyphosate and 3 kg a.i./ha of propyzamide (total discounted cost of \$505/ha). The Glenbranter site had seven herbicide applications with a total of 13.5 L/ha of glyphosate, 3 kg a.i./ha of propyzamide and 5 L/ha of paraquat (total discounted cost of \$843/ha).

The 1.5+1.5 stock (1.5 year seedbed + 1.5 year transplant bed) was graded into two height classes (less than or greater than 23 cm). The 9- to 22-cm stock is valued at \$120/1000; the 25- to 31-cm stock is valued at \$130/1000 (Crabtree and Cumming 1989) and can cost \$8/1000 more to handle (Dauncy 1989). For purposes of this paper, it will be assumed that 2500 trees per hectare (TPH) were planted. Diameters were not measured at age 6 and therefore a survival–height index was calculated by multiplying percent survival by mean height. Treatment values used for survival and height are represented by the mean of fenced and unfenced treatments.

Results

Herbicide treatments were deliberately excessive for experimental purposes (operational applications are not broadcast and weed control is not intended to last for 5 years). Survival of the short stock with no weed control ranged from 34% (Huntly), to 63% (Kershope) and 76% (Glenbranter). Use of herbicides increased survival of short stock to 66, 92, and 87%, respectively. However, at the Glenbranter and Huntly sites, survival of taller transplants was high (89–93%) regardless of the degree of competition; thus, use of herbicides did not improve survival with larger stock. Therefore, the need to use herbicides to increase seedling survival is greatest when using poor quality stock. When using the taller stock, use of herbicides improved survival only at the Kershope site (60% without herbicides; 87% with herbicides) where grass cover was well established, tall, and vigorous at time of planting.

Without weed control, 6-year heights of the short and tall stock averaged 97 and 140 cm, respectively. Weed control increased heights to 123 cm for the short stock and 164 cm for the tall stock. At the Glenbranter site, the height of the tall stock without herbicides (142 cm) was about the same as short stock with herbicides (145 cm). At the Huntly site, the height of the tall stock without herbicides (150 cm) was twice that of the short stock with herbicides (75 cm).

When evaluating survival and height together with a survival–height index (Fig. 1), it is apparent that, at the Glenbranter site, the additional investment of \$45/ha in taller transplants (25 vs. 15 cm) produced as much additional growth by age 6 as an additional \$843/ha investment in weed control for short transplants. At the Huntly site, the gain from the additional \$45/ha investment in 31-cm transplants is more than twice that from an additional \$505/ha investment in herbicides to improve growth of 9-cm transplants. Only at the Kershope site, where grass competition was well established at planting, did a \$468/ha investment in weed control with 22-cm transplants result in greater growth than a \$45/ha investment in 30-cm transplants. It is apparent that, with Sitka spruce, stock size and intensive use of herbicides are partly (Kershope) or wholly (Glenbranter and Huntly) exchangeable.

Texas

Materials and methods

A nursery trial investigating different levels of nitrogen fertilization was established with loblolly pine (*Pinus taeda* L.) at the Indian Mound Nursery near Alto, Tex. (Barber et al. 1991). Although nine different nitrogen fertilization treatments were used in the nursery, only two are considered here: (*i*) no nitrogen fertilization; and (*ii*) 168 kg/ha applied with increasing rates (starting with 5 kg/ha in June and ending with 86 kg/ha in August). The 1+0 seedlings were outplanted in Anderson County on a fine sand and in Upshur County on a sandy loam soil. In April and May, six herbicide treatments (involving hexazinone, sulfometuron, and imazapyr) were sprayed in a 0.9-m spot over the top of half of the seedlings. Seedlings were measured for groundline diameters (GLD) and heights (H) after three growing seasons. A volume index was determined for each tree by the following formula: Conic volume $= 0.2618 \times \text{GLD}^2 \times H$. A survival volume index was calculated using the formula average conic volume × survival.

This analysis will use the results of the mean of herbicide treatments and will assume a total cost for herbicide treatment of \$80/ha. Cost of applying 168 kg/ha of nitrogen in the nursery is assumed to be \$100/ha or approximately 5 cents/ 1000 seedlings.

Results

The effect of nursery treatment and weed control on survival varied by site. The sandy loam soil at the Upshur site contained adequate soil moisture, and survival was generally good. Third-year survival ranged from 80 to 87% and was not

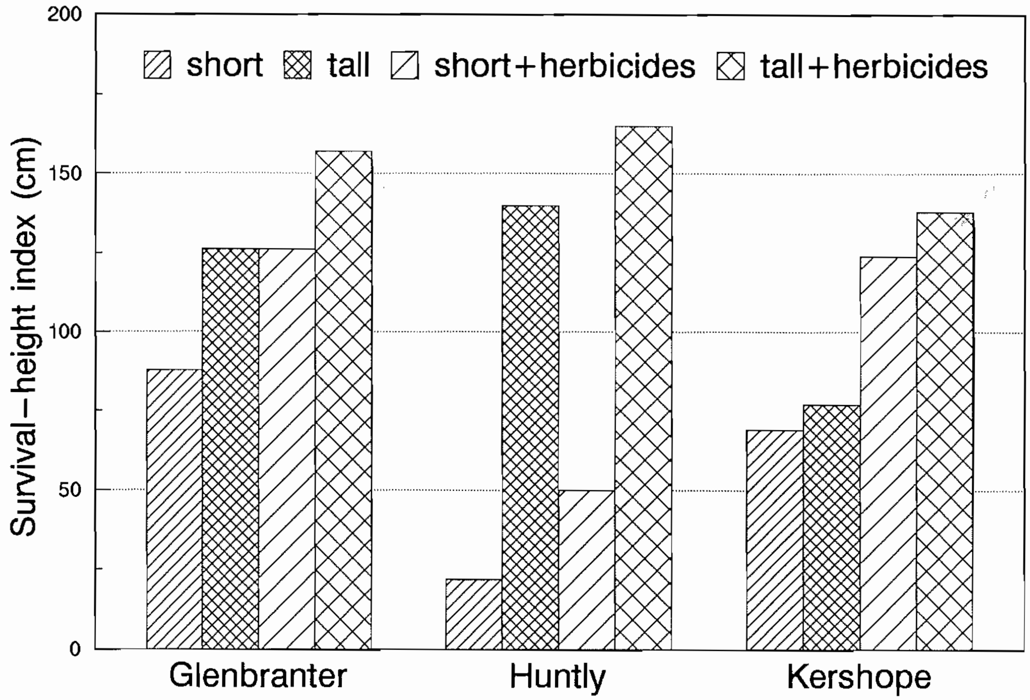

FIG. 1. Effect of transplant size and 5 years of weed control with herbicides on 6-year survival–height index (percent survival × average height) of *Picea sitchensis* on three uncultivated sites in Scotland. At planting, the short transplants averaged 15, 9, and 22 cm at the Glenbranter, Huntly, and Kershope sites, respectively; the tall transplants averaged 25, 31, and 30 cm, respectively. Six-year means represent the average of deer-excluded and -nonexcluded areas (adapted from Nelson 1990).

affected by either fertilization in the nursery ($p = 0.58$) or herbaceous weed control ($p = 0.44$). However, soil moisture was less on the sandy soil at the Anderson site and both treatments increased survival ($p < 0.001$). At the Anderson site, investing approximately 5 cents/1000 seedlings (by adding nitrogen in the nursery) increased survival by 14–19%. In contrast, investing $80/ha in spot applications of herbicides increased survival by 18–22%. The combination of nitrogen fertilization with the spot application of herbicides was additive and resulted in 96% survival, compared with 59% without fertilization or weed control. The addition of fertilizer in the nursery had a significant ($p < 0.001$) effect on mean GLD at planting. At the Anderson site, the difference in initial seedling size (2.9 mm root collar diameter for unfertilized seedlings and 3.6 mm for fertilized seedlings) likely accounted for the difference in survival (Barber et al. 1991).

Conic volume of seedlings at 3 years was greater at the Anderson site than at the Upshur site. At the Anderson site, nitrogen fertilization and weed control significantly increased seedling growth ($p < 0.001$). The nitrogen treatment doubled average tree conic volume (1258 vs. 633 cm^3) as did weed control (1158 vs. 620 cm^3). However, at the Upshur site, only the nitrogen treatment had a significant effect ($p = 0.01$) on seedling volume. Seedlings fertilized with nitrogen in the nursery had 70% more volume (775 vs. 457 cm^3). Although weed control increased average seedling volume by 12% (680 vs. 608 cm^3), the difference was not statistically significant ($p = 0.32$). Interactions between nursery and field treatments for conic volume were not observed for either site ($p > 0.60$).

When evaluating survival and conic volume per tree (Fig. 2), it is apparent that, at the Anderson site, the additional investment of 6 cents/1200 seedlings in nursery nitrogen fertilization produced as much additional volume as an additional $80/ha investment in weed control for unfertilized seedlings. At the Upshur site, the growth gain from the additional investment in nitrogen was greater than that realized by applying herbicides.

Alabama (1982)

Materials and methods

The relative importance of stock type, herbaceous weed control, and planting date on loblolly pine growth was examined on two sites in the Piedmont Plateau of Alabama (South and Barnett 1986). Container-grown and 1+0 bare-root seedlings were planted in March and May at a density of 2500 TPH. Two levels of herbaceous weed control were evaluated: (*i*) no herbicide application as the experimental control and (*ii*) a band application of sulfometuron at 0.56 kg a.i./ha in March of 1982 and again in March of 1983. Although survival and heights at age 3 years were reported, costs of weed control, container-grown seedlings, and bare-root seedlings were not mentioned. Cost of the weed-control treatment and seedling costs are estimated as follows: sulfometuron at $425 per kg a.i.; application cost at $50/ha; container-grown stock at $90/1000; and bare-root stock at $30/1000. Remeasurements of height and diameters were made in 1991 and total volume outside bark for each measurement tree was calculated using an equation by Van Deusen et al. (1981). Owing to a loss of trees from beaver (*Castor canadensis* Kuhl) damage, only two replications on the creek site were measured. All four replications were measured on the ridgetop site.

Results

Although 3rd-year survival of seedlings was high (92% on the creek site and 90% on the ridgetop site), soil moisture at time of planting was correlated with survival. At both sites, soil moisture and initial seedling survival were greater in

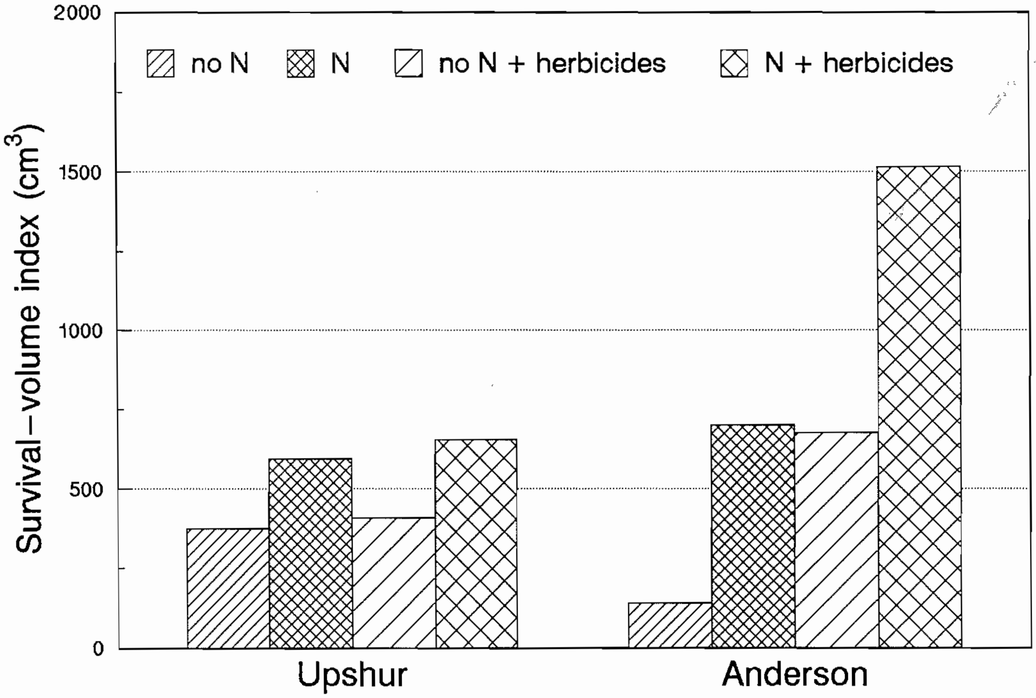

FIG. 2. Effect of applying 168 kg/ha of nitrogen in the nursery and applying a spot application of herbicides in the field on the 3rd-year conic volume per hectare of *Pinus taeda* on two sites in east Texas.

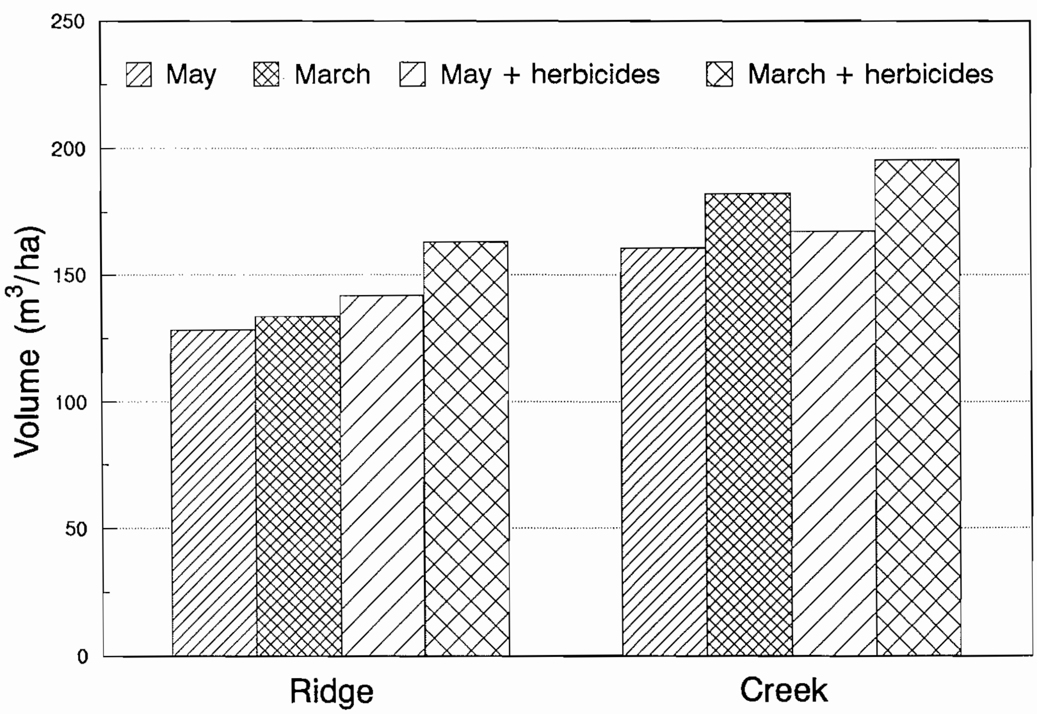

FIG. 3. Effect of planting date and two applications of herbicides on the 9th-year volume of *Pinus taeda* planted on two sites in Alabama. Means represent the average of container-grown and bare-root seedlings.

March than in May. Where soil moisture was low, survival of container seedlings was greater than for bare-root seedlings. However, by age 8, seedling survival was not related to main effects at either site ($p > 0.10$ for the ridgetop site and $p > 0.30$ for the creek site). Weed control at the ridgetop site significantly improved survival only when seedlings were planted in May ($p < 0.05$).

Volume per hectare at age 8 was not affected by stock type at either site ($p > 0.75$). The additional $150/ha investment in container-grown seedlings did not produce additional volume for either site. Planting date (Fig. 3) affected volume on both sites ($p < 0.05$). On the creek site, planting in March (188 m^3/ha) produced 16% more volume than planting in May (162 m^3/ha). On the ridgetop, planting in March (148 m^3/ha)

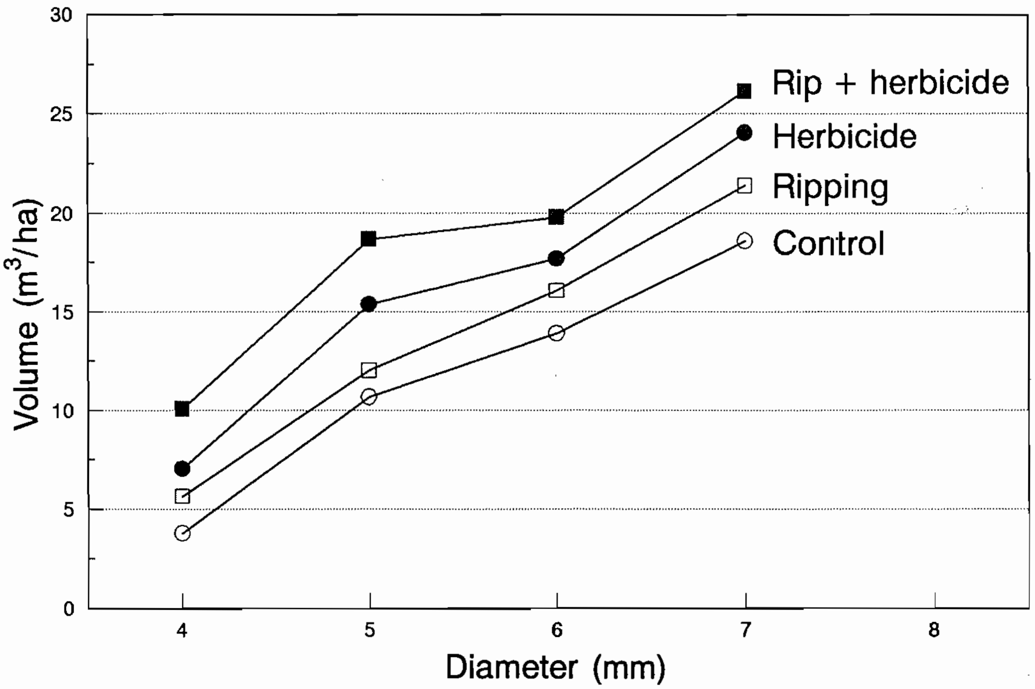

FIG. 4. Effect of various combinations of seedling diameter, ripping, and a spot application of hexazinone on the 4th-year conic-volume index of *Pinus radiata* in New Zealand (adapted from Balneaves 1989).

produced 10% more volume than planting in May (135 m^3/ha). There were no interactions among main effects at either site. Investing $457/ha in two herbicide applications increased volume production at age 8 by 16% (152 vs. 131 m^3/ha) at the ridgetop site (p = 0.002). Although this investment increased volume production by 6% at the creek site (181 vs. 171 m^3/ha), the difference was not significant (p = 0.19). On this site, it was more beneficial to plant in March without using herbicides than to use herbicides to improve the performance of seedlings planted in May.

New Zealand

Materials and methods

A factorial trial investigating root collar diameter (RCD) classes and site preparation was established at the Castle Downs Forest in Western Southerland (Balneaves 1989). Seedlings of 1+0 Monterey pine (*Pinus radiata* D. Don) were graded into four RCD classes of 4, 5, 6, and 7 mm. Site preparation treatments were: (*i*) control; (*ii*) ripping to a depth of 60 cm; (*iii*) one application of hexazinone at 4 kg a.i./ha applied over each seedling at 0.5-m radius; and (*iv*) a combination of (*ii*) and (*iii*). Cost of the various treatments are estimated as follows: ripping at $60/ha; weed control at $40/ha; and seedlings at $50, $55, $60, and $70/1000 for the 4-, 5-, 6-, and 7-mm seedlings, respectively. Stem diameter (10 cm above ground level) and height were measured 4 years after planting. A conic-volume index was calculated for each tree and volume per hectare was calculated using the formula: volume/ha = average conic volume × survival × 1000 TPH.

Results

Survival of 4-mm stock ranged from 75 (control) to 89% (ripping and spot applications of hexazinone). Use of 7-mm stock increased survival to greater than 90% on all treatments. Therefore, the need to use ripping or herbicides to increase seedling survival is greatest when using poor-quality stock. Without ripping or weed control, a 1-mm increase in RCD increased survival by 5%. With ripping and weed control, survival increased by 2% per millimetre increase in RCD.

Based on conic volume per hectare (Fig. 4), it is apparent that an additional investment of $20/ha seedlings in 7-mm seedlings produced as much additional growth by age 4 years as an additional $100/ha investment in ripping and herbicides when using 5-mm seedlings. The 7-mm seedlings without site preparation cost $80/ha less and produced 85% more volume/ha at age 4 than 4-mm seedlings with ripping and herbicides.

South Africa

Materials and methods

A study was established in the southern Cape Province to examine survival and growth of Monterey pine in response to seedling grade and various methods of site preparation. A split-split-plot design was used in a factorial combination to compare four methods of soil cultivation (whole plots), two levels of weed control (subplots), and two size classes of planting stock (sub-subplots) (Zwolinski 1992). Although four soil cultivation treatments were used, only two (pitting and ripping) are reported here. Pitting involves digging a pit (45 cm wide by 20 cm deep) using hand labor at a cost of $46/ha. Ripping to a depth of 60 cm cost approximately $67/ha.

Subplots were treated with either (*i*) the standard method of weed control involving slashing weeds by hand 1 year after planting to prevent overtopping of the planted trees or (*ii*) total weed control for 1 year involving use of herbicides in addition to slashing. Herbicides included 2 kg a.i./ha of glyphosate broadcast 3 months before planting and again 1 month before planting. Seven months after planting, a broadcast application of 2 kg a.i./ha of hexazinone was used.

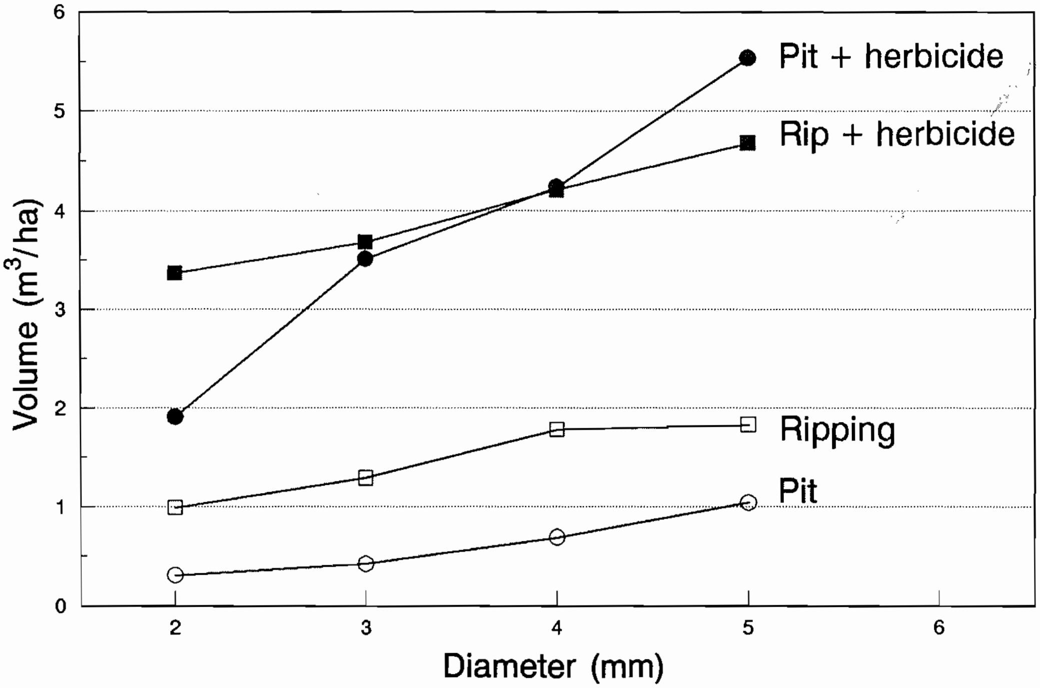

FIG. 5. Effect of various combinations of seedling diameter, ripping, and total weed control for 1 year on 2nd-year conic-volume index of *Pinus radiata* in South Africa.

Hoeing and slashing were applied when deemed necessary. The standard method of weed control cost $190/ha while total weed control for 1 year cost $401/ha.

Bare-root 1+0 seedlings were grown at the Lottering nursery at a bed density of 160/m^2. For the purposes of this paper, seedlings were grouped into four initial GLD classes (1.5–2.4, 2.5–3.4. 3.5–4.4, and 4.5–5.4 mm) and were valued at $30, $35, $42, and $50/1000 seedlings, respectively. Two years after planting, *H* and GLD were measured. A conic-volume index was determined for each tree and volume per hectare was calculated using the formula: volume/ha = average conic volume × survival × 1372 TPH.

Results

GLD at planting was positively correlated with seedling survival after two seasons. A 1-mm increase in seedling diameter increased survival by 7%. Survival of the 2-mm stock averaged 62% while 5-mm stock averaged 85%. There was no interaction between seedling grade and weed control or between seedling grade and method of soil cultivation. Although the main effects of soil cultivation and weed control on survival were not significant, a significant interaction was present (p = 0.049). With pitting treatments, herbicides and hoeing reduced survival of low-grade seedlings (by 9%); however, where ripping was used, herbicides and hoeing increased survival of the low-grade seedlings by 6%.

Conic volume per hectare at age 2 was improved with increases in both seedling diameter and intensity of weed control (Fig. 5). However, a significant interaction between soil cultivation and weed control was observed ($p < 0.05$). Ripping improved volume per hectare when given the standard level of weed control but did not improve volume production when total weed control was provided. The interaction between seedling size and weed control (p = 0.012) was one of scale rather than rank. The relationship between diameter of seedlings and volume per hectare was much greater with total weed control than with the standard level of weed control (Fig. 5).

Alabama (1983)

Materials and methods

A study designed to investigate the effect of herbaceous weed control on growth of loblolly pine was undertaken on the Upper Coastal Plain of Alabama (Zutter et al. 1986). In January 1983, the area was planted at a density of 1736/ha with 1+0 bare-root, genetically improved (Coastal Plain) loblolly pine seedlings. For the purpose of this paper, seedlings were grouped into three initial GLD classes (2.5–3.4, 3.5–4.4, and 4.5–5.4 mm). Three levels of weed control were evaluated: (*i*) control of hardwood sprouts but no control of herbaceous weeds; (*ii*) control of hardwood sprouts plus one broadcast application of sulfometuron at 0.42 kg a.i./ha in April of 1983; (*iii*) control of hardwood sprouts plus total herbaceous control for 2 years using sulfometuron at 0.42 kg a.i./ha and a directed application of glyphosate (2% solution) during the 1st year plus 0.26 kg a.i./ha of sulfometuron and two directed applications of glyphosate during the 2nd year. Remeasurements of height and diameters were made in 1991 and a conic-volume index for each measurement tree was calculated. Volume per hectare was calculated using the formula: volume/ha = average conic volume × survival × 1736 TPH. Cost of weed-control treatments and seedling costs are estimated as follows: glyphosate, $11/L; sulfometuron, $425/kg a.i.; application cost, $50/ha; 3-mm seedlings at $30/1000; and 5-mm seedlings at $50/1000.

Results

Survival of 3-mm stock ranged from 83 (control) to 88% (2 years of herbaceous weed control). Use of 5-mm stock increased survival to greater than 95% on all treatments. A 1-mm increase in seedling diameter increased survival by 7% if weeds were not controlled or by 6% with 2 years of weed control.

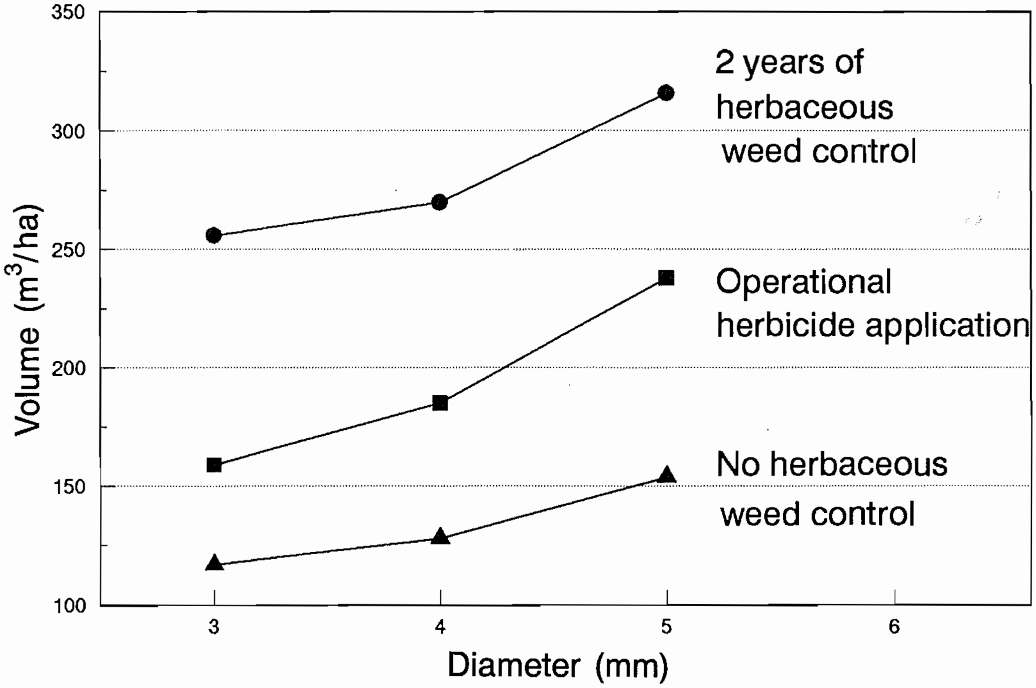

FIG. 6. Effect of seedling diameter and various levels of herbaceous weed control on the 8th-year conic-volume index of *Pinus taeda* in Alabama.

TABLE 1. Incremental costs, normal yield at rotation using low-grade bare-root stock, and percent increase in volume per hectare required to recover a 6% return on investment

Location		Incremental cost (\$/ha)	Normal yield (m^3/ha)	Required gain (%)
Nursery practice				
New Zealand	7-mm seedlings	20	500	2
South Africa	5-mm seedlings	27	330	4
Alabama	Container stock	150	190	37
	5-mm seedlings	35	190	9
Scotland	30-cm transplants	45	600	4
Texas	168 kg N/ha	0.06	190	0.02
Silvicultural practice				
New Zealand	Ripping	60	500	6
	1 SAH	40	500	4
South Africa	TWC (1 year)	212	330	32
	Ripping	67	330	10
Alabama	TWC (2 year)	588	190	155
	1 BAH	228	190	60
Scotland	TWC (5 year)	510	600	43
Texas	1 SAH	90	190	24

NOTE: For this analysis, the discounted value of wood is assumed to be \$2/m^3. At a 6% interest rate, this is equivalent to a harvest value of \$8.58/m^3 for a 25-year rotation or \$49.30/m^3 for a 55-year rotation. SAH, spot application of herbicide; BAH, broadcast application of herbicide; TWC, total weed control.

Volume per hectare at age 8 was significantly improved with increases in seedling diameter and intensity of weed control ($p < 0.001$). There was no interaction between seedling diameter and weed-control treatment ($p = 0.72$). Planting 5-mm seedlings instead of 3-mm seedlings increased wood volume at age 8 by 32% without herbaceous weed control and 23% with herbaceous weed control. However, the relationship between seedling diameter and volume per hectare was stronger with weed control than without (Fig. 6). Investing an additional \$35/ha for 5-mm seedlings (without weed control) increased volume production to about the same magnitude as an investment of \$228/ha for a single application of sulfometuron where 3-mm seedlings were planted.

Discussion

Potential growth gains and costs of silviculture versus nursery practices have rarely been contrasted. It is apparent from Table 1 and Fig. 2 that it is illogical to save money by eliminating nitrogen fertilization in the nursery while, at the same time, applying herbicides in the field to promote growth.

TABLE 2. Early growth gains from planting large-diameter conifer stock without use of herbicides (A) compared with gains achieved from treating small-diameter stock with herbicides (B)

Location	Age (yr)	Stock size: Herbicides not used (A)	Stock size: Herbicides used (B)	Growth comparison	Source
New Zealand	4	7-mm RCD[1]	4-mm RCD	A>B[1]	Balneaves 1989
Texas	3	3.6-mm GLD[1] + N	2.9-mm GLD	A>B	Fig. 2
Scotland	6	31-cm HT[1]	9-cm HT	A>B′[1]	Nelson 1990
New Zealand	3	4.0-mm RCD	2.7-mm RCD	A>B	Glass et al. 1991
New Zealand	3	>30-cm HT	Ungraded	A=B	Albert et al. 1980
Alabama	8	5-mm GLD	3-mm GLD	A=B	Fig. 5
New Zealand	2	8-mm RCD	4-mm RCD	A=B	Baker and Ledgard 1991
Scotland	6	25-cm HT	15-cm HT	A=B′	Nelson 1990
Texas	3	3.2-mm GLD + N	3.0-mm GLD	A=B	Fig. 2
New Zealand	3	>30-cm HT	Ungraded	A<B	Albert et al. 1980
Scotland	6	30-cm HT	22-cm HT	A<B′	Nelson 1990
Alabama	8	5-mm GLD	3-mm GLD	A<B′	Fig. 5
South Africa	2	5-mm GLD	2.8-mm GLD	A<B′	Fig. 4

[1]GLD, groundline diameter; RCD, root collar diameter; HT, shoot height; N, 168 kg/ha of nitrogen; B, operational herbicide treatment; B′, research treatment to provide total control of herbaceous weeds.

Fertilizing with nitrogen in the nursery is probably the least expensive way to improve field growth. Early growth of loblolly pine has previously been related to the nitrogen status of the seedling at planting (Switzer and Nelson 1967; Larsen et al. 1988, 1989; Blake and South 1990). In Mississippi, increasing the rate of nitrogen fertilization in the nursery to 336 kg/ha total increased individual tree volume at age 16 years by 6% (Autry 1972). However, to be profitable, the 6 cent investment per regenerated hectare need only increase volume per hectare at harvest by 0.02% (Table 1). The potential gains from spending $60 to $80/ha on herbaceous weed control will not be optimized if the nursery manager cuts back on nitrogen to reduce seedling costs.

Planting date has a dramatic effect on field performance and will be a key factor in integrated approaches to regeneration. Planting in dry soil or just before the hot and dry season can reduce survival and growth. Therefore, planting date can be just as important as choice of silvicultural treatments. Use of container stock and (or) herbicides has been suggested as a way to extend the planting season of loblolly pine into late spring. However, extending the planting season into May can have a greater impact on volume growth than either the use of container stock or herbaceous weed control. Data from the Alabama (1982) study illustrates that planting in May with container stock and applying two applications of herbicides cost an additional $710/ha but produced only 1–7 m^3/ha more than planting bare-root seedlings in March without herbicides. When all acreage cannot be planted during the rainy winter months, woodlands managers should start planting bare-root seedlings in the fall on sites were soil moisture is adequate for good seedling survival. This integrated approach to regeneration would be less expensive and more productive than extending planting into spring using more expensive container-grown stock.

Increased growth can result from either planting large-diameter stock or reducing herbaceous competition. However, the cost of herbicides is often more than the cost of using high-grade seedlings. Therefore, the volume increase needed at harvest to justify the use of herbicides can range from 4 to 24% (or more) while that needed to justify the use of high-grade seedlings ranges from 2 to 9% (Table 1).

In almost all studies, large-diameter seedlings grew more than small-diameter seedlings. In most cases, the use of higher grade seedlings alone resulted in gains equal to or greater than those from applying an operational herbicide treatment to low-grade seedlings (Table 2). Intensive treatments involving total weed control for 1–5 years are usually required to make low-grade seedlings outperform the growth of high-grade seedlings in the presence of herbaceous weeds. Therefore, it makes no sense to save $25 to $45/ha by planting low-grade seedlings if $60 to $100/ha must be spent for a single operational herbicide application to improve their growth. For example, the typical operational cost for a band application of herbicide by machine in the southern United States is $62/ha. The cost to apply a treatment by hand with backpack sprayers is $86/ha (Dubois et al. 1991). The cost of a single weeding in Scotland can exceed $100/ha (Crabtree and Cumming 1989).

Many industrial nurseries in the southern United States, South Africa, and Great Britain are operated as cost centers and, therefore, produce the minimum size of stock that will result in acceptable survival. In the southern United States and South Africa, most bare-root seedlings are less than 4 mm in RCD (Boyer and South 1988; Donald 1986); in Britain, 40% of the Sitka spruce is less than 25 cm tall (Dauncy 1989). In contrast, woodlands managers in New Zealand have taken an integrated approach to reforestation and have set higher standards for plantable seedlings. As a result, the target pine seedling in New Zealand has a mean RCD greater than 5 mm and seedlings are culled if the RCD is less than 4 mm (New Zealand Forest Research Insititute 1988). For Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) in New Zealand, the target seedling has a RCD of 8–10 mm (Baker and Ledgard 1991).

The cost of providing total weed control for 2–5 years for a research study (Table 1) can be 5 to 10 times higher than that for a single operational herbicide application. Likewise, the gains from an extended period of weed control will likely be greater than those obtained from a single operational herbicide application (e.g., Fig. 6). However, some economists have used operational costs for herbaceous weed control but cite volume gains from research studies that involve total weed control (i.e., Glover et al. 1989; Miller et al. 1991). Such analyses will prove to be overoptimistic if the volume response to the operational treatment is less than that for the total weed control treatments.

In 1982, most loblolly pine nurseries were producing seedlings with a mean RCD of less than 4 mm (Boyer and South 1988). Therefore, the majority of weed-control studies conducted with loblolly pine during the 1980s were not conducted with grade 1 seedlings (those with RCD greater than 4.7 mm). Researchers who recommend using herbicides to improve loblolly pine seedling survival have likely tested the effects of herbicides on low-grade seedlings.

Future research needs

Since the response to vegetation management practices depends on the grade of planting stock used, researchers who conduct weed-control studies should report the size of planting stock used (current papers rarely report mean RCD, shoot heights, root weights, etc.). Research to improve plantation growth through silvicultural practices should include a greater than average grade of planting stock to determine if observed gains from these practices are as large as when using average planting stock. This is necessary because nursery practices may provide similar growth gains but cost dramatically less than large investments in site preparation and weed control.

All studies in this report used standard nursery practices that produced conventional-sized stock. For example, mean diameters for bare-root pines used in South Africa, Texas, and two Alabama studies were 3.5, 3.3, 3.5, and 3.6 mm, respectively. However, seedlings with much larger diameters can be produced in bare-root nurseries with little added expense by sowing seed earlier, sowing at lower density, and increasing nitrogen fertilization. If pine seedlings could be grown to a mean RCD of 10–12 mm, would early growth continue to increase in a linear fashion? Results for early height growth of longleaf pine (*Pinus palustris* Mill.) suggest a linear trend for RCD up to 20 mm (Lauer 1987). However, literature for other pine species is not much help in this regard since the maximum RCD tested is usually only 6 or 7 mm. Nevertheless, one might expect a point of diminishing returns where the growth response to ever increasing size would diminish. More work is needed to define the range in RCD where diminishing returns occur and then to determine which nursery practices consistently produce such stock economically. Also, all nursery practices that produce seedlings with a large RCD may not have equal effects on outplanting performances. Research that identifies key mechanistic relationships between seedling culture and outplanting problems is an important area for future research efforts.

Increasing seedling size can affect handling costs (Dauncy 1989) as well as planting productivity. However, longleaf pine seedlings with RCD of 10–14 mm are operationally planted with machines in the southern United States. Thus, machine planting loblolly pine or Monterey pine seedlings having large diameters would not be a problem. However, techniques used to hand plant seedlings may have to be altered. Research is needed to determine if optimum seedling size (determined by field performance) varies with machine versus hand planting. Furthermore, planting tools used to hand plant large-diameter seedlings may need to be changed. Hoedads and planting bars are commonly used in the United States to plant 3- or 4-mm stock, but Long (1991) stated that shovels should be the only tool used when hand planting seedlings with large root systems. Shovels are used for Monterey pine in New Zealand and for large-diameter transplant stock in the Pacific Northwest region of the United States (Blake and South 1991). Extension training may be necessary where tree planters are unaccustomed to hand planting stock with large root systems.

Growth response to weed control will vary with (*i*) the degree to which competing vegetation has invaded the site and (*ii*) the time that trees are planted. Weed control may have greater effects on sites where weeds are well established before planting than on sites where weeds invade after planting. However, little work has been done to determine to what degree timing of weed establishment influences the response to weed control. Similarly, time of planting may strongly influence both the growth response to seedling grade as well as the need for weed control. In the southeastern United States, fall planting can greatly increase growth of seedlings relative to winter or spring planting. Since fall droughts are frequent in this area, herbaceous weed control in late summer or early fall may be necessary to increase the level of soil moisture and reduce the risk of plantation failure.

Since outplanting density affects merchantable volume production and economic returns, this factor should be carefully considered when integrating regeneration practices. Some researchers recommend outplanting as many as 3200 TPH, while others recommend outplanting 750–1000 TPH. The additional cost per hectare for using high-grade stock will be four times greater at 3200 TPH than at 800 TPH. However, owing to density-related competition, merchantable volume production at ages above 20 years are not strictly proportional to the number of trees planted. Therefore, incremental gains from planting high-grade stock will not be proportional to planting density. As a result, the economic advantage of using high-grade seedlings is much greater when outplanting densities are low (South 1993).

Lastly, this work emphasizes that recommendations for nursery practices be made with respect to outplanting performance. Too often, recommendations are based on minimizing nursery production costs and have resulted in high seedbed densities, reduction of nitrogen fertilization to less than 125 $kg \cdot ha^{-1} \cdot crop^{-1}$, or reduced irrigation during the fall. However, rarely are studies done to determine if these cost-saving measures alter growth after outplanting. Future research should be aimed at integrating nursery and silvicultural practices to improve plantation performance while, at the same time, reducing the overall regeneration costs.

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