The role of vegetation management for enhancing productivity of the world's forests

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Summary

The management of competing vegetation has evolved with forest management over the past half century and is now an integral part of modern forestry practice in many parts of the world. Vegetation management, primarily using herbicides, has proven especially important in the establishment of high-yield forest plantations. There has been a substantial amount of research quantifying the wood yield gains from the management of competing vegetation over the past few decades. We reviewed results from 60 of the longest-term studies in North America (Canada and US), South Africa, South America (Brazil) and New Zealand/Australia. About three-quarters of the studies reported 30–500 per cent increases in wood volume from the most effective vegetation treatments. In North America, where the longest-term studies for a variety of tree species were between 10 and 35 years old (or from 20–100 per cent of rotation age), gains in wood volume ranged from 4–11 800 per cent in Pacific north-western forests, 14–5840 per cent in the south-eastern forests, and 49–5478 per cent in northern forests. In South Africa and South America (Brazil), several full-rotation (6–8 years) studies with eucalyptus indicate 29–122 per cent and 10–179 per cent increases in wood volume yield, respectively, from effective vegetation management. In New Zealand, time gains of 1 to 4 years from early vegetation control in radiata pine plantations translated into 7–27 per cent increases in wood volume yield over a 25- to 30-year rotation.

Introduction

Forest vegetation management (FVM) is an integral part of successful silviculture around the world. Walstad and Kuch (1987) define FVM in the first textbook about the subject as 'the practice of efficiently channelling limited site resources into usable forest products rather than into noncommercial plant species'. The definition of FVM also has been expanded to include

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'managing the course and rate of forest vegetation succession to achieve silvicultural objectives ...' (Wagner, 1994). In North American silviculture textbooks (such as Smith *et al.*, 1997), FVM generally includes treatments such as release (including cleaning, weeding and liberation) and site preparation. These treatments are generally directed at reducing competition for site resources (light, soil water and soil nutrients) between desired trees and associated plants. Another form of forest vegetation management is the introduction of non-crop species to improve site quality, to suppress unwanted species, or to provide forage for grazing animals (Richardson, 1993).

Vegetation management can be used throughout the development of a forest stand and provides one of the best opportunities to ensure that stands of the desired species composition and structure develop within an economically feasible period of time. Indeed, most forest regeneration efforts around the world would fail or be severely delayed without effective FVM. Intensive silviculture designed to increase the yields of wood fibre per hectare is dependent upon effective vegetation management.

Over the past several decades, there has been a substantial research effort aimed at quantifying increases in forest productivity associated with FVM (primarily using herbicides) in the world's forests. Most of the published research, however, has reported growth responses for only several years following treatment. A comprehensive literature review of yield gains from FVM in North American studies conducted by Stewart *et al.* (1984) included almost exclusively short-term growth responses (i.e. several years after treatment) as there were no longer-term data available at the time.

Documenting the benefits of FVM on forest productivity, however, requires measurement over a significant portion of a stand rotation (preferably the entire rotation) to document the long-term growth and yield response associated with specific treatments. Toward this goal, there is a growing body of longer-term studies for many forest types that have documented growth and yield changes over a significant portion of the forest rotation. In some cases, especially for short-rotation tree species, full rotation data are now available.

Although results from some of these studies have been reported in the Proceedings of the International Conference on Forest Vegetation Management (see *Canadian Journal of Forest Research*, Vol. 23, Part 10 (1993), *New Zealand Journal of Forestry Science*, Vol. 26, Part 1/2 (1996), *Canadian Journal of Forest Research*, Vol. 29, Part 7 (1999) and *Annals of Forest Science*, Vol. 60, No. 7 (2003)) and elsewhere, there has been no formal review or synthesis of these works. The purpose of this paper is to review results from the longest-term studies documenting gains in wood yield associated with managing vegetation (primarily using herbicides) in forests around the world. We focus on regions (North America, South Africa, South America and New Zealand/Australia) where forests have been intensively managed for wood fibre production and where research on stand responses to vegetation management was available. Efforts were made to identify long-term studies (>10 years) documenting yield gains from herbicide use in Scandinavia and central Europe, but none were found due to the lack of herbicide usage in the region (Philippe Balandier, (CEMAGREF, France) and Göran Örlander (Växjö University, Sweden), personal communication). Studies documenting yield gains from controlled experiments in North America (Canada and US), South Africa, South America (Brazil) and New Zealand/Australia were reviewed. We briefly describe forest and vegetation management in each region, and then summarize results from studies that have quantified wood yield gains for a substantial portion of the forest rotation (≥10 years), or for most or all of the rotation for short-rotation tree species, following effective vegetation management (Tables 1 and 2).

North America (Canada and US)

Half of Canada (418 million ha) is covered by forest and currently holds about 10 per cent of the world's forest area and 30 per cent of the world's boreal forest (Natural Resources Canada, 2004). Approximately 28 per cent (119 million ha) is currently managed for timber production, with only 0.4 per cent harvested annually. Nearly all (94 per cent) of Canada's forests are publicly owned. Softwood species dominate 67 per cent of the forest, with mixed woods and hardwoods

Table 1: Wood volume gains from the most effective treatments for managing competing vegetation in the longest-term experiments from North America (Canada and US), South Africa and South America (Brazil)

Tree species	Length of measurement after treatment (years)	Mean stem volume from untreated plots	Mean stem volume from most effective vegetation control treatment	Volume gain from treatment	Units	Wood volume yield increase (%)	No. of study sites/locations*	Authors
North America (Pacific Northwest)								
Pinus ponderosa	35	116.83	121.92	5.09	$m^3\ ha^{-1}$	4	1 site, OR	Busse *et al.*, 1996
Pinus ponderosa	28	113.7	246.7	132.9	$m^3\ ha^{-1}$	78 and 580	2 sites, CA	Powers *et al.*, 2005
Pinus ponderosa	27	1.0	119.0	118.0	$m^3\ ha^{-1}$	11800	1 site, CA	McDonald and Powers, 2004
Pinus ponderosa	21	10.2	319.0	308.8	$m^3\ ha^{-1}$	3035	1 site, CA	Lanini, 2003
Abies concolor	21	0.7	13.6	12.8	$m^3\ ha^{-1}$	1712	1 site, CA	Lanini, 2003
Pinus ponderosa	20	45.9	88.4	42.5	$m^3\ ha^{-1}$	93	1 site, CA	Oliver, 1990
Pseudotsuga menziesii	15	15.2	84.0	68.9	$m^3\ ha^{-1}$	454	4 sites, OR	Yildiz, 2000
Pinus contorta	15	6.9	17.5	10.6	$m^3\ ha^{-1}$	153	1 site, BC	Simard *et al.*, 2005
Pseudotsuga menziesii	14	0.010	0.035	0.025	$m^3\ tree^{-1}$	245	1 site, OR	Hanson, 1997
Pseudotsuga menziesii	12	0.008	0.023	0.015	$m^3\ tree^{-1}$	200	1 site, OR	Hanson, 1997
Pinus ponderosa	14	0.013	0.071	0.058	$m^3\ tree^{-1}$	464	1 site, OR	Hanson, 1997
Tsuga heterophylla	12	0.050	0.150	0.100	$m^3\ tree^{-1}$	200	3 sites, OR	Newton and Cole, 2000
Pseudotsuga menziesii	10	39.0	89.0	50.0	$m^3\ ha^{-1}$	128	6 sites, OR & WA	Harrington *et al.*, 1995
Pseudotsuga menziesii	10	7.8	28.9	21.1	$m^3\ ha^{-1}$	272	4 sites, OR	Stein, 1995
Pseudotsuga menziesii	10	0.0270	0.0590	0.032	$m^3\ tree^{-1}$	119	1 site, OR	Monleon *et al.*, 1999
Abies concolor	10	0.00005	0.00060	0.034	$m^3\ tree^{-1}$	1012	1 site, CA	McDonald and Fiddler, 2001a
Pinus ponderosa	10	0.00036	0.00612	0.351	$m^3\ tree^{-1}$	1593	1 site, CA	McDonald and Fiddler, 2001b
Pinus ponderosa	10	15.2	29.7	14.5	$m^3\ ha^{-1}$	59–270	3 sites, CA	Powers and Reynolds, 1999

Table 1: Continued

Tree species	Length of measurement after treatment (years)	Mean stem volume from untreated plots	Mean stem volume from most effective vegetation control treatment	Volume gain from treatment	Units	Wood volume yield increase (%)	No. of study sites/locations*	Authors
North America (south-eastern)								
Pinus taeda	30	106.4	125.2	18.9	$m^3\ ha^{-1}$	18	1 site, LA	Clason, 1989
Pinus taeda	27	5.0	297.0	292.0	$m^3\ ha^{-1}$	5840	1 site, AL	Glover and Zutter, 1993
Pinus elliottii	23	155.1	273.7	118.6	$m^3\ ha^{-1}$	76	15 sites, GA and FL	B. D. Shiver, unpublished data
Pinus palustris	20	49.7	69.4	19.7	$m^3\ ha^{-1}$	40	3 sites, AL	Michael, 1980
Pinus taeda	15	151.7	252.5	100.8	$m^3\ ha^{-1}$	30–148	13 sites across seven states	Miller *et al.*, 2003b
Pinus taeda	12	59.2	178.1	119.0	$m^3\ ha^{-1}$	201	25 sites across SC, GA and AL	Shiver and Martin, 2002
Pinus taeda	12	76.9	129.8	52.9	$m^3\ ha^{-1}$	33–131	3 sites, AR and MS	Glover *et al.*, 1989
Pinus taeda	10–12	125.1	214.7	89.6	$m^3\ ha^{-1}$	37–122	6 sites, GA	Borders and Bailey, 2001
Pinus taeda	11	171.4	195.2	23.8	$m^3\ ha^{-1}$	14	1 site, LA	Haywood and Tiarks, 1990
Pinus taeda	10	99.4	119.0	19.7	$m^3\ ha^{-1}$	20	1 site, LA	Haywood, 1994
North America (northern)								
Picea glauca	30	0.018	0.029	0.011	$m^3\ tree^{-1}$	53–96	3 sites, ON	Sutton, 1995
Abies balsamea	28	52.4	191.4	139.0	$m^3\ ha^{-1}$	265	1 site, NB	MacLean and Morgan, 1983
Abies balsamea and *Picea rubens*	22	12.0	61.3	49.3	$m^3\ ha^{-1}$	411	1 site, ME	Daggett, 2003
Picea glauca	12	1.2	4.9	3.6	$m^3\ ha^{-1}$	300	1 site, BC	Harper *et al.*, 1997
Picea glauca	12	1.4	9.6	8.2	$m^3\ ha^{-1}$	591	1 site, BC	Biring *et al.*, 1999

Table 1: *Continued*

Tree species	Length of measurement after treatment (years)	Mean stem volume from untreated plots	Mean stem volume from most effective vegetation control treatment	Volume gain from treatment	Units	Wood volume yield increase (%)	No. of study sites/locations*	Authors
Picea glauca	10	0.3	1.0	0.6	$m^3\ ha^{-1}$	194	1 site, BC	Biring and Hays-Bayl, 2000
Picea glauca	10	0.7	1.0	0.3	$m^3\ ha^{-1}$	49	1 site, BC	Biring *et al.*, 2001
Picea engelmannii	10	2.0	4.4	2.4	$m^3\ ha^{-1}$	124	1 site, BC	Biring *et al.*, 2003
Pseudotsuga menziesii and *Pinus ponderosa*	10	0.1	3.9	3.8	$m^3\ ha^{-1}$	5478	1 site, BC	Harper *et al.*, 1998
Picea mariana	10	0.002	0.007	0.005	$m^3\ tree^{-1}$	111 and 477	2 sites, ON	Pitt *et al.*, 2004
Pinus banksiana	10	11.4	24.7	13.3	$m^3\ ha^{-1}$	116	1 site, ON	Wagner, 2003
Pinus resinosa	10	4.7	14.6	9.9	$m^3\ ha^{-1}$	211	1 site, ON	Wagner, 2003
Pinus strobus	10	2.2	7.0	4.8	$m^3\ ha^{-1}$	216	1 site, ON	Wagner, 2003
Picea mariana	10	1.8	7.9	6.2	$m^3\ ha^{-1}$	349	1 site, ON	Wagner, 2003
South Africa								
Eucalyptus hybrid	7	137.8	223.9	86.1	$m^3\ ha^{-1}$	62	1 site	Little, 1999
Eucalyptus hybrid	7	160.5	207.4	46.9	$m^3\ ha^{-1}$	29	1 site	Little *et al.*, 2002
Eucalyptus hybrid	7	206.2	285.5	79.3	$m^3\ ha^{-1}$	38	1 site	Little, 2003
Eucalyptus dunnii	6	77.4	171.9	94.5	$m^3\ ha^{-1}$	122	1 site	K.M. Little, unpublished data
South America (Brazil)								
Eucalyptus grandis	6.5	212.0	518.0	306.0	$m^3\ ha^{-1}$	144	1 site	de Toledo *et al.*, 2003b
Eucalyptus grandis	3	117.5	287.5	170.0	$m^3\ ha^{-1}$	122 and 179	2 sites	Zen, 1986
Eucalyptus urograndis	4	93.5	129.0	35.5	$m^3\ ha^{-1}$	10 and 108	2 sites	de Toledo *et al.*, 2003a

*State/province codes for North America: AL = Alabama, AR = Arkansas, BC = British Columbia, CA = California, FL = Florida, GA = Georgia, LA = Louisiana, ME = Maine, NB = New Brunswick, ON = Ontario, OR = Oregon, SC = South Carolina.

Table 2: Influence of vegetation control on time required to reach a target tree volume for radiata pine in New Zealand (i.e. time gain following vegetation control)

Location	Age (years)	Time gain (years)	Competitor	Duration of control (years)	Reference
Tranters block (Selwyn Plantation Board)	15	4.0	Grass/broom	First 3	J. Balneaves, personal communication
Paringa (Ashley Forest)	15	3.0	Grass	First 1.5	J. Balneaves, personal communication
Ashley Forest	18	4.0–6.0	Gorse	First 11*	Balneaves and McCord, 1990
Burnham (slash retention[†])	14	1.25	Broom/grass	Age 8–14	J. Balneaves, personal communication
Burnham (windrow[‡])	14	1.5	Broom/grass	Age 8–14	J. Balneaves, personal communication
Rotorua	3	1.3	Buddleia/pampas	3	Richardson *et al.*, 1996
Rotorua	3	1.5	Grasses	0.5	Richardson *et al.*, 1996
Tokoiti Forest	6	1.7	Grass	Age 0–7	B. Richardson, unpublished data
Waiuku	18	1.0	Pampas	Age 0–18	West *et al.*, 1988
Kaingaroa (atrazine/amitrole)	15	1.0	Grass	First	DuPont NZ Ltd, unpublished data
Kaingaroa (hexazinone)	15	2.0	Grass	First 2	DuPont NZ Ltd, unpublished data
Ohakuri (V-blade[†])	8	1.5[§]	Cape broom/bracken	First 4	B. Richardson, unpublished data
Ohakuri (no cultivation)	8	1.5[§]	Cape broom/bracken	First 4[¶]	B. Richardson, unpublished data
Wainui	11	0.75–2.0	Grass	First 3s	B. Richardson, unpublished data
Tasmania	14	2.0	Woody species	1–3	Wilkinson *et al.*, 1992

*Comparison of weed control for 11 years *vs* conventional regime of 1 year control.
[†]Site preparation treatment that maximized growth.
[‡]Site preparation treatment that minimized growth.
[§]Based on mean tree volume; values represent minimum benefit because of increase in proportion of trees pruned from weed control treatments.
[¶]First year hexazinone treatment; hand-releasing years 2–4.
[#]Mean tree volume and stand volume based on pre-thinning mortality figures.

composing 18 per cent and 15 per cent, respectively. Commercial timber, pulp and paper production is central to Canada's economy, which is the world's leading exporter of forest products ($42.9 billion CDN). In 2002, forests contributed $29.9 billion (CDN) of the nation's gross domestic product and directly employed some 361 400 people (Natural Resources Canada, 2004).

One-third of the land area in the United States of America (302 million ha) is covered by forest (Smith *et al.*, 2001). Forty-two per cent of US forestland is publicly owned, either by individual states or the federal government. Of the total forest area, 67 per cent (204 million ha) is classed as timberland capable of producing more than 1.4 m^3 ha^{-1} a^{-1} and not legally restricted from timber harvesting. Eleven per cent of US timberlands are plantations, with two-thirds occurring in the southern states (Smith *et al.*, 2001). More than half (58 per cent) of the volume of growing stock is in softwoods and the remaining 42 per cent in hardwoods. US forests are an important part of the economy. In 1996, the value of roundwood forest products ($22.5 billion US) was surpassed only by corn ($25.1 billion US) as the leading agricultural commodity in the US (AF&PA, 2001).

Vegetation management

The management of unwanted or competing vegetation is vital to successful forest management across the US and Canada (Walstad and Kuch, 1987; Thompson and Pitt, 2003). Forests in the Pacific north-western, south-eastern and northern regions of North America have unique vegetation problems that, if left unmanaged, can substantially reduce the growth and survival of desired tree species (Wagner *et al.*, 2004). A variety of methods are used to manage forest vegetation in each region, including mechanical equipment, herbicides, prescribed fire and manual cutting (Walstad and Kuch, 1987; Thompson and Pitt, 2003). Mulches, grazing animals and cover cropping also are available methods, but are relatively minor (Harrington and Parendes, 1993; Comeau *et al.*, 1996; Wagner *et al.*, 2001).

A substantial amount of research has been conducted in the US and Canada over the past several decades documenting growth and yield increases associated with FVM (Wagner *et al.*, 2004). Results are summarized here for studies in Pacific north-western (California, Oregon, Washington, British Columbia), south-eastern (south-eastern US states) and northern (north-eastern states, Lake states, Canadian boreal and sub-boreal) forests (Table 1).

Volume gains in Pacific north-western forests

Some of the first long-term projections of yield enhancements associated with herbicide treatments were presented in a series of four unreplicated case studies involving Douglas-fir (*Pseudotsuga menziesii*) plantations in western Oregon (Brodie and Walstad, 1987). Growth and yield projections from herbicide-treated and untreated sites indicated that early differences in stand development translated into 60 per cent increases in merchantable volume at the end of a typical Douglas-fir rotation (60–75 years) for three of the four cases. The increase in merchantable volume at 60 years for the fourth case was 15 per cent greater than for untreated sites.

A 10-year study of Douglas-fir response to various herbicide and manual methods of competition release on six sites in the Coast Range of Oregon and Washington (Harrington *et al.*, 1995) revealed that when herbicides effectively controlled all competing vegetation around saplings, stem volume was more than double that of untreated plots 10 years after treatment (12–13 years after planting). Monleon *et al.* (1999) also demonstrated a doubling of Douglas-fir stem volumes at year 10 in western Oregon from the early reduction in shrub densities with herbicides. Another study in the Oregon Coast Range recently demonstrated that complete vegetation removal for the first 5 years of stand development increased Douglas-fir volume per hectare after 15 years by 454 per cent relative to plots that received no vegetation control (Yildiz, 2000). Stein (1995) found that site preparation using herbicides on four sites in the Oregon Coast Range resulted in a 272 per cent increase in the Douglas-fir stem volume per hectare after 10 years when survival was taken into account. A 12-year study using a mixed species Nelder design with various combinations of western hemlock (*Tsuga heterophylla*), red alder (*Alnus rubra*) and salmonberry (*Rubus spectabilis*) in the Oregon Coast Range showed a threefold increase in stem volume yield for western hemlock grown without shrub and herbaceous vegetation (Newton and Cole, 2000). Simard *et al.* (2005) documented the growth response of lodgepole pine (*Pinus contorta*) to various densities of Sitka alder (*Alnus viridus*) and herbaceous vegetation in a central British Columbia experiment. Although early vegetation control reduced pine survival and the presence of alder increased available nitrogen, lodgepole pine stand volumes at 15 years were 153 per cent higher on plots where all woody and herbaceous vegetation was controlled than on plots without any vegetation management.

On more xeric sites in the Pacific Northwest, Busse *et al.* (1996) reported 35 years of growth by ponderosa pine (*Pinus ponderosa*) to various planting densities and the presence or absence of competing vegetation on a low productivity site in central Oregon. Removal of competing vegetation increased wood volume by only 5 m^3 ha^{-1} (4.4 per cent) above the plots where vegetation was present among the various density treatments. Powers *et al.* (2005) examined 28 years of growth response by ponderosa pine in northern California following herbicide treatment and nitrogen fertilization. Results from the same experiment on two soil types revealed a 580 per cent and 78 per cent increase in stand volume from vegetation removal alone. In another long-term study with ponderosa pine, McDonald and Powers (2004) reported 27 years of growth response to four levels of shrub density. Pine stand volumes were 11 800 per cent higher on plots with no shrubs than those with the highest shrub density. In this study, even the lowest density of shrubs reduced stand volumes by two-thirds.

Lanini (2003) examined 21 years of growth for three conifer species after three site preparation treatments and up to 2 years of follow-up release treatments were applied in northern California. Brushraking followed by up to 2 years of herbicide release increased the volume growth of ponderosa pine and California white fir (*Abies concolor*) by 3035 per cent and 1712 per cent, respectively, relative to a hydroax site-preparation treatment and no release. The third conifer species (*Pinus lambertiana*) had very low survival (<3 per cent) in all treatments due to other factors.

Oliver (1990) followed the 20-year growth and development of planted ponderosa pine in northern California in 2,4,5-T herbicide-treated and untreated plots of various planting densities. Regardless of planting density, total volume per hectare of pine stands was 93 per cent greater for stands treated with herbicide. Another study with ponderosa pine on three northern California sites, known as the 'Garden of Eden' experiment (Powers and Reynolds, 1999), compared the effect of various combinations of herbicide, insecticide and fertilizer treatments on 10-year volume growth. Vegetation control had the strongest influence on plantation growth among the three treatments, increasing volume by 270 per cent, 173 per cent and 59 per cent above the untreated control on each of the three sites.

Using 14-year measurements from a south-western Oregon study, Hanson (1997) found that the stem volume of individual ponderosa pines was about 464 per cent higher on plots without vegetation than when shrubs and hardwoods were maintained at a high density. A study of 10-year growth responses for ponderosa pine and California white fir in northern California found individual-tree stem volume increases of 1593 per cent and 1012 per cent, respectively, following various years of vegetation control after tree planting (McDonald and Fiddler, 2001a, b).

Two experiments in south-western Oregon with 12- and 14-year measurements of Douglas-fir growth showed that the mean volume per tree was about 200 per cent and 245 per cent higher, respectively, when hardwoods and herbs were controlled using herbicides (Hanson, 1997). In addition, the early negative influence of competing vegetation led to significant underestimations of the growth potential for these forests. Significant upward corrections of 50-year site index curves were needed if vegetation was controlled early in stand development. These substantial increases in young stand growth from FVM has prompted a re-evaluation of metrics traditionally used to measure forest productivity for modelling long-term wood supplies for large forest areas.

Volume gains in south-eastern forests

The potential yield gains associated with intensive management of competing forest vegetation in North America were documented first by forest researchers and managers in the south-eastern states (Elwell, 1967; Grano, 1970; Smith and

Schmidtling, 1970). Michael (1980) provided one of the first reports of long-term gains 20 years after 2,4,5-T aerial release to longleaf pine (*Pinus palustris*) that resulted in 40 per cent more wood volume. In one of the longest studies in the south-east, Glover and Zutter (1993) measured the 27-year yields for loblolly pine (*P. taeda*) that were planted following no treatment into dense residual understorey hardwoods and with no herbicide, mechanical and manual methods of site preparation. Variable levels of hardwood control among the study plots provided a unique opportunity to quantify how various densities of unwanted hardwoods influenced the yield of loblolly pine. Herbicide treatments and scarification with a bulldozer provided the best control of hardwood vegetation. Total pine volume at 27 years was 58-fold higher on herbicide-treated than untreated plots. A strong relationship (R^2 = 0.95) was found between the basal area of loblolly pine at year 27 (the end of the rotation) and number of hardwood stems 3 years after site preparation. Therefore, vegetation dynamics established early in stand development by herbicide or other vegetation control treatments were found to have a long-term influence on species composition and stand yield through the entire rotation.

Probably the earliest region-wide study (15 sites) of intensive vegetation control treatments in the south-east was a site preparation study established in 1980 with slash pine (B. D. Shiver, unpublished data). After 23 years, controlling all herbaceous and woody vegetation resulted in total volume gains of 76 per cent. Gains in volume were evident by age 5 years and were maintained over the rotation. While the age of peak mean annual increment in total stand volume did not changed from that exhibited by less intensively managed plantations, total wood volumes produced were substantially higher. As in the Pacific Northwest, traditional site index curves were found to be inadequate for projecting the growth of pine stands under intensive management regimes.

Another region-wide site preparation study with loblolly pine (Shiver and Martin, 2002) included 25 locations across South Carolina, Georgia and Alabama. The treatments included total vegetation (woody and herbaceous) control with herbicides, a typical site preparation treatment including herbicides and two other mechanical treatments. After 12 years, the combined herbicide, burn and herbicide treatment increased merchantable pine volume by 201 per cent relative to the untreated control.

One of the most comprehensive studies examining yield enhancements from FVM was conducted by Miller *et al.* (1991, 1995a–c; 2003a, b), Zutter and Miller (1998) and Zutter *et al.* (1999). The same experimental design was replicated in 13 plantations across seven southern states and four physiographic provinces of the region. Loblolly pine plantations were monitored for 15 years (or over 60 per cent) of the typical 24-year pulpwood rotation. A factorial combination of two woody control treatments (no woody control *vs* complete woody plant control) and two herbaceous control treatments (no herbaceous control *vs* complete herbaceous plant control) was established. Herbicides were used before planting and annually through crown closure (3–5 years after planting) to establish and maintain the treatments. Pine yields at year 15 were strongly influenced by herbicide treatments applied during the first 3–5 years after planting. Controlling both woody and herbaceous vegetation increased merchantable wood volumes by 67 per cent (range among sites was 30–148 per cent) above that on plots that were only site prepared. Control of only woody vegetation increased merchantable pine volume on 11 sites by 14–118 per cent and gains on treated plots increased as hardwood and shrub abundance increased on the check plots. Gains from early control of only herbaceous vegetation (leaving woody vegetation) were somewhat less, increasing only 17–50 per cent on 10 sites (Miller *et al.*, 2003b). No gains and some losses occurred when control of one vegetation component enhanced competition from other types of vegetation; otherwise gains were generally additive when both vegetation components were controlled.

Borders and Bailey (2001) studied intensive treatments for loblolly pine plantation management at six sites in Georgia (including sites with high shrub density). After intensive mechanical site preparation and planting high-performance half-sib seedlings, continuous vegetation control increased merchantable volume through ages 10–12 years from 37–122 per cent. Adding repeated fertilization further enhanced yields. Borders and Bailey (2001) concluded that growth rates were comparable to those obtained at other high biomass production areas for loblolly pine throughout the world (e.g. South Africa, Brazil and Australia).

Glover *et al.* (1989) found that regularly controlling herbaceous vegetation using herbicides from planting to crown closure in young loblolly pine stands increased merchantable volume after 12 years by 33, 96 and 131 per cent on three sites in Arkansas and Mississippi. Other long-term studies of intensive vegetation control have come from Louisiana's nutrient-deficient Coastal Plain and have documented loblolly pine volume increases of 14–20 per cent over 10–30 years (Clason, 1989; Haywood and Tiarks, 1990; Haywood, 1994). In the longest of these studies, Clason (1989) reported that volume gains remained constant from years 20 to 30.

Volume gains in northern forests

MacLean and Morgan (1983) published results from one of the earliest studies on the effect of herbicide release in northern forests. Plots where phenoxy herbicides were used to release young balsam fir (*Abies balsamea*) in northern New Brunswick were compared with those that were manually cleared and with those that received no treatment. The herbicide treatments were applied in 1953 and the plots remeasured in 1981 (28 years after treatment). The total stem volume of balsam fir was 265 per cent greater in herbicide-treated plots than in untreated control plots.

In another early Canadian study, Sutton (1995) reported the combined influence of fertilization, irrigation and vegetation control (using herbicides and mechanical methods) on the 30-year response of planted white spruce (*Picea glauca*) in eastern Ontario. Results from three sites indicated that spruce stem volume was from 53 to 96 per cent greater with vegetation control than without treatment. Vegetation control was the only treatment among the three producing statistically significant differences in tree growth after 30 years.

In a study of spruce-fir (red spruce (*Picea rubens*) and balsam fir) in Maine, Daggett (2003) examined the effects of aerial herbicide application and pre-commercial thinning (PCT) on long-term stand development. This study, initiated in 1977, is the longest examination of the newer and most commonly used herbicides (glyphosate and triclopyr) in North America. Although total wood volumes (with hardwoods included) were not increased by herbicide or PCT treatments 22 and 13 years after treatment, respectively, the proportion of wood volume in 29-year-old balsam fir and red spruce was substantially increased by herbicide treatment. Among 14 herbicide treatments tested, softwood composition was 74 per cent in herbicide-treated plots compared with 23 per cent in untreated plots. Daggett (2003) also compared the influence of herbicide and PCT treatments on the merchantable volume of softwoods using several standards. Using the lowest standard (i.e. using the smallest merchantable top diameters), softwood volume was increased by 171 per cent in herbicide-only plots relative to untreated plots. When including only the newer herbicides (glyphosate and triclopyr), merchantable softwood volume increased 264 per cent above untreated plots. The effect of the herbicides was enhanced further if the stands were later subjected to PCT and previous herbicide application enhanced the later effectiveness of PCT. When herbicides and PCT were used in combination, merchantable softwood volume at 29 years was 411 per cent greater than the untreated controls.

Ten-year growth responses of planted black spruce (*Picea mariana*) and associated vegetation were studied for 10 years following several competition release treatments on two sites in north-eastern Ontario by Pitt *et al.* (2004). Five growing seasons of annual vegetation removal using repeat applications of glyphosate herbicide produced nearly complete domination by spruce with 111 per cent and 477 per cent increases in individual tree stem volume relative to that of untreated plots. The degree of stem volume gain among treatments was positively correlated with the level of vegetation control during the first few years after treatment.

Several studies from British Columbia have more than a decade of growth response measurements for several conifer species following a variety of site preparation and release treatments. A replicated study by Biring *et al.* (2003) found 124 per cent increases in the stem volume of Engelmann spruce (*Picea engelmannii*) following herbicide treatments when reductions in both tree growth and survival were considered. Several unreplicated trials with 10–12 years of measurements found 49 per cent to over 5400 per cent gains in stem volume for several conifer species (Harper *et al.*, 1997, 1998; Biring *et al.*, 1999, 2001; Biring and Hays-Bayl, 2000).

In a recent Ontario study examining the responses of young northern forest plantations to various timings and durations of vegetation control, Wagner *et al.* (1999) found that nearly all of the potential productivity in early stand development could be obtained if vegetation was controlled for a critical period after planting jack pine (*Pinus banksiana*), red pine (*Pinus resinosa*), eastern white pine (*Pinus strobus*) and black spruce. Ten-year measurements from this study indicate that these earlier patterns are maintained for the first decade of stand development (Wagner, 2003). Stem volume production for jack pine, red pine, eastern white pine and black spruce increased by 116, 212, 216 and 349 per cent, respectively, during the first 10 years if surrounding vegetation was controlled for the first 1–3 years after planting.

South Africa

The South African forestry industry grows a variety of commercial tree species, including *Pinus* spp. (52 per cent of the area), *Eucalyptus* spp. (39 per cent) and *Acacia mearnsii* (8 per cent). Of the 1.4 million ha that are planted, 75 000 ha are re-established annually. Silvicultural practices are designed to take full advantage of the productivity potential of each site through the use of site preparation, vegetation management, fertilization and appropriate spacing.

Of the total roundwood production in 2002 (16.6 million m^3), 56 per cent was used for pulpwood, 37 per cent for sawlogs and 3.8 per cent for mining timber. Eucalypt and pine sawtimber rotations are 26 and 28 years, respectively. Pulpwood fibre rotations are 8 years for eucalypts and 16 years for pines. As most of the trees are planted at densities ranging from 1111 to 1666 stems ha^{-1}, site capture occurs within 1–2 years (9–12 growing months) for eucalypts and 3–5 years for pines.

Rotation-length vegetation management

The management of vegetation in South Africa occurs during the entire rotation and can be divided into three phases: (1) between harvesting and planting; (2) between planting and canopy closure; and (3) between canopy closure and harvest. Each phase presents a set of unique vegetation problems and management challenges.

The length of time between harvesting and planting is generally kept to a minimum. Seldom is land left in an unproductive state for any length of time. If necessary, a broadcast herbicide application is made just prior to planting. This preplant treatment often delays the timing of the first weeding operation, which can occur from 30 to 60 days after planting (Little and Rolando, 2005) and results in the almost complete eradication of all vegetation as a non-selective, broad-spectrum herbicide (glyphosate) is used.

The period between the planting of trees and canopy closure is considered to be the most important period for vegetation management. A number of experiments have been conducted related to optimizing vegetation control operations during this period and include determination of minimum row-weeding distances, timing of vegetation control operations, use of inter- and cover-crops, selective control of vegetation and linking vegetation control to other silvicultural practices (Little and Schumann, 1996; Little *et al.*, 2002; Little, 2003; Little and Rolando, 2005). After trees are planted, vegetation control using a combination of glyphosate and manual weeding is generally used during the establishment period. These treatments are normally timed to reduce any competitive influence that competing vegetation might have on tree growth.

Between canopy closure and harvest, high planting densities (1111–1666 ha^{-1}) combined with rapid growth allow planted trees to competitively exclude nearly all other vegetation. Even where full canopy closure is not achieved (e.g. in stands that are poorly and/or unevenly stocked), the influence of vegetation on post-establishment growth is minimal (Little and Rolando, 2002; Little, 2004). Where vegetation does occur, control of invasive plants is carried out as required by legislation. This, together with the selective control of other woody plants, helps to reduce under-canopy fuel loads and risks of uncontrolled fires, reduces the seed bank of unwanted plants, prevents re-establishment of undesirable plants and improves site access for other silvicultural operations.

This three-phase management strategy restricts development of unwanted vegetation on most sites. Any competing plants that do establish tend to develop from seed. These plants, however, are generally controlled before being allowed to overtop desired trees. Vegetation that does establish will tend to exhibit rapid growth and high seed production early in their lifecycle. Therefore, most vegetation occupying forest plantations tends to be either annuals or perennials that are controlled early in their lifecycle or 'difficult to control' perennials that propagate by specialized vegetative structures.

Volume gains from vegetation management

Vegetation management has been shown to be critical immediately after plantation establishment, with a number of experiments demonstrating substantial growth benefits from vegetation control (Morris, 1994; Little and Rolando, 2001; South *et al.*, 2001; Little and van Staden, 2003). Environmental factors associated with elevation determine the degree of vegetation-induced growth suppression of planted trees. At lower elevations, the type, abundance and competitive influence of vegetation and thus degree of vegetation control required, is dependent upon the tree species that has been planted, historical land use, silvicultural practices and local physiographic, edaphic and climatic conditions (Mason, 1993; Little and Rolando, 2001; Jarvel and Pallett, 2002; Little and Rolando, 2005). Above 1500 m a.s.l., growth losses from competing vegetation are rarely significant.

Vegetation management studies in eucalypt plantations (Little, 1999, 2003; Little *et al.*, 2002, K.M. Little, unpublished data) have produced 29–122 per cent increases in final volume when grown on a pulpwood rotation (Table 1). Current vegetation management experiments with pines in South Africa are 8 years and less, thus no long-term data are currently available. Early- to mid-rotation data from these trials, suggest 10 to >100 per cent increases in stem volume from vegetation management (Morris, 1994; Kotze, 2002; South *et al.*, 2001; Rolando and Little, 2004).

South America (Brazil and Chile)

The South American forest products sector is dominated by plantation silviculture. Brazil and Chile provide a good example of how the plantation-based forest industry has developed in South America. The industrial roundwood production of Brazil is 103 million m^3, while that of Chile is 24.5 million m^3 (FAO, 2003), corresponding to 67 per cent and 16 per cent, respectively, of the total South American industrial roundwood output. Together these two countries account for 83 per cent of the industrial roundwood production on the continent (and 8.1 per cent of world production). In both countries, the majority of wood production is derived from plantations. In Brazil, 62 per cent of all industrial roundwood consumption comes from plantations; including 100 per cent of all pulp and paper output (Sociedade Brasieira de Silvicultura, 2003). Chile is more dependent upon planted forests, with 95 per cent of all industrial roundwood produced in the country coming from plantations (Instituto Forestal, 2004). At least 66 per cent of all South American industrial roundwood production is estimated to come from plantations. It is possible that this percentage would be higher if contributions from Argentina and Uruguay were included. These two countries are also heavily dependent upon plantation silviculture for their wood supplies (FAO, 2001). Both countries together contribute an additional 5.5 per cent to roundwood production in South America.

Plantations and vegetation management

Plantation silviculture in the temperate southern zone (i.e. subtropics or tropical areas of South America) is generally an intensively managed system directed at maximizing productivity. For example, Brazil grows primarily *Eucalyptus* spp. and *Pinus* spp. plantations that rely on chemical site preparation combined with mechanical ripping and pre-planting fertilization. Eucalyptus planting stock is typically from clonal material, while pine planting stock is typically from first or second generation seed orchard material. The typical rotation length for eucalyptus plantations is 6 years with average growth rates from 25 to 40 m^3 ha^{-1} a^{-1}. Pines generally require twice the rotation length (around 15 years for a pulpwood rotation) and achieve 60–70 per cent of the growth rates for eucalypts.

Vegetation management is essential for achieving high rates of productivity for *E. urograndis* and *P. eliottii* plantations in Brazil, or *E. globulus* and *P. radiata* plantations in Chile. Herbicides provide the foundation for vegetation management wherever intensive plantation management has developed. Pre-emergent herbicides (such as oxyfluorfen) as well as directed post-emergent sprays of glyphosate are generally used. In addition, forest managers in Brazil and Chile use manual labour with hoes or machetes when herbicide use is impractical. Depending on site and stand conditions, rotary mowers may be employed for vegetation control between rows of planted trees. Competition from other vegetation is generally greatest during the first 18 months in eucalypt plantations and during the first three years in pine plantations. After this, crown closure often begins to provide sufficient shade to reduce seed germination of understorey vegetation.

One of the most important aspects of vegetation management in Brazilian and Chilean forest plantations is that the vast majority of planting sites are former agricultural lands. Few plantations in South America have been established by converting native forests. The success of federal tree planting programmes in the 1970s and 1980s in both countries resulted from planting nonproductive coffee and citrus plantations, or degraded pasture lands. As a result, competing vegetation in these plantations generally arise from annual and perennial herbaceous species.

Volume gains from vegetation management

As in other parts of the world, most studies from South America report only first year growth responses to vegetation control (Couto and Medeiros, 1993; da Silva *et al.*, 1997; Brendolan *et al.*, 2000; Constantin *et al.*, 2000), but there are a few studies that have measured eucalypt growth for 3 or more years. Zen (1986) reported that keeping a *E. grandis* plantation vegetation free, primarily from *Imperata brasiliensis*, in southern Brazil resulted in a 3-year wood volume increase from 94 m^3 ha^{-1} for the untreated control plots to 262 m^3 ha^{-1} on vegetation-free plots, a 179 per cent increase. These 3-year measurements were half of the rotation. Keeping the plantation vegetation free for 60, 120 and 180 days increased 3-year wood volumes by 145 per cent, 198 per cent and 178 per cent, respectively, with Zen (1986) concluding that maintaining the site vegetation free for only 120 days after planting was sufficient to obtain all the possible growth advantages. Results were similar on a different site in the same study, where the majority of competition came from bracken fern (*Pteridium aquilinum*), with growth increases of 122 per cent over the untreated control plots after only 60 days of vegetation control. Given the high productivity of these sites, eucalypt crown closure probably occurred at around 12 months. Couto and Medeiros (1993) also reported that most increases in eucalyptus volume growth occurred early in the rotation and that vegetation control beyond 4 months provided little benefit.

de Toledo *et al.* (2003a), also working in southern Brazil, provided additional data about the long-term growth response of eucalypts to effective vegetation control. This study examined the effect of the width of a vegetation control band in eucalypt hybrid *E. grandis* × *E. urophylla*, typically known in Brazil as *E. urograndis*. The authors tested band widths of 0–1.5 m on one side, maintaining them for different lengths of time and reported growth responses at 4 years (of a 6-year rotation) on two sites. When comparing tree growth on plots without vegetation control to plots with vegetation control applied to 1-m-wide strips (total band width 2 m) for 12 months, there was a 108 per cent volume increase on one site and a 10 per cent increase on a second site. Substantially higher growth response on the first site was due to it being a former pasture where vegetation abundance was high. The second site was established on a previous eucalypt plantation where vegetation abundance had been greatly reduced during the preceding rotation. de Toledo *et al.* (2003a) concluded that at 49 months after planting, a 0.50-m strip on either side of the planting row was not sufficient to keep eucalypts 'free' of competition.

Another study by de Toledo *et al.* (2003b) examined the effect of vegetation control on eucalypt productivity for a full rotation of 6.5 years. This study in southern Brazil compared 16 levels of pasture grass control on a site that was previously planted with eucalypts. At 6.5 years after planting, the best treatment increased stem volumes by 144 per cent, from 212 m^3 ha^{-1} for the untreated plots to 518 m^3 ha^{-1} for the plots with the most effective vegetation control.

New Zealand and Australia

Australia has 155 million ha of native forests, including 43.8 million ha of closed forest (81 per cent to 100 per cent crown cover) and open forest (51–80 per cent crown cover). Some 22.3 million ha of closed and open forest is either privately owned or leased, while the balance is multiple-use forest (11.0 million ha), conservation reserves (8.4 million ha), or other categories of public ownership (2.1 million ha) (Source: National Association of Forest Industries 2004; www.nafi.com.au). Australia has ~1.3 million ha of plantation forests, with radiata pine being the dominant plantation species (70 per cent of plantation area). Other conifer species include slash pine (*P. elliottii*), Caribbean pine (*P. caribaea*), loblolly pine and *Araucaria* spp., in northern east-coast environments (Queensland and New South Wales), and maritime pine (*Pinus pinaster*). There are a variety of eucalypt plantations mainly in Tasmania, Victoria and Western Australia. The forest industry is one of Australia's largest resource-based industries.

About 30 per cent of New Zealand's land (26.7 million ha) is covered by forest, including 1.8 million ha of plantations (NZFOA, 2004). Plantation forestry in New Zealand is synonymous with radiata pine which is grown on about 90 per cent of the plantation area. The second species is Douglas-fir (6 per cent of plantation area) followed by a small amount of other conifers and hardwoods (mainly *Eucalyptus* species). The majority of the forest ownership is private. The forestry sector contributes about 4.0 per cent of New Zealand's GDP and forestry product exports have a total value of about NZ$3.5 billion.

Plantation forests in New Zealand and Australia are distributed over a wide range of climates and soil types. In general, the forests of Australia are found in lower rainfall environments than those in New Zealand (Boomsma and Hunter, 1990). The majority of Australian plantations receive <1200 mm rainfall per year, with over half receiving <900 mm per year (Booth and McMurtrie, 1988). In contrast, most plantations in New Zealand have been established in wetter environments with a mean annual rainfall in the North Island of 1450 mm (range 870–2300 mm) (Hunter and Gibson, 1984). Nevertheless, there are also very dry sites in New Zealand, particularly on the South Island, where annual rainfall can be as low as 650 mm. Fertility of forest soils varies widely in both Australia and New Zealand. Fertilizers are typically applied where there are obvious nutritional problems. In recent years, the trend in both countries has been to afforest former pasture sites with high fertility (Turner and Lambert, 1991).

Vegetation management and growth responses

Vegetation management is a routine practice in plantation forests of Australia and New Zealand that is carried out to achieve multiple objectives (Richardson, 1993). The most common aim, however, is to reduce resource competition from associated vegetation so that site resources (water, light, nutrients) are available to crop trees.

Richardson (1991, 1993) summarized many studies that all reported large percentage gains in radiata pine (*Pinus radiata*) tree volume (or an index of tree volume) following vegetation control. Maximum percentage gains (Richardson, 1991) ranged from ~1000 per cent 1 year after planting to ~80 per cent after 10 years (Squire, 1977; Brunsden, 1980; Cellier and Stephens, 1980; Nambiar and Zed, 1980; Balneaves, 1982; Turvey *et al.*, 1983; Sands and Nambiar, 1984; West, 1984; Ellis *et al.*, 1985; Turvey and Cameron, 1986; Squire *et al.*, 1987; Baker *et al.*, 1988; Balneaves and Christie, 1988; Ray *et al.*, 1989; Smethurst and Nambiar, 1989; Balneaves and McCord, 1990). More recent studies of interactions between trees and surrounding vegetation in the first years after planting show similar results (Richardson *et al.*, 1996, 1997a, b; Mason and Kirongo, 1999; Watt *et al.*, 2003).

A smaller number of experiments with vegetation management treatments have been undertaken in both Australia and New Zealand with other tree species such as Douglas-fir (Preest, 1977), *Eucalyptus* spp. (Schonau, 1984; Messina, 1990), *Acacia melanoxylon* (Messina and Barton, 1985) and *Araucaria cunninghamii* (Constantini, 1989).

The substantial variation in growth response observed among these studies is the result of (1) interactions between a large number of variables including site and climatic factors, (2) vegetation and tree characteristics, (3) type and duration of vegetation management treatments, and (4) the way that growth responses of treated and untreated stands are reported. Vegetation management research in New Zealand since the early 1990s has moved away from simply measuring long-term growth responses to different treatments, and instead has focused on improving understanding about the underlying mechanisms of plant competition. The reason for this approach is that with such a large number of variables contributing to both long- and short-term growth responses to vegetation management, it would be impractical to install and monitor sufficient experiments to cover all interactions of interest. Consequently there are relatively few long-term studies to report beyond those covered in previous reviews.

Snowdon and Waring (1984) identified two types of growth response to silvicultural treatments. Type 1 responses result from treatments that have little or no permanent effect on soil characteristics and lead to parallel growth trends between treated and untreated stands. Type 2 responses are characterized by an absolute change in productivity (an increase in site carrying capacity) and a divergence of growth curves for treated and untreated stands (Snowdon and Khanna, 1989). Mason (1992) discussed the implicit assumptions required to obtain both types of growth responses. The positive response to vegetation control is generally considered to be short term, and therefore Type 1 (Snowdon and Khanna, 1989).

The best method for assessing whether responses to vegetation treatments are Type 1 is to measure the time difference between treated and untreated stands, i.e. the difference between the current age of the untreated stand and the age of the treated stand at which the volume was identical (Figure 1). Using the time axis as a means for comparison is preferable to the growth axis because even where the growth curves are parallel, proportional effects expressed in terms of basal area or volume will continue to change (Mason, 1991). When a Type 1 condition exists, the time difference will remain constant after the initial period of divergence. This approach is most appropriate in stand conditions where interspecific competition occurs during a relatively short phase during the early part of a rotation. Where other tree species are available to competitively displace crop trees in the final canopy, such as is found in many North American forest systems where broadleaved trees are the major competitor (described above), divergence of growth curves between treated and untreated stands can occur for the entire rotation. This effect would produce a pattern similar to a Type 2 response, although no absolute change in site productivity has occurred.

Experiments to measure long-term growth trends

Relatively few experiments in New Zealand or Australia have been measured for the duration or with the frequency required to confirm the nature of the growth response to vegetation management. Two experiments designed to measure the radiata pine growth response to spot vegetation control are exceptions to this generalization (Richardson *et al.*, 1996). One experiment was established in Kaingaroa forest (North Island, New Zealand) on a second rotation site that was oversown with a grass species (*Holcus lanatus*) prior to planting. The second experiment was established in Tokoiti Forest (South Island, New Zealand) on a coastal, ex-pasture site. Treatments were applied to evaluate the effect of area and duration of spot vegetation control, including complete vegetation control and no vegetation control.

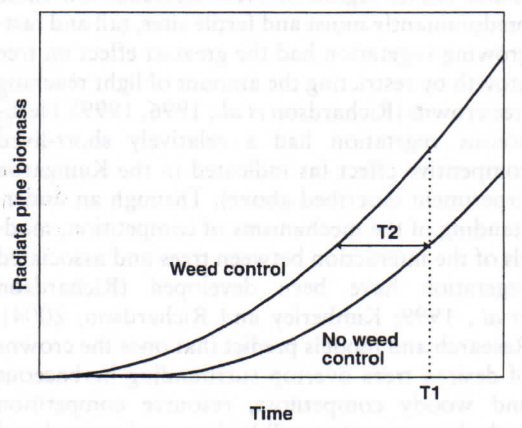

Figure 1. Growth benefit to radiata pine from vegetation control. At time T1, T2 represents the effective age difference with and without initial vegetation control.

After 5 years in the Kaingaroa Forest experiment, tree stem volume in the vegetation-free plots had increased by 54 per cent compared with trees in no-vegetation-control plots (B. Richardson, unpublished data). This yield gain was equivalent to a time gain of about 1 year from complete vegetation control. With a Type 1 response, it is assumed that this time gain will be maintained until the end of the rotation, typically about age 28–30 years and long before maximum productivity is reached. By age 6 years in the Tokoiti Forest experiment, tree stem volume in vegetation-free plots had increased by 400 per cent compared with trees in no-vegetation control plots (B. Richardson, unpublished data). This yield gain was equivalent to a time gain of 1.8 years from complete vegetation control. The larger growth gain from complete vegetation control in Tokoiti Forest may have been related to the lower annual rainfall (annual mean of 800 mm at Tokoiti compared with about 1500 mm at Kaingaroa). One important finding from these two trials was that the duration of the treatment effects on tree growth was relatively short, about 3 years at Kaingaroa and about 5 years at Tokoiti. These results support the contention that tree growth following vegetation control generally follows a Type 1 response.

Detailed studies on the mechanisms of competition between trees and surrounding vegetation were undertaken in the 1990s in the Central North Island (CNI) region of New Zealand. On these predominantly moist and fertile sites, tall and fast-growing vegetation had the greatest effect on tree growth by restricting the amount of light reaching tree crowns (Richardson *et al.*, 1996, 1999). Herbaceous vegetation had a relatively short-lived competitive effect (as indicated in the Kaingaroa experiment described above). Through an understanding of the mechanisms of competition, models of the interaction between trees and associated vegetation have been developed (Richardson *et al.*, 1999; Kimberley and Richardson, 2004). Research and models predict that once the crowns of desired trees overtop surrounding herbaceous and woody competitors, resource competition with this vegetation will be low, and treated and untreated stands will grow along parallel trajectories (Type 1 response) (Figure 1).

Even on dry sites with longer-lived shrub competitors, there is evidence to suggest that vegetation control leads to a Type 1 growth response, even if the period of stand divergence is relatively long. For example, on a site in Canterbury (South Island, New Zealand) with low summer rainfall (annual average of ~600 mm), broom (*Cytisus scoparius*), a woody shrub, was removed from plots in a 9-year-old stand of radiata pine (Richardson *et al.*, 2002). The treated plots were kept free of broom for a further 3 years. At the end of this period, trees in plots with broom removed had a 23 per cent increase in height growth increment and a 24 per cent increase in basal area increment. Water balance models (Richardson *et al.*, 2002) indicated that broom reduced tree growth by reducing root-zone water storage. By age 14 years, the pine crowns developed to a point where broom was competitively excluded by the pine. Although no further measurements were taken, it seems reasonable to assume that pine growth would have followed a similar trajectory to trees of the same size in the original vegetation-free plots.

Time gains from vegetation management

A model predicting the survival and growth of radiata pine up to 5 years old in the CNI region was synthesized using 27 site preparation experiments, many that included a vegetation management component (Mason, 1992; Mason and Whyte, 1997; Mason *et al.*, 1997). The model indicated that vegetation control was the single most important treatment in this region for improving tree growth and survival, the latter variable being particularly important on sites prone to frost. The effects of vegetation control on tree growth were greatest at low elevations and there was some evidence that vegetation control was necessary to receive any growth benefit from fertilizer applications. Stand uniformity (lower variance in height and diameter) also was improved with vegetation management.

Table 2 summarizes growth benefits following vegetation control from a range of field trials at various locations across New Zealand, including the CNI region. The growth benefit is expressed in terms of the time gain of the treated compared with untreated stands (i.e. the difference between the current age of the untreated stand and the age of the treated stand at which the volume was identical). These data need to be interpreted conservatively, because in some of the experiments inappropriate pruning and thinning masked treatment effects. In several of the trials, there also was initial vegetation control across the entire experiment; the vegetation control *vs* no vegetation control comparison was established at a later date. Nevertheless, these data suggest an overall time gain of from 1 to 4 years following early vegetation control on many sites. There also was some suggestion that the time gain on dry sites is greater than on moist sites.

Volume gains over a rotation

The percentage wood volume gain from a time gain of 1–4 years over a full rotation (4–17 per cent of rotation age) has been calculated using growth data from permanent sample plots in Kaingaroa Forest. Tree volume (mean annual increment 19.2 m^3 ha^{-1}) and cumulative annual increment (35 m^3 ha^{-1}) were calculated for 25- to 30-year-old plots (typical rotation age for radiata pine). Using this approach, a time gain of 1–4 years would increase wood volume from 7 to 27 per cent at the end of the rotation.

Conclusions

The longest-term data from 60 controlled experiments around the world have demonstrated that substantial gains in wood volume yield can be obtained when competing vegetation is effectively managed. About 25 per cent of the studies in Table 1 had volume gains from 100 to 200 per cent. Over half (55 per cent) had 50–300 per cent yield increases. Three-quarters (74 per cent) of the studies produced yield gains from 30 to 500 per cent. The proportional yield gains ranged several orders of magnitude among studies, but there was no clear pattern by region. There also was no apparent correlation between the yield gain and the length of measurement following treatment.

Although generalizations are difficult among these highly varied forest regions and experimental conditions, it appeared that the highest yield gains (>1000 per cent) occurred in experiments where there was substantial regeneration failure of desired tree species without controlling competing vegetation. Gains of 100–1000 per cent generally occurred in studies where unwanted hardwoods and/or shrubs were able to competitively displace desired tree species in the final canopy. Yield gains from 10 to 100 per cent appeared to be associated most often with growth delays from competition with herbaceous vegetation or shrubs that were not able to competitively displace desired trees.

It is important to note that the results from the studies presented here reflect the largest yield increases that were obtained among the treatments that were compared in each study. In many cases, these treatments reflect vegetation management practices (e.g. control of all vegetation for several years) that are not typically being used in the region studied. It is also true that many of the treatments that proved most effective in the studies are regularly applied, or started being practiced as a result of the documented growth responses presented in many of these long-term studies. For example, the control of herbaceous vegetation in young plantations was not thought to be practical or economical in many regions until substantial growth gains were demonstrated in the kinds of studies presented here. Today, control of herbaceous vegetation is a routine silvicultural practice in intensively managed forest plantations around the globe.

The objective of this review was not to describe the yield gains that result from typical operational practices, but to summarize the documented yield gains that can be biologically achieved from managing competing vegetation in forests around the world. The financial, ecological and social acceptability of practices reported in the studies presented here must be evaluated by individual forest managers and landowners in each region.

Continued monitoring and analysis of these and other studies must continue in order to quantify the rotation-length influence of forest vegetation management, especially in regions with long (>50 year) forest rotations. It will only be through developing a substantial rotation-length database that the financial returns from managing forest vegetation can be estimated with greater certainty.

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