

LONG-TERM ECOLOGICAL IMPACTS OF SELECTIVE HARVESTING ON A NEW ZEALAND CONIFER-HARDWOOD FOREST

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ABSTRACT

Maintaining the stability and productivity of residual forest after harvesting is a crucial requirement of sustainable forest management. We assessed the long-term (43-year) impact of group selective harvesting using ground extraction of one-third of merchantable volume on 30 ha of mixed conifer/hardwood forest at Pureora, North Island, New Zealand. Selective harvesting did not substantially alter canopy composition or the population structure of conifers in the two 15-ha harvested blocks. It did not adversely affect the stability of the residual forest, with similar mortality rates in merchantable conifer trees in the 15-ha control (0.7%/year) and residual conifers in the two harvested blocks (0.6%/year, 0.8%/year). Tree mortality in harvested blocks was not related to harvesting disturbance. Productivity was somewhat reduced by selective harvesting (0.3, 0.2 m³/ha/year in harvested blocks; 0.4 m³/ha/year in the control) because of reduced tree densities. Net merchantable volume increment was negative in conifer species in all blocks, ranging from -0.4 to -0.6 m³/ha/year. Although regeneration of major canopy species had largely recovered within a decade of harvesting, much more time will be needed for the forest as a whole to recover fully.

Keywords: rain forest; selective harvesting; ecological impacts; conifers.

INTRODUCTION

Despite some early successes in south Asia and elsewhere, sustainable rain forest management has remained something of an elusive goal, subject to the ever-changing social and political contexts in which forestry operates (Bruenig 1996). New Zealand is no exception. The natural rain forests (Dawson & Sneddon 1969)

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that originally covered most of the country have been progressively destroyed since the arrival of humans some 800 years ago. They provided virtually all of the country's timber needs until their eclipse in 1959 by exotic plantation-grown conifers (New Zealand Forest Service 1975). With subsequent clearance intended for many forests, uncontrolled logging — removal of all merchantable trees with no regard for residual forest condition — was long the standard management practice in indigenous forests.

Sustained-yield management was practised only on an experimental scale in the North Island until 1975, when a revised policy was implemented (New Zealand Forest Service 1977) in response to growing public dissatisfaction with forest clearance and an increasing national awareness of the heritage values of indigenous forest. A brief phase of partial logging — “thinning from above”, a crude substitute for selection management, sometimes accompanied by replanting (Beveridge *et al.* 1985) — largely ended in 1984 with a Government decision to halt harvesting in most indigenous forests in Crown tenure. The sophisticated selection management schemes mimicking natural forest dynamics in beech (*Nothofagus* spp.) and podocarp forests that followed in limited areas of the South Island were terminated by the Forests (West Coast Accord) Act 2000.

The demand for high-quality timber, including indigenous species not available from plantations, has persisted, however. Together with a growing recognition that timber supply and the maintenance of ecological integrity in indigenous forests need not be mutually exclusive, this led to the Forests Amendment Act 1993. This Act allows the continuing harvest of significant volumes of indigenous timber on freehold land under a “sustainable forest management plan” approved by the Ministry of Forestry, and sets annual or periodic timber harvest “at a rate matching the forest's productivity and retaining its natural values and ability to continue to provide a full range of products and amenities in perpetuity” (Ministry of Forestry 1997). For the first time in New Zealand's history, substantial areas of indigenous forest are coming under sustainable management. Some 584 plans and permits involving 112 500 ha of forest are currently in operation (Ministry of Forestry unpubl. data).

Selection management, the silvicultural system involving the removal at intervals of single trees or small groups of trees selected from throughout a forest stand (Matthews 1991), was undertaken experimentally in North Island podocarp forests in five trials in the 1960s and 1970s. Although the theoretical objectives of the selection system are the improvement of the structure, the merchantable quality, and thus the commercial value of the forests (Matthews 1991), the primary objective of the earliest trials was to find an ecologically acceptable and economically viable alternative to uncontrolled logging. The harvesting and ecological focus was the podocarps, principally rimu (*Dacrydium cupressinum* Lamb.) and matai

(*Prumnopitys taxifolia* (D. Don) de Laub.). Some hardwoods, mostly tawa (*Beilschmiedia tawa* (A. Cunn) Kirk), were also removed.

The primary ecological objective of maintaining a stable residual forest imposed constraints on harvesting methods. Conifers tend to be clumped and so, to minimise damage to residual trees, groups were removed. After harvesting, groups of conifer seedlings were planted on disturbed ground to supplement advance growth. Buffers of intact forest were left around harvested blocks as a protective measure, and an equivalent area of forest was left untreated as a control.

Despite the lack of replication, long-established large-scale selective harvesting trials such as these provide invaluable opportunities to evaluate the long-term ecological impacts of the removal of small groups of trees — as in current harvesting operations — on the health and stability of the residual forest. In this study, we used the results of the latest assessment of one of the two original trials to answer the following questions:

- Did selective harvesting alter the population structure and canopy composition of conifers?
- Did selective harvesting affect the stability of the residual forest?
- Did selective harvesting affect the productivity of the residual forest?
- Did selective harvesting affect the regeneration of major canopy species?
- Has the forest recovered from selective harvesting?

More generally, we ask:

- Is the group selection system suitable for the kind of forest and species here?

BACKGROUND

Ecology

The forests of the Volcanic Plateau in the centre of New Zealand's North Island occur on sites devastated by volcanism *c.* 1800 years ago and have unusually high conifer densities. They are characterised by “cohorts” of mature to senescent populations of rimu and matai with restricted age ranges and a few younger trees in which diameter and age are only weakly related (e.g., Herbert 1980). The conifer “regeneration gap” (an absence of small trees 10–30 cm dbh) is apparent in some places but not in others. Their successional status has engendered considerable debate. Cameron (1954) suggested a regeneration cycle operating at a patch scale in which conifers and hardwoods alternate, later demonstrated by Beveridge (1973). On a larger scale, McKelvey (1963) interpreted the spatial sequence of conifer densities decreasing at increasing distances from the eruption centre (Lake Taupo) as an indirect chronosequence. Three concentric forest zones around the lake corresponded to three stages of linear succession towards “climax” forest, with

conifers declining and hardwoods increasing progressively in importance over space and time.

Ogden & Stewart's (1995) refinement of McKelvey's model — large distinct cohorts of conifers regenerating after a major disturbance, succeeded by smaller and less distinct cohorts, with hardwoods becoming increasingly important — is the best available (Smale *et al.* 1997). With most trees aged between 500 and 700 years, matai is older on average than rimu (400–600 years), and miro (*Prumnopitys ferruginea* (D. Don) de Laub.) is younger (A.Katz unpubl. data; Herbert 1980; Lusk & Ogden 1992; Smale *et al.* 1987). Storm-damaged crowns are common in rimu and matai. Extensive decay is common in the root systems of rimu and matai but not miro (Hood *et al.* 1989), a major predisposing factor in their demise. In some forests, younger rimu trees are also present (Herbert 1980). Widespread fallen totara (*Podocarpus totara* D. Don) indicate that it was once a significant component of these forests. Substantial collapses of canopy conifer populations — and thus changes in forest structure and composition — have occurred in places in the recent past and can be expected elsewhere in future; a new conifer cohort is well advanced in some places (e.g., Herbert 1986) but not in others (e.g., Smale *et al.* 1987).

In contrast, where prominent as a canopy species, tawa occurs in all-aged continuously regenerating populations with a much younger average age than the conifers (e.g., West 1995), and often appears to be ascendant (e.g., Smale *et al.* 1985). Conifer↔hardwood regeneration cycles, involving a variety of species other than tawa, are evident in places (Beveridge 1973; Herbert 1986). Canopy gaps of different average size favour regeneration of different canopy species (e.g., Lusk & Ogden 1992). Conifers favoured by increasing levels of canopy disturbance are — in order — miro, rimu, matai, and totara (Ogden & Stewart 1995) and amongst widespread hardwoods tawa, kamahi (*Weinmannia racemosa* L.f.), hinau (*Elaeocarpus dentatus* (J.R. & G.Forst.) Vahl.), and rewarewa (*Knightia excelsa* R. Br.) (unpubl. data).

Study Area

The trial was in a large tract of forest at 550 m a.s.l. on an undulating plateau. Soils were podsolised Pumice Soils (Hewitt 1992) derived from rhyolitic Taupo Tephra c. AD 200 (Rijkse 1977). Climate was cool-temperate and humid, with a mean annual temperature of 10–12.5°C and a mean annual rainfall of 1800 mm (New Zealand Meteorological Service 1985).

The forest type (rimu-matai/tawa-kamahi, a regionally widespread forest type intermediate between conifer- and hardwood-dominant forest) consists of frequent conifers emergent over denser hardwood tiers. Estimated average merchantable volume of the type for conifers is 280–290 m³/ha and for hardwoods 14 m³/ha (National Forest Survey unpubl. data). Before harvesting, diameter distributions of

merchantable conifers and tawa were unimodal (Fig. 1). Despite a limited diameter range, the mature conifers were uneven-aged; seven, sound, felled, rimu trees were between 440 and 620 years old.

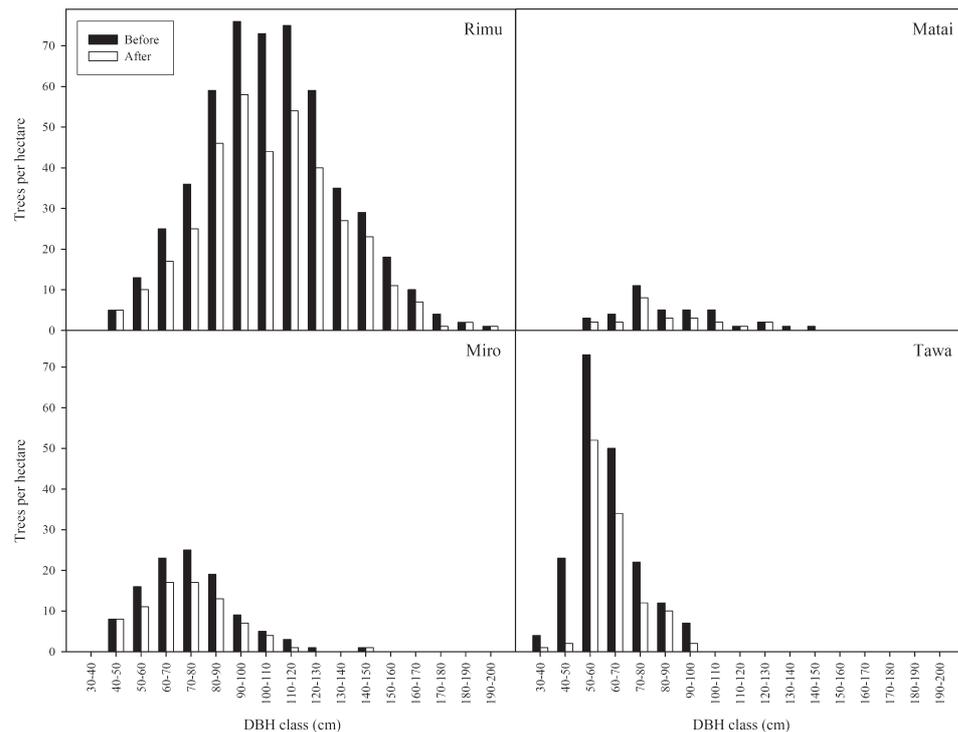


FIG. 1—Diameter distributions of major species before and after selective harvesting in 30 ha of mixed conifer-broadleaved forest at Pureora, North Island, New Zealand.

Trial Design

The trial consisted of three contiguous 15-ha blocks, each surrounded by a buffer of intact forest. One block (A) was left as a control. They were relatively homogeneous, although one harvested block (C) was more dissected. One-third of the merchantable volume was removed in 1961 from each of two harvested blocks (Smale *et al.* 1987), mostly from the centres of natural groups in Block B and the edges of natural groups in Block C. Two-thirds of the area of harvested blocks remained undisturbed (Beveridge & Herbert 1978). Tree selection aimed at felling apparently unhealthy, leaning, or thin-crowned trees in preference to healthy ones, avoiding damage to residual trees. Large seedlings of rimu, kahikatea (*Dacrycarpus dacrydioides* (A.Rich.) de Laub.), and totara were planted in groups in harvested gaps.

METHODS

Data Collection

Before harvesting, all trees considered merchantable were measured for diameter at breast height (1.4 m, dbh) and merchantable height (i.e., to bottom of the crown or lowest incidence of major defect), mapped, and permanently tagged. Cull trees (i.e., unmerchantable because of obvious defect) were also mapped. Mortality assessments were undertaken in 1980 and 2004, in which mode of death (uprooting, snapping, standing death) was noted. In 2004, the diameters of all surviving trees were remeasured.

In 1981, foliage density profiles were sampled by the point height intercept method in the unlogged (A) and harvested (B) blocks (Leathwick 1982) at 250 sample points randomly located in each block. At each point, a vertical line of sight was established with a gimballed sighting device. The height above ground and the species of all vegetation intercepted, including branches, were recorded.

Regeneration of conifers and tawa 0.15–3 m tall was sampled in 359 2-x-5-m plots at 20-m intervals along randomly located transects in 1959 before harvesting, and after it in 1973 and 1984. Random distances were traversed to transect starting points from the south-eastern edge of each block.

After harvesting in 1961 additional plots were established to monitor long-term forest recovery on a more detailed scale. Sixteen 0.04-ha, circular, growth plots were established randomly in the control block and in felled coupes in harvested blocks, in which the diameters of all stems >10 cm dbh were measured. Growth plots were classified according to predominant phase of the forest growth cycle (gap, building, mature) and remeasured in 2004. In felled coupes six 0.28-ha cruciform plots were also established in which the type and intensity of ground disturbance were recorded at fixed intervals along each arm. Vegetation cover was recorded qualitatively in four classes (abundant, frequent, occasional, rare) at each point in 1963, 1965, 1974, and 1984.

Data Analysis

From point height intercept data, species cover, i.e., the percentage of sample points in which a particular species was recorded, and foliage density in 1-m intervals were calculated and compared between blocks by minimum significant contrast tables (Mainland *et al.* 1956).

Mortality rates (m) of conifers were calculated by species by block for each assessment period (1961–80 and 1980–2004):

$$m = 1 - (N_1/N_0)^{1/t}$$

where N_1 = the number of original trees alive at the end of assessment period t ,
 N_0 = the number of trees at the start of that period (Sheil *et al.* 1995).

A generalised additive model was used to generate the probability of conifer mortality with distance from major extraction tracks (a measure of harvesting disturbance). Piece-wise cubic spline curves were generated by the `ns()` function in `Splines 6 for Windows` (1999; MathSoft Inc., Seattle), and fitted to the logit of the probability of a tree dying. Tree deaths were assumed to be independent of each other; a binomial distribution was specified for the responses.

Periodic mean annual merchantable volume increment of conifers (1961–2004) was calculated by species by block using original and final diameter at breast height measurements, mean species' merchantable heights for 5-cm diameter classes, and the volume functions of Ellis (1979). Trees whose original diameter measurement was adjusted for deformity were excluded, along with obvious gross outliers.

RESULTS

Impacts of Harvesting on Population Structure and Canopy Composition of Conifers

Harvesting substantially reduced the mean diameter of matai in one harvested block (B) and increased it in the other (C); diameter of miro was reduced in both blocks (Table 1). Over all species, however, mean diameters of conifers and tawa were

TABLE 1—Initial, harvested, and residual mean diameters of merchantable conifer trees in the 1961 selective harvesting trial, Pureora (standard errors in parentheses).

	Initial mean diameter (cm) (SE)	Harvested mean diameter (cm) (SE)	Residual mean diameter (cm) (SE)
Block A (control)			
Rimu	105.8 (1.8)	—	—
Matai	85.5 (2.8)	—	—
Miro	70.8 (2.1)	—	—
Kahikatea	95.2 (4.3)	—	—
All conifers	96.8 (1.5)	—	—
Tawa	59.2 (1.3)	—	—
Block B (harvested)			
Rimu	110.3 (1.6)	112.9 (2.8)	108.8 (1.8)
Matai	84.5 (4.3)	97.3 (9.0)	77.3 (3.5)
Miro	71.8 (2.6)	76.8 (4.6)	70.2 (3.1)
Kahikatea	96.5 (6.1)	92.5 (5.9)	105 (14.5)
All conifers	102.8 (1.5)	105.6 (2.5)	101.4 (1.5)
Tawa	58.6 (1.3)	57.6 (2.2)	59.1 (1.7)
Block C (harvested)			
Rimu	103.5 (1.8)	102.0 (3.2)	104.0 (2.1)
Matai	91.0 (6.3)	79.8 (6.2)	100.7 (9.3)
Miro	78.6 (2.7)	83.8 (5.7)	76.1 (2.9)
All conifers	97.4 (1.6)	96.7 (2.8)	97.7 (1.9)
Tawa	58.2 (1.3)	59.8 (2.3)	57.5 (1.5)

scarcely altered. The diameter distributions of conifers in harvested stands echoed pre-existing ones (Fig. 1), and so harvesting had barely altered them. A disproportionately large number of tawa in the 40- to 50-cm-diameter range and a small number in the 80- to 90-cm range were harvested, and so tawa distributions were slightly altered.

Harvesting scarcely altered canopy composition of the residual forest in terms of relative density, basal area, or importance of conifer species (Table 2). The commonest, rimu, increased slightly in importance at the expense of other conifers.

In 1981, 20 years after harvesting, mean foliage density 7–11 m above ground was significantly lower ($p<0.05$) and that below 1 m was significantly higher ($p<0.05$) in the harvested block (B) than the control block (Leathwick 1982). Otherwise, overall foliage density profiles were similar in harvested and unlogged forest. Tree ferns (mostly *Dicksonia squarrosa* (G.Forst.) Swartz), the short-lived seral tree wineberry (*Aristotelia serrata* (G.Forst.) Oliver), and a liane (*Rubus cissoides* A.Cunn.) were significantly ($p<0.01$) more common in harvested than in control blocks.

TABLE 2—Relative density (%), relative basal area (%), and relative importance (%) of canopy conifers (>30 cm dbh) before and after harvesting in the 1961 selective harvesting trial, Pureora.

	Relative density		Relative basal area		Relative importance	
	Initial	Residual	Initial	Residual	Initial	Residual
Block A (control)						
Rimu	62	–	67	–	65	–
Matai	11	–	9	–	10	–
Miro	17	–	13	–	15	–
Kahikatea	10	–	10	–	10	–
Totara	<1	–	<1	–	<1	–
Block B (harvested)						
Rimu	75	76	80	82	77	79
Matai	6	6	5	5	6	5
Miro	13	14	9	10	13	12
Kahikatea	6	4	6	3	5	4
Block C (harvested)						
Rimu	73	76	78	81	76	79
Matai	4	3	4	3	4	3
Miro	19	18	16	14	18	16
Others	4	3	2	2	2	2

Impacts of Harvesting on Residual Forest Stability

Over the 43-year assessment period, 218 (20%) of the 1071 merchantable conifer trees that remained in the three blocks died. Mortality rates in residual trees differed

among species and blocks. Among species, they were highest in matai, lower in miro, and lowest in rimu (Table 3). Among blocks, mortality rates were lowest in one harvested block (B), slightly higher in the unlogged control (A), and slightly higher again in the other harvested block (C). Although overall mortality rates did not differ between assessment periods, the mortality rate of matai doubled in Block C, whereas those of kahikatea and miro declined substantially in B and C respectively. There was no recruitment to the canopy of any conifer species in any block.

TABLE 3—Annual mortality rates (%) by species of major merchantable conifer trees over three assessment periods in control and harvested blocks in the 1961 selective harvesting trial, Pureora.

	1961–1980	1980–2004	1961–2004
Block A (control)			
Rimu	0.6	0.8	0.7
Matai	0.5	0.4	0.5
Miro	0.9	1.1	1.0
Kahikatea	0.3	0.2	0.2
All species	0.6	0.7	0.7
Block B (harvested)			
Rimu	0.4	0.6	0.5
Matai	1.8	1.3	1.5
Miro	0.8	1.0	0.9
Kahikatea	0.6	0	0.3
All species	0.6	0.7	0.6
Block C (harvested)			
Rimu	0.8	0.7	0.7
Matai	0.8	1.6	1.2
Miro	1.2	0.5	0.8
All species	0.9	0.7	0.8

Mode of death was established in 60% of dead trees in 2004. Standing death was most common overall and in emergent rimu and matai, and uprooting in canopy miro (Table 4). Mean diameters of dead trees did not differ significantly from the stand average in all species (Table 5).

TABLE 4—Mode of death (%) where known by species of major merchantable conifer trees in control and harvested blocks in the 1961 selective harvesting trial, Pureora.

Species	Mode of death		
	Standing dead	Uprooted	Snapped
Rimu (n=93)	43	25	32
Matai (n=11)	46	36	18
Miro (n=31)	26	45	29
All species (n=135)	40	30	30

TABLE 5—Mean diameters (cm) of dead trees and live residual trees in the 1961 selective harvesting trial, Pureora (standard errors in parentheses).

Species	Block A (control)		Block B (harvested)		Block C (harvested)		All blocks	
	Dead trees	Live residual	Dead trees	Live residual	Dead trees	Live residual	Dead trees	Live residual
Rimu	104.0 (3.5)	105.8 (1.8)	111.5 (4.4)	108.8 (1.8)	97.8 (4.5)	104.0 (2.1)	103.6 (2.2)	106.4 (1.1)
Matai	83.0 (5.6)	85.5 (2.8)	77.0 (5.4)	77.3 (3.5)	101.5 (19.4)	100.7 (9.3)	84.4 (4.3)	85.1 (4.1)
Miro	68.6 (2.8)	70.8 (2.1)	67.6 (3.1)	70.2 (3.1)	73.5 (4.5)	76.1 (2.9)	71.3 (2.5)	72.2 (1.5)
Kahikatea	82.9	95.2 (4.3)	71.1	105 (14.5)	132.1	132.1	88.7 (10.7)	97.8 (4.3)

Diameter growth rates of residual conifers were fastest in kahikatea, significantly slower in rimu and miro, and significantly slower again in matai (Table 6). Tawa growth rates were similar to those of kahikatea. Growth rates were similar in harvested and control blocks. There was no relationship between diameter increment and initial diameter in any conifer species.

Mortality probability vs distance curves provided no evidence of any relationship between a tree's distance from harvesting disturbance and the probability of its dying over the next 43 years (for Block B: χ^2 (3 df) = 5.304, $p=0.15$; for Block C: χ^2 (3 df) = 2.039, $p=0.56$).

TABLE 6—Diameter increment (PMAI* 1961–2004: mm) of residual merchantable conifer trees (standard errors in parentheses) [sample size in brackets] in control and harvested blocks in the 1961 selective harvesting trial, Pureora. Tawa data from an unpublished report by M.Smale & M.Kimberley.

Species	Block A (control)	Block B (harvested)	Block C (harvested)	All blocks
Rimu	1.1 (0.1) [145]	1.3 (0.09) [153]	1.3 (0.1) [118]	1.2 (0.06) [416]
Matai	0.6 (0.1) [27]	0.5 (0.2) [7]	1.0 (0.2) [4]	0.6 (0.09) [38]
Miro	1.0 (0.1) [36]	1.4 (0.2) [23]	1.4 (0.2) [28]	1.2 (0.09) [87]
Kahikatea	1.8 (0.3) [28]	1.7 (0.4) [6]	–	1.8 (0.3) [34]
Tawa (1961–1980)	–	–	–	1.6 (0.06) [213]

* PMAI = periodic mean annual increment

Impacts of Harvesting on Productivity

Gross and net merchantable volume increment was higher in the control than harvested blocks because of the reduced number of trees left after harvesting (Table 7). Net increment was negative in all major species in all blocks. Internal decay, however, is likely to have reduced that increment substantially. Basal area increment in growth plots over 43 years averaged 0.5 m²/ha/year in harvested patches, similar to that in building-phase patches of unlogged forest (0.4 m²/ha/

TABLE 7—Volume increment (PMAI 1961–2004: m³/ha) of merchantable conifer trees in control and harvested blocks in the 1961 selective harvesting trial, Pureora.

Species	Gross			Net		
	Block A (control)	Block B (harvested)	Block C (harvested)	Block A (control)	Block B (harvested)	Block C (harvested)
Rimu	0.30	0.27	0.21	–0.49	–0.37	–0.28
Matai	0.02	0.02	<0.01	–0.02	–0.04	–0.03
Miro	0.03	0.03	0.02	–0.08	–0.03	–0.05
Kahikatea	0.07	0.01	0	0.04	0.01	0
All species	0.42	0.33	0.24	–0.55	–0.43	–0.36

year). After harvesting, diameter growth increased in juvenile tawa previously suppressed by overtopping conifers (Ogden & West 1981), a response to increased illumination and reduced interspecific competition

Impacts of Harvesting on Regeneration of Major Canopy Species

Densities of advance growth 0.15–3 m tall were similar in 1973 (~1800–3100 conifers/ha, ~3900–7700 tawa/ha) and 1984 (~3000–3900 conifers/ha, ~5300–6300 tawa/ha) to those before harvesting (~1700–4100 conifers/ha, ~5000–10 900 tawa/ha). Only tawa remained significantly reduced (by about 50%, $p < 0.01$) in Block B. Because two-thirds of the area of harvested blocks remained undisturbed (Beveridge & Herbert 1978), at least this proportion of advance growth would have been bypassed during logging. Losses incurred during harvesting had largely been recouped in the following decade or so, conifers from seed and tawa from both seed and vegetative regrowth of damaged stems.

As elsewhere (Hinds & Reid 1957), miro was far more important as juveniles than as a canopy tree, comprising nearly 60% of all juvenile conifers over all blocks in 1984 compared with 16% of canopy trees. Rimu was the next most common species (24%), followed by matai (9%) and kahikatea (9%).

Recovery of Forest after Harvesting

Two-thirds of the area of harvested blocks remained as residual forest with structure intact (Beveridge & Herbert 1978). Where forest structure was lost altogether, primary successions reflected the type of ground disturbance. Scraped, compacted sites were colonised by putaputaweta (*Carpodetus serratus* J.R. & G.Forst.), megagrasses (especially *Cortaderia fulvida* (Buch. (Zotov), sedges (*Uncinia* spp. and *Carex* spp.), and ground ferns. By 1984, they supported thickets of putaputaweta and coprosmas (*Coprosma rotundifolia* A.Cunn. and *C. tayloriae* A.P.Druce ex G.T.Jane) over dense ferns. Rimu seedlings established on these sites — some 5000 seedlings/ha by 1978 (Beveridge & Herbert 1978) — and now form thickets up to 7 m tall, foreshadowing dense conifer stands there.

Churned soil containing humus was colonised by wineberry and tree fuchsia (*Fuchsia excorticata* (G.Forst.) L.f.), most wineberry collapsing under the weight of lianes and succumbing to its natural lifespan after 15–20 years, and tree fuchsia to browsing by introduced possums (*Trichosurus vulpecula* Kerr). Rimu, tawa, and, to a lesser extent, matai seedlings are now frequent on these sites.

Sites covered by harvesting slash were colonised by wineberry, tree fuchsia, pate (*Schefflera digitata* J.R. & G.Forst.), fivefinger (*Pseudopanax arboreus* (Murr.) Philipson), kamahi, tree ferns (mostly *Dicksonia squarrosa*), and ground ferns. By 1984, they were dominated by tree ferns or ground ferns, most wineberry having

died, and fuchsia and most kamahi and fivefinger having succumbed to possum browsing. Kamahi is an important species in conifer regeneration cycles in these forests (Beveridge 1973), and its demise may have significant long-term consequences for forest structure and composition. Rimu and tawa seedlings are now frequent on these sites.

Forest structure was partially lost in growth plots in harvested coupes, initiating secondary successions. Initially, in terms of density, they most resembled mature control plots. However, in terms of changes in density over the following 43 years and of basal area, they most resembled building-phase control plots. This is despite the fact that harvested plots were initially dominated numerically by tawa and building-phase control plots by conifers. Forty-three years after removal of an average of 58% of basal area, it had returned to 60% of pre-harvest levels. Nearly a century will be needed, on average, for harvested growth plots to recover 80% of their previous basal area (Smale *et al.* 1987); more time would obviously be needed where forest structure had been lost altogether, and less by the forest as a whole. Similar estimates have been made for warm-temperate (Horne & Gwalter 1987) and subtropical (Smith & Nichols 2005) rain forest in mainland Australia. Where well-developed tawa advance growth survived harvesting, harvesting conifers merely shortened the canopy replacement process. Similar responses are likely where conifer advance growth has survived harvesting; rimu and miro developing around kamahi stumps grew much faster with full overhead light than under a canopy (Smale & Kimberley 1986).

Over all harvested plots, the relative density of conifers >10 cm dbh declined and that of tawa increased after harvesting (Fig. 2). Since 1976, however, recruitment into the subcanopy of totara planted after harvesting in 1961 has begun to reverse

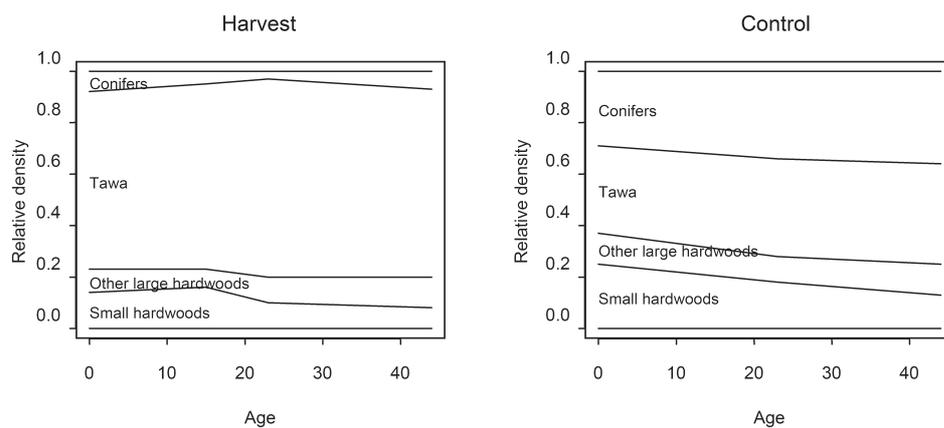


FIG. 2—Change in relative density of major species groups (conifers, tawa, other large hardwoods, small hardwoods) >10 cm dbh in 0.04-ha circular growth plots over 43 years after selective harvesting in mixed conifer/broadleaved forest at Pureora.

the decline in conifers, at the expense of tawa. Small hardwoods increased in relative density until 1976 and have declined since. In control plots, the relative density of both conifers and tawa has continued to increase slowly and that of small hardwoods to decline. Over all harvested plots, the relative basal area of conifers has continued to decline and that of tawa to increase (Fig. 3). In control plots, the relative basal area of tawa initially increased slightly at the expense of conifers, but since 1984 conifers have increased slightly at the expense of tawa.

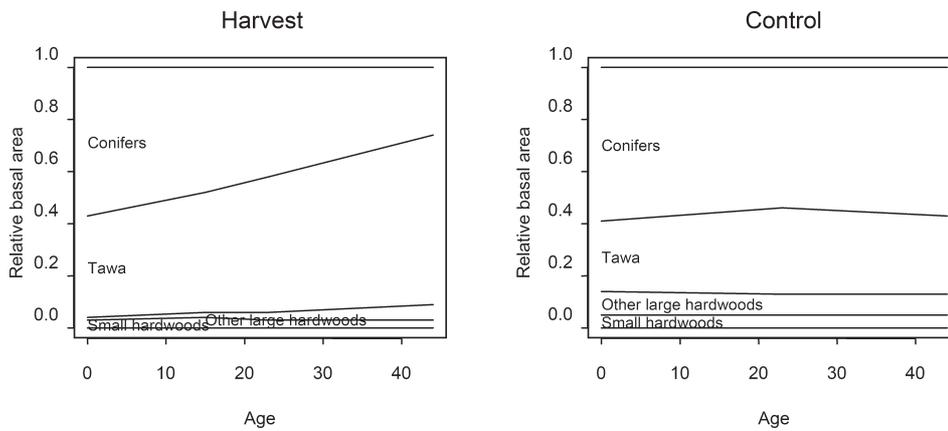


FIG. 3—Change in relative basal area of major species groups >10 cm dbh in 0.04-ha circular growth plots over 43 years after selective harvesting in mixed conifer/broadleaved forest at Pureora.

Conifers planted in harvested gaps with minimal subsequent releasing have performed well, with overall survivals of ~80% and mean annual height increments of 15 cm in 1981 (G.A. Steward unpubl. data). Rimu is the key species for planting because it has the widest site tolerance, survives long periods of suppression, is the least palatable to introduced mammals, and its overall performance is the best of the conifers (Beveridge *et al.* 1985). By contrast, limited experimental planting of tawa elsewhere in the region has been less successful (Knowles & Beveridge 1982).

DISCUSSION

Impacts of Harvesting on Residual Forest Stability and Productivity

Higher overall mortality rates in matai (0.8%/year) than rimu (0.6%/year) probably reflect the greater average age of matai (~600 years) than rimu (~500 years) in the region (A. Katz unpubl. data; Herbert 1980; Lusk & Ogden 1992; Smale *et al.* 1987). Although mortality rates of matai were higher in both logged blocks than in the control, populations in logged blocks were smaller and the differences may be less meaningful than they appear. The higher incidence of uprooting in miro than rimu or matai reflects the generally sounder root systems of miro (Hood *et al.* 1989).

In contrast to the stable mortality rates of conifers in this trial where only merchantable (i.e., apparently sound) trees were monitored, mortality rates have doubled over the same period in 20, 0.4-ha, permanent plots in other podocarp forests in the region. Cull trees are likely to be contributing disproportionately to this increase. Unlike the trial, all trees were tagged in those plots. In later sustainable management trials in the region where cull trees were also tagged, they made a disproportionate contribution to residual tree mortality in all blocks, harvested or not (Smale *et al.* 1999). Net volume decrement in both harvested and unlogged forest is widespread in the region (Smale *et al.* 1999).

Tree felling is most similar in its ecological effects to windsnap, one of the less common modes of natural death at Pureora. The most common (standing death) leaves the whole tree, including the bole, to disintegrate slowly *in situ*. Although windsnap may follow, the reduced amount of crown and bole left means that gaps formed by standing death are likely to be smaller than those created by felling, windsnap, or uprooting of live trees. Removal of tree boles creates harvesting gaps that are fundamentally different from natural ones, leading potentially to different regeneration patterns (Norton 1995). Natural treefall leaves tree boles to decay on the forest floor, providing “safe sites” for the regeneration of kamahi (Wardle 1966) and some conifers.

Impacts of Harvesting on Regeneration of Major Canopy Species

Even light selection harvesting can substantially reduce advance growth of major canopy species, with recovery to pre-harvest levels taking at least 15 years. Tawa re-invades logging-disturbed ground more slowly than conifers, a reflection of its establishment requirement for substrates with some humus and more overhead shelter (Carswell *et al.* in press). Assuming average growth rates (*see* Hinds & Reid 1957), estimated times for major canopy species to reach 60 cm dbh are ~240 years for rimu and tawa and over 300 years for matai and miro. Despite the conifer↔hardwood regeneration cycles operating in these forests (Beveridge 1973), the sites most readily available for planting — gaps created by felling conifers — appear suitable for conifer seedlings.

Recovery of Forest after Harvesting

Loss of forest structure can be total (e.g., at skid sites) or partial (e.g., where advance growth has survived felling of an overtopping tree). Total loss shifts the forest forward around the canopy replacement cycle to the gap phase and initiates primary or secondary successions, depending on how much the underlying substrate is disturbed. Partial loss shifts it to gap or building phases, depending on its severity, and initiates secondary successions. Thus harvesting results in a smaller proportion of mature forest and correspondingly larger proportions of younger (gap and building) phases.

Changes in harvested growth plots mirror those in growth plots in building-phase forest. Selective harvesting in these plots has accelerated one of the natural canopy replacement processes in these forests (Beveridge 1973), the transition from mature forest to building-phase forest that occurs with the death of conifers with tawa advance growth beneath them.

Suitability of the Selection System for the Forest Type and Species

Harvesting is the operation that most profoundly affects forest structure and ecosystem functioning, and the success of the selection system depends on proper execution of the first harvest in primeval forest (Brüenig 1996). The group selection system used here (removal of one-third of merchantable volume by harvesting groups of trees, targeting those with poorer health) has had relatively little impact on the structure and composition of the canopy of the residual forest. Although it did not adversely affect the stability of the residual forest, productivity was reduced by selective harvesting because of reduced tree densities and the absence of compensating conifer recruitment. Regeneration of major canopy species had largely recovered within a decade and a half of harvesting, but much more time will be needed for the forest as a whole to recover fully.

The selection system is suitable for continuously regenerating shade-tolerant species (Matthews 1991) adapted to a small-scale disturbance regime, i.e., regenerating in the understorey of tall forest or in small gaps. Such species characteristically have “reverse J” (≈negative exponential) diameter distributions that harvesting is supposed to maintain (Matthews 1991). Harvesting did maintain existing diameter distributions, but no species had a “reverse J” distribution. Elsewhere, tawa (Smale *et al.* 1986) and miro often show this pattern, but rimu and matai almost never (Enright & Ogden 1995).

In aiming to mirror natural replacement patterns, the size of felling coupes is critical for the use of harvesting as a silvicultural tool (Benecke 1996). Natural canopy gaps in similar forest average 0.014 ha (Smale & Kimberley 1983; Smale *et al.* 1997), the critical maximum size for regenerating tawa in the region (P.R.Nieuwland unpubl. data). Tawa maintains large banks of advance growth, long-lived, slow-growing, shade-tolerant seedlings that develop slowly to maturity under intact canopies, although growth is greatly enhanced by higher light levels (Smale & Kimberley 1986; West 1995); it appears well suited to the true selection system (Smale *et al.* 1986). Rimu is more light-demanding and its persistent shade-tolerant seedlings (Smale & Kimberley 1986) need at least disintegrating overstories (Herbert 1986) or small gaps in order to develop further; it appears better suited to the group selection system that creates larger gaps than the true selection system (Matthews 1991). Maintaining both conifers and hardwoods in the same tract of forest is likely to necessitate artificial disturbance at a range of scales.

Felling cycles are an important issue in forests managed by the selection system (Matthews 1991). With most rimu and matai trees nearing the end of their normal lifespans (650, 600 years respectively — Enright & Ogden 1995), mortality rates are likely to increase and existing cohorts to largely disappear within the next century or so. Further harvests will be possible for only a limited period and their frequency will be restricted by the need to allow recovery from previous harvesting. Salvage of dead trees by air or using existing extraction tracks seems appropriate in managed forests. Where advance growth is not already well developed, there will be a substantial delay — even with planting — before further harvesting can occur. Long-term changes in forest structure and composition and declining timber yields have been predicted with selection harvesting repeated at 30- to 40-year intervals in Australian rain forests (Horne & Hickey 1991); similar studies of the impact of repeated harvests are needed here.

CONCLUSIONS

The primary objective of the trial, finding an ecologically acceptable alternative (i.e., one that maintains a stable residual forest) to uncontrolled logging, has been achieved. Its success in terms of economic viability cannot be gauged, because costs were not recorded during harvesting. However, this objective falls well short of the theoretical aim of the selection system: improving the quality and value of the forest (Matthews 1991). The selection system is often regarded as the most natural one but few natural forests resemble it, and careful intervention is needed to maintain it.

Despite its limitations, however, the trial has provided valuable insights not only into the likely impacts of some current selective harvesting practices but also into the ecology of much of the forest in the region. A good understanding of the ecology of natural forests is an essential prerequisite for successful (i.e., “near-natural”) manipulation of them. Relatively old canopy populations of rimu and matai with net volume decrement, restricted age ranges, and few small trees — together with their long rotations — suggest that proper group selection management of these species is attainable only in the long term. Their ecological characteristics — adaptation to infrequent large-scale disturbances and declines in their absence — suggest that such management will inevitably lead to long-term changes in the structure and composition of the forest that will differ from those that would have occurred without it (*see* Norton 1995). However, they may remain within the range of outcomes occurring naturally in these forests. With a shorter lifespan and all-aged continuously regenerating populations adapted to more frequent small-scale disturbances, tawa may be more amenable to selection management mimicking natural population processes.

In similar forest elsewhere in the central North Island, removal of conifers during partial logging 30–50 years ago has not favoured conifer regeneration (Carswell *et*

al. in press); higher levels of disturbance are probably required to promote conifers. The current widespread natural ascendancy of tawa in mixed conifer/tawa forest in the region, and the failure of selective conifer harvest to substantially alter the conifer/hardwood balance in the regeneration phase, suggest that maintenance of conifers at current densities is an unrealistic management objective in medium-density podocarp forests such as these. More work remains to be done on the ecological impacts of sustainable management on indigenous forests, and long-established harvesting trials with comparable unlogged controls can help show how closely (or otherwise) selection management mirrors the natural dynamics of these forests.

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