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GROWTH AND YIELD OF TOTARA IN PLANTED STANDS

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ABSTRACT

Stands of totara (*Podocarpus totara* D. Don) have been established in many regions for a variety of reasons including the long-term option of harvesting high-value specialty timber. Thirteen stands of planted totara ranging in age from 10 to 94 years were assessed for performance, and a crude model was developed using eight stands to give an indication of the potential yield. Most were small woodlots that had received little or no after-planting care and two had been planted as shelterbelts.

Stands were assessed in the mid-1980s and again 10–12 years later for both height and diameter growth. There was a large variation in growth between individual stands. This reflected major differences in site and climate, stand density, and management history. Height/age curves were developed based on mean heights of stands, and diameter/age curves were constructed using mean stem diameters supplemented where possible with incremental diameters derived from core measurements. Basal area/age and volume/age curves were derived from the height/age and diameter/age curves.

Predictions of stand growth for totara based on stands with densities around 1000 stems/ha indicated average height would be 15 m and diameter >30 cm at age 60 years. Initially, growth in basal area and volume is slow but this begins to increase from about 20 years. Estimated stand volume was 470 m^3/ha at 60 years, reaching 800 m^3/ha at 80 years. Stand density not only influenced diameter growth but also had an effect on stem form of trees.

Keywords: indigenous forest; growth; silviculture; plantation; *Podocarpus totara.*

INTRODUCTION

With the clearance of indigenous forest in most regions of the country and with limitations on the harvesting of most remaining natural stands, there is now a scarcity of indigenous timber for high-value products. As a result, there is increasing interest in establishment of woodlots of indigenous species in New Zealand to provide a long-term source of timber. Among the indigenous conifer timber species, totara has excellent potential for growing in stands as a long-term timber supply. Totara can tolerate a wide range of sites, has proven wood quality including natural durability of heartwood, has good growth rates, tolerates high light levels suiting it to management in even-aged stands, and has a high public profile including a significant cultural identity (Best 1942; Simpson 1988). A major feature of the species is that it occurs in nearly all regions of the country (Hinds & Reid 1957).

Totara has been established in planted stands in many regions (Pardy *et al.* 1992). Reasons for planting vary and include restoring native forest remnants, providing shelter on farms, improving wildlife habitat, providing amenity and recreational facilities, controlling erosion, and improving water quality, as well as the long-term option of providing a resource of high-value specialty timber. Most plantations are not extensive. Some have performed poorly because they were planted on difficult sites and received minimal post-planting care (e.g., Beveridge *et al.* 1985; Bergin & Pardy 1987). Other, older stands provide some indication of potential growth rates and potential timber yields. Totara has been planted mostly as a single species in small stands, and also as shelterbelts, across a range of site types. This paper describes the performance of a selection of these stands and the development of a preliminary growth and yield table.

STUDY SITES AND HISTORY

In 1985–86 the Forest Research Institute undertook a survey to assess established stands of indigenous trees planted throughout the country (Pardy *et al.* 1992). Of the 55 stands and shelterbelts located and measured, 13 stands were dominated by totara — 12 of them in the North Island and one in the South Island (Fig. 1). These stands were measured again between 1996 and 1998. Eleven sites comprised small plantations of totara and two were shelterbelts. Brief site descriptions and stand histories are given below, and site and climatic data are given in Table 1. Soil descriptions are from Soil Bureau *Bulletin 5* (Soil Bureau 1954) for the North Island and *Bulletin 27* (Soil Bureau 1969) for the South Island. Climate records are from the New Zealand Meteorological Service (1983).

Ages ranged from 10 to 94 years. Stand density in nine of the plantations ranged between 975 and 2500 stems/ha. It was difficult to accurately estimate stand densities for the two shelterbelts at Kamo, a small grove at Cornwall Park (where only a small number of trees had been planted and consequently the stand had a large edge effect), and a stand of totara underplanted in pine (*Pinus ponderosa* P.Lawson et Lawson) at Kaingaroa.

Puhipuhi, Northland

Two stands, each less than half a hectare in size, were part of a 120-ha planting of totara at Puhipuhi between 1904 and 1909 by the then Lands Department with the purpose of providing a long-term timber resource. Seedlings were planted at 1.2 × 1.5 m spacing. At planting the site was dominated by grass and bracken (*Pteridium esculentum* (Forst.) Kuhn) which resulted in high initial mortality. A large fire in 1913 left only small pockets of intact trees, and few remnant stands exist today on farmland. Soils are Taraire friable clay and gravelly clay, derived from basalt of low natural fertility.

Earlier reports indicated that by the mid-1950s cattle were roaming through the heavily shaded stands, and thinnings were considered to be of little value due to lack of heartwood. Today the remnants are located on dairy farmland and are still unfenced. There is no understorey vegetation. The two stands measured are approximately 500 m apart, one at a density of 1275 stems/ha and the other at 1925 stems/ha.

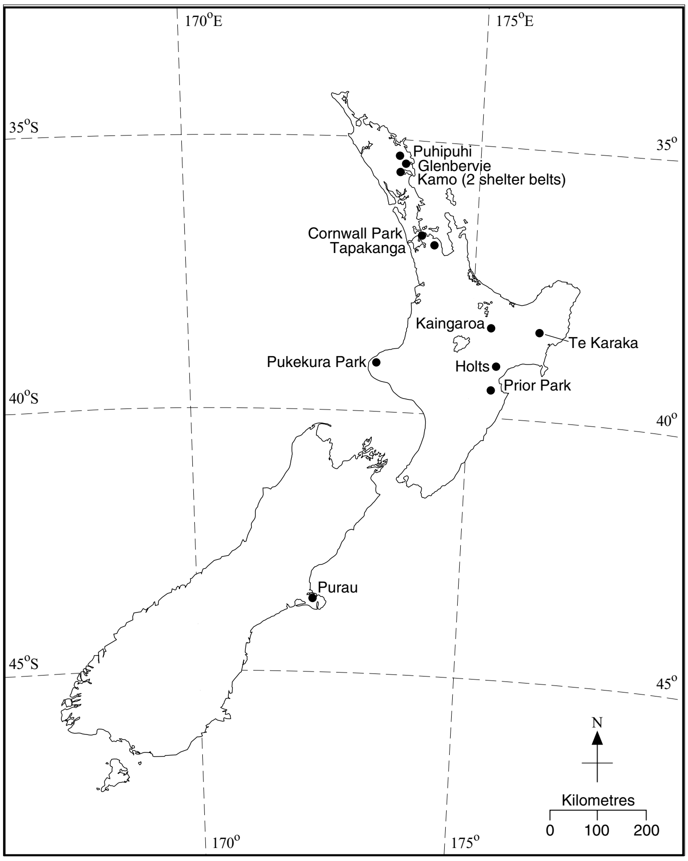

FIG. 1–Location of the 11 plantations and two shelterbelts used to develop a growth and yield model for totara. Two stands were located at Puhipuhi.

Glenbervie Forest, Northland

In 1952 a small stand of totara was planted at 4 × 2 m spacing near the top of a broad ridge as part of an early indigenous planting programme at Glenbervie Forest. The site vegetation, including bracken, gorse (*Ulex europaeus* L.), and other ground ferns, was burnt before tree planting. There was considerable early mortality due to prolonged summer dry periods and suppression by regrowth of bracken and gorse, although there was some partial releasing of seedlings from competing vegetation undertaken during the first 5 years after planting. The soils are Marua clay loam hill soil, derived from greywacke of low to medium natural fertility.

Kamo, Whangarei

In 1955 a single row of totara was planted at approximately 1 m spacing along a fenceline as a shelterbelt at the base of a slope. The seedlings were temporarily fenced off from grazing stock during early years and there was high survival, but tree form has been

TABLE 1–Site and climatic data for each stand. For most stands, climatic data was taken from the nearest weather station statistics (NZ Meteorological Service 1983). Stands are arranged from youngest to oldest (*refer to* Table 3 for stand ages).

Locality	Type of stand	Altitude (m)	Aspect (º)	Slope (º)	Annual rainfall (mm)	Daily mean temp (ºC)	No. of ground frosts/year	Sunshine hours†
Tapapakanga Regional Park, Firth of Thames*	Plantation	35	95	18	1296	14	3	2102
Holt's Forest Trust, Hawke's Bay	Plantation	240	275	5	1756	11.9	62	-
Kaingaroa Forest, central North Island	Underplanted	544	-	0	1483	10.7	99.5	-
Kamo, Northland	Shelterbelt	40	-	0	1600	15.4	7.2	1925
Glenbervie Forest, Northland	Plantation	107	20	10	1934	13.7	42.1	-
Te Karaka, East Coast	Plantation	80	135	20	1010	13.8	45.5	2172
Pukekura Park, New Plymouth	Plantation	49	220	10	1539	13.5	6.6	2114
Cornwall Park, Auckland	Small grove	45	-	0	1112	15.5	0	2102
Purau, Banks Peninsula	Plantation	20	270	15	666	11.6	88.7	1974
Prior Park, Hawke's Bay	Plantation	65	-	0	850	13.5	54	2245
Puhipuhi, Northland (2 stands)	Plantation	260	-	0	1950	14	15	2045
Kamo, Northland (older shelterbelt)	Shelterbelt	45	360	5	1600	15.4	7.2	1925

* Climate information from Tapapakanga Regional Park Management Plan, except sunshine hours from Auckland station.
† Not all weather stations assessed sunshine hours.

poor with the lack of tending. The soil is Ohaeawai silt loam derived from basalt with medium to high natural fertility.

Kamo, Whangarei (older shelterbelt)

A double-row shelterbelt of totara exists on a grassed site which was previously part of Ruatangata Forest Tree Nursery. The rows were planted in 1904 along the brow of a gentle slope at a spacing of 1.5 m between and within rows and, as a result of early releasing, survival was good. Approximately half of the trees have single leaders with heavy branching on the sides exposed to full light. One part of the shelterbelt was adjacent to a small stand of large eucalypts (*Eucalyptus* sp.) which have recently been removed. As with the nearby younger shelterbelt, the soil is Ohaeawai silt loam derived from basalt.

Cornwall Park, Auckland

A small totara grove of 12 trees was planted in 1927 in Cornwall Park, Auckland, for amenity purposes. Trees were planted at 5 × 5 m spacing on a flat grassed site which has been mowed ever since planting. The plot was small, and almost half of the trees are effectively edge trees. There has been no tending of the trees since planting and, because of edge effects and the wide spacing, trees have large diameters and stems are multi-leadered and heavily branched.

Tapapakanga Regional Park, Firth of Thames

The Forest Research Institute established a totara provenance trial on a 1-ha site in 1988 within the Tapapakanga Regional Park, on the western coast of the Firth of Thames. The objective of the trial was to monitor long-term differences in growth and form of trees raised from seed collected at 36 different locations throughout the country (Bergin & Kimberley 1992). The trial site was in grass and was fenced at planting. The trial layout comprised eight contiguous blocks of planted totara with over 1000 trees planted in lines at 2 × 2 m spacing. The stand has been intensively monitored since planting and seedlings were hand released from vigorous growth of exotic grass, particularly kikuyu (*Pennisetum clandestinum* Hochst.), for 5 years after planting. Survival was over 95% and growth has been good, with canopy closure beginning 7–8 years after planting. The soils of the planting site are brown granular loams, comprising Opita clay loam, silt loam, and clay.

Kaingaroa Forest

In 1962, over 24 000 podocarp seedlings were planted in Cpt 1071 in Kaingaroa Forest beneath a 36-year-old stand of *Pinus ponderosa* which provided a canopy to protect the seedlings on this cold upland site. The planting included almost 9000 totara established at a spacing of 3.6 × 1.8 m. After planting, the stand was left untended.

The site is flat with Pekepeke shallow sandy soil. At the time of planting the understorey consisted of small tree ferns and ground ferns. Early inspections indicated that totara had a high survival rate (85%) but average height growth was only 2 m over the first 13 years of growth. By 1975 the vegetation beneath the thinning pines comprised tree ferns (*Dicksonia* and *Cyathea* spp.) up to 2.5 m high and abundant ground ferns, particularly *Blechnum novae-zelandiae* T.C.Chambers & P.A.Farrant, and blackberry (*Rubus* sp.

(*R. fruticosus* agg.)). There was no difference in growth performance between totara that had been protected by a deer fence and trees that were not fenced.

Te Karaka, Gisborne

A 0.4-ha stand of totara was planted at Te Karaka north-west of Gisborne in 1947. The site was covered originally in kanuka (*Kunzea ericoides* (A.Rich.) J.Thompson) and manuka (*Leptospermum scoparium* J.R. & G.Forst.). The soils on this steep-to-rolling hill country are Pouawa sandy loam hill soils of medium natural fertility. Totara seedlings were planted at a variable spacing ranging from 2 to 4 m with the original purpose of reducing erosion above a water dam, and also to provide a future timber resource. Seedlings were hand-slasher-released from grass competition in the early years. On at least three occasions trees were pruned, with the last pruning in 1983.

In the 1986 assessment, the stand was 39 years old and averaged 17 cm in diameter and 10.6 m in height. Average height of pruned stems was 3.2 m with a range of 2.5–4.5 m. Branch stubs appeared to be occluding. Survival was over 90%. Growth of this nearly 40-year-old stand was considered slow, possibly due to establishment on a moderately exposed site with little other vegetation and to the low rainfall in this region. The canopy had closed and the previous grass cover thinned out. As the site has been permanently fenced to exclude stock, totara regeneration is prolific in patches within the stand.

Holt's Forest Trust

This totara plantation, covering approximately 0.5 ha and planted in 1963, is located at Holt's Forest Trust at Waikoau, about 40 km north-west of Napier, Hawke's Bay. Soils are Gisborne sandy loam derived from Gisborne ash, and are of low to medium natural fertility. Seedlings were planted on a gentle slope that had been cleared of bracken and blackberry, and were released by hand from regrowth on a regular basis. Spacing of trees varied between 1.5 m and 3 m within and between rows. Prior to the first assessment in 1985, all trees had been pruned heavily (to an average of 3.4 m) leaving small crowns, often multi-leadered. The stand at this stage was open but by the second assessment in 1996 canopy closure had occurred. There has been no thinning of this stand.

Prior Park, Hawke's Bay

This plantation was established in 1908 on a property known as Prior Park at Wharerangi, about 15 km north-west of Napier (Hocking 1948). The site is fertile valley bottom with soils that are fairly compact grey brown loams. The stand covers an area of 0.3 ha, with an original spacing that varied from 2 m to 2.5 m. There was good survival in early years with little mortality found during a 1948–49 inspection within a completely closed stand. The dominant trees at this stage were 15–17 m high, with occasional trees up to 30 cm in diameter. Height to base of green crown was 8–10 m, with generally heavy branching and a considerable proportion of multiple leaders. There apparently was light early releasing from grass in early years but there has been no pruning or thinning of the stand.

At the 1985 assessment there were 144 live and 15 dead trees. Both cattle and sheep had access to the stand and were using it for shelter, and this practice has continued.

Pukekura Park, New Plymouth

The 49-ha Pukekura Park (including the adjoining Brooklands Park) in New Plymouth includes many plantings of indigenous tree species. The park is undulating, with hills and ridges dissected by small gullies and streams. Soils are fine, soft, non-cohesive, New Plymouth yellow brown loams.

A 2-ha area adjacent to Brooklands Drive was planted in 1936 with various indigenous tree species, including a small area in totara. Lines were cut through bracken and tutu (*Coriaria arborea* Lindsay) cover, the ground was cultivated by spade, and seedlings were planted at 1.8 × 1.8 m spacing. The totara were released by hand in the early years. Stands were lightly thinned to remove unthrifty and malformed trees in 1968, and large side branches were removed from some trees. Totara has a greater incidence of multi-leadered stems than the other podocarps planted throughout the block.

Purau, Banks Peninsula

A small stand of totara was planted in 1910 on a slope in pasture at Purau, south of Diamond Harbour, Banks Peninsula. At planting, partial shelter was provided by natural kanuka, fivefinger (*Pseudopanax arboreus* (Murr.) Philipson), and *Olearia* species. The soils are Pawson hill soils, mostly silt loams developed from greywacke with some basalt and rated as medium natural fertility. Initial spacing was 2 × 2 m.

When inspected in 1986 and in 1998, cattle trampling and damage to root systems were evident. Gaps in the stand indicated some earlier mortality had occurred. Growth has been slow compared with similar-aged totara on other sites. Stem form of interior trees is considered good for an untended stand, with clear boles up to 7 m.

METHODS

Assessment of Stands

The assessment during the 1980s survey involved documenting the history of each stand including year planted, method and pattern of planting, and any information available on early growth and management (Pardy *et al*. 1992). Within each larger stand, up to 30 trees were permanently identified and measured for dbh (diameter at breast height 1.4 m). The height of a sample of up to 10 trees was measured using a hypsometer. Edge trees were avoided except in shelterbelts.

Between 1996 and 1998, the 13 totara-dominated stands were revisited and the original trees remeasured. Where possible, a circular Permanent Sample Plot (PSP) (Ellis & Hayes 1997) up to 22.8 m in diameter (0.04 ha) was installed so as to include most of the original measured trees. The PSPs were used to derive a stand density estimate for each stand.

Sampling of Increment Cores

Where landowner permission had been granted, increment cores were taken in order to extend the diameter growth record of the stand. Cores from up to 20 trees covering the range of small, medium, and large diameters were taken from each stand. Techniques used to sample cores were similar to those described by Norton (1998). Cores were taken at 1.4 m above ground and holes were immediately plugged with petroleum jelly to prevent entry of water and insects. Cores were mounted in blocks and sanded down using progressively finer grades of sandpaper.

The descriptions of normal ring boundaries and false rings by Norton & Ogden (1987) were used in identifying ring types. An assumption was made that one growth ring represented 1 year of growth. Only those cores that passed through or near the pith and had clear rings giving good estimates of stand age were used for diameter measurements. The numbers of rings were counted and the distance between each ring was recorded using an ADDO-X ring counting machine.

Data Analysis

Analysis of data involved obtaining mean stand height and then developing height, diameter, basal area, and volume/age curves.

Height/diameter curves

Because only a sample of canopy tree heights covering the range of diameters was taken in each plot, it was necessary to estimate the heights of the other trees to obtain a reliable estimate of mean height. To achieve this, a height/diameter relationship was fitted for each stand, and this relationship was used to estimate heights of the remaining trees. The following equation was used:

$$H = aD^b \qquad [1]$$

where H = height

D = diameter at breast height

a and *b* are coefficients estimated by nonlinear regression.

Mean heights were then obtained for each stand, using both estimated and measured heights.

Height/age curves

Various height/age functions were tested against the height data (Table 2). The Weibull equation is the cumulative form of a widely used probability distribution function that has proved to be a good model of tree growth (Yang *et al.* 1978). The Chapman-Richards equation (Richards 1959) is one of the most commonly used forestry growth equations, as is the Schumacher equation (Schumacher 1939). In addition to the above three-parameter

TABLE 2–Equations of height/age and dbh/age curves used to test for the best fit for data from the 11 totara plantations and two shelterbelts.

Equation	Height/age equation	Dbh/age equation
Power	$H = 0.5 + aT^b$	$D = a(T-5)^b$
Weibull	$H = 0.5 + a\left(1 - e^{-bT^c}\right)$	$D = a\left(1 - e^{-b(T-5)^c}\right)$
Chapman-Richards	$H = 0.5 + a\left(1 - e^{bT}\right)^c$	$D = a\left(1 - e^{b(T-5)}\right)^c$
Schumacher	$H = 0.5 + ae^{\frac{1}{bT^c}}$	$D = ae^{\frac{1}{b(T-5)^c}}$

growth functions, a simple power function requiring only two parameters was tested. The functions were all assigned an intercept of 0.5 m to account for height of seedlings at planting.

All curves were fitted using nonlinear mixed models using the SAS macro NLINMIX (Littell *et al.* 1996). Both anamorphic and polymorphic forms were tested. Anamorphic curves were fitted by treating the asymptote parameter, a, as random and the parameters, b and c, as fixed. Polymorphic curves were fitted by treating the slope parameter, b, as random and the remaining parameters as fixed. The log-likelihood was used to judge the fit of each equation.

Diameter/age curves

Mean diameters at breast height from the 1996–98 assessment were supplemented, where possible, using diameters derived from core measurements for 20 or 30 years prior to the last measurement. These core diameter estimates were used in preference to the 1986 diameter measurements because of the longer time series represented. This produced up to four diameter measurements spaced at 10-year intervals for seven stands, using between three and 19 cores per stand (Table 3).

TABLE 3–Increment cores used to extrapolate diameter growth back from last stand measurement for selected planted stands of totara. One ring is assumed to equal 1 year of growth.

Location	Stand age (years)	Cores used to measure diameter growth	Years extrapolated back from last stand assessment
Holts Forest	33	4	20
Kamo	43	3	20
Te Karaka	50	6	20
Prior	88	4	30
Purau	86	7	30
Puhipuhi (1925 stems/ha)	89	19	30
Puhipuhi (1275 stems/ha)	91	7	30

The same growth functions used for the height/age analysis were tested for suitability as diameter/age functions. The equations were modified to give a predicted dbh of zero at age 5 years to account for the time taken for seedlings to reach a measurable size at breast height 1.4 m (Table 2). The functions were then fitted using NLINMIX to the diameter/age data. Both anamorphic and polymorphic forms of the equations were tested.

Basal area and volume vs *age curves*

Estimated total stem volume was derived from the basal area (obtained from the diameter/age equation) and height (from the height/age equation) using the kauri (*Agathis australis* (D.Don) Lindley) pole stand volume function of Ellis (1979):

$$V = 2.071 \ln(D) + 0.8386 \ln(H) - 3.14 \qquad [2]$$

where V = total stem volume under bark (dm^3)
H = total tree height (m)
D = dbh (cm).

Currently, a volume table for totara does not exist. However, of the available volume tables, the height and diameter ranges of the trees used in developing a kauri pole stand equation were most similar to those of the totara trees in this study and that equation was therefore used.

Mean annual increment (MAI) estimates were also obtained. There appeared to be no significant mortality in some stands and it was difficult to determine when stand mortality occurred in other stands. Mortality was therefore not taken into account with these models.

RESULTS

Stand Growth and Yield

There were major differences in growth and yield among stands (Table 4). This was particularly evident with diameter growth, and between the plantations and the shelterbelts and the widely spaced grove in Cornwall Park. The average MAI for diameter across all nine plantations was 4.8 mm compared to an average of 8.3 mm for the two Kamo shelterbelts and Cornwall Park. There was less variation in height growth rate with average annual height increment across all 13 stands of 26 cm.

In the two Puhipuhi stands the influence of stand density on diameter was apparent with average diameters 10 cm greater in the lower density stand (35 cm dbh) than in the dense stand (25.9 cm dbh). In contrast, trees in the similarly aged 94-year-old shelterbelt at Kamo, also in Northland, had an average 48.3 cm dbh, reflecting the lower degree of competition between trees in the double-row shelterbelt at Kamo.

Mean diameter of the widely spaced trees at Cornwall Park (73.6 cm) was more than double that of similarly aged trees in higher density stands at Prior Park, Hawke's Bay, and Pukekura Park, New Plymouth. Relatively slow growth was recorded for stands in Te Karaka, Kaingaroa, and Banks Peninsula. For example, average diameter at Te Karaka (19.6 cm) was less than in the slightly younger stand at Glenbervie (29.2 cm). For stand densities of 1000 stems/ha or more, and for stands over 60 years of age, volumes ranged from 380 m^3/ha at the poorly managed South Island site at Purau to 1297 m^3/ha for one of the Puhipuhi stands in Northland. Mean annual increments in these older stands ranged from 4.4 to 16.1 m^3/ha. Over all stands (ages 10–94 years) the mean annual volume increments were from 3.2 to 16.1 m^3/ha, reflecting the wide ranges in diameter growth (3.2–10.5 mm/year) and in height growth (13–44 cm/year).

The large difference in growth rates between planted stands is a consequence not only of the different stand ages but also of the wide range of sites, their location in different regions, the different climates and soil types, and the different stand management histories (Table 1). Widely distributed plantations of totara with comparable stand density (around 1000 stems/ha) ranging in age from 46 to 91 years illustrate this variability (Table 4). Of the older plantations, the well-managed Taranaki stand at Pukekura Park which has a favourable climate and relatively fertile soils had the fastest growth rate for diameter (MAI 5.7 mm), height (MAI 30 cm), and volume (MAI 16.1 m^3/ha). In contrast, the poorly managed stand located on one of the driest and coldest sites at Purau on Banks Peninsula had one of the slowest diameter growth rates (MAI 3.2 mm). Intensive trampling damage by cattle to exposed root systems over many years no doubt contributed to the poor growth of this stand. Tree growth was also slower at the dry Te Karaka site on the east coast of the

TABLE 4–Stand characteristics and performance of 13 planted stands of totara. Stands are arranged from youngest to oldest.

Location	Stand type	Age (years)	Stand density (stems/ha)	Mean diameter* (cm)	Diameter MAI (mm)	Mean height (m)	Height MAI (cm)	Basal area (m^2/ha)	Total stem volume (m^3/ha)	Total stem volume MAI (m^3/ha)
Tapapakanga	Plantation	10	2500	8.0	8.0	4.4	44	13.4	31	3.2
Holt's Forest	Plantation	33	1975	15.4	4.7	9.3	28	37.5	167	5.1
Kaingaroa†	Underplanted	36	–	12.9	3.6	7.8	22			
Kamo	Shelterbelt	43	–	39.9	9.3	17.0	40			
Glenbervie	Plantation	46	975	29.2	6.3	12.3	27	67.9	393	8.6
Te Karaka	Plantation	50	1100	19.6	3.9	12.0	24	34.7	197	4.0
Pukekura	Plantation	62	1078	35.6	5.7	18.6	30	118.9	992	16.1
Cornwall Park‡	Small grove	70	–	73.6	10.5	20.3	29			
Purau	Plantation	86	1100	27.7	3.2	11.2	13	70.3	380	4.4
Prior	Plantation	88	1000	39.4	4.5	18.3	21	128.0	1141	13.0
Puhipuhi	Plantation	89	1925	25.9	2.9	20.0	22	101.2	972	11.0
Puhipuhi	Plantation	91	1275	35.0	3.8	22.9	25	128.3	1297	14.2
Kamo (older)	Shelterbelt	94	–	48.3	5.1	20.2	21			

* Diameter at breast height (1.4 m).
† Stand density not determined as totara planted within a stand of semi-mature *Pinus ponderosa*.
‡ Difficult to determine stand density because of large edge effect for this small stand.

North Island (diameter MAI 3.9 mm; volume MAI 4.0 m^3/ha) than in the similarly aged stand at the higher rainfall Glenbervie site (diameter MAI 6.3 mm; volume MAI 8.6 m^3/ha). The relatively slow growth at Kaingaroa was due to a combination of factors. This stand was located near the upper elevation limit of totara (Bergin 2002) and had a low daily mean temperature and a high frequency of frosts (Table 1). The "nurse" crop of *Pinus ponderosa* may have ameliorated the harsh upland conditions during establishment years, but the persistent pine overstorey is likely to have slowed growth in later years. Although only 10 years old, the Tapapakanga stand demonstrated the fast early growth of totara in plantations established on a lowland site where high-quality seedlings were established and good post-planting care was carried out.

Growth Prediction Equations

Height/age curve

The three-parameter height/age growth functions tested fitted the data from all 13 stands better than the two-parameter power function (Table 5). In all cases, anamorphic curves were superior to polymorphic curves. Although all the three-parameter models gave very similar fits, the Chapman-Richards equation was chosen because its asymptote was considered more realistic than that for the other models:

$$H = 0.5 + a\left(1 - e^{-0.0188T}\right)^{1.10} \quad [3]$$

where H is mean height, and T is stand age. The random effect, *a*, had a mean value of 23.3.

TABLE 5–Log likelihood values for height/age and dbh/age equations used to determine the most appropriate height/age and diameter/age curves for the totara plantation data.

Equation	Height/age equation		Dbh/age equation	
	Anamorphic	Polymorphic	Anamorphic	Polymorphic
Power	–41.07	–41.77	84.71	76.32
Weibull	–40.15	–41.65	84.92	82.83
Chapman-Richards	–40.15	–41.65	83.59	DC*
Schumacher	–40.05	–40.41	84.71	DC*

* DC = Did not converge

A comparison of predicted height with actual measurements (Fig. 2) indicates considerable variability in performance between stands. Early height growth of totara in the best-performing stands was up to 50 cm per year although this growth rate slowed with increasing age. However, the slowest-growing stands at the equivalent age achieved only half this growth rate.

Diameter/age curve

Stand measurements from the 13 plantations, supplemented by diameter measurements from growth ring counts for seven of the stands, were used to develop a dbh/age relationship. Considerable difficulty in obtaining convergence was experienced while fitting the three-parameter growth functions to dbh/age data. This was clearly caused by the fact that the diameter growth showed little or no tendency to slow, even though stands

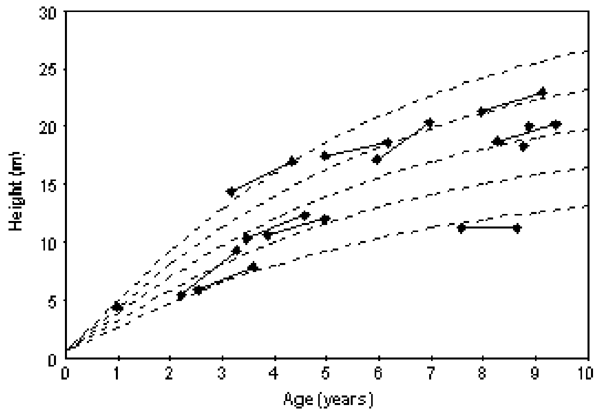

FIG. 2–Height measurements of 13 totara stands. Ten stands had two assessments about 10 years apart and three stands had only one measurement. Dashed lines give fitted height/age curves for site indices of 8, 10, 12, 14, and 16 m. Seedlings were assumed to be 50 cm high at planting.

approaching 100 years of age were included in the data. The asymptotic parameter could therefore not be estimated with any confidence. The simpler two-parameter Power growth curve gave nearly as good a fit as the best three-parameter curve, and was therefore adopted as the standard dbh/age curve:

$$\text{dbh} = a \times (T - 5)^{0.790} \qquad [4]$$

where T is stand age. The random site parameter, a, had a mean value of 0.0139. This equation applies only to unthinned stands.

A comparison of predicted diameter with actual measurements (Fig. 3) showed large variation in growth between stands. While many stands had attained 30 cm dbh from around 60 years onwards, in faster-growing stands a diameter of at least twice that could be achieved.

Basal area/age and volume/age curves

A basal area/age curve (Fig. 4) and a volume/age curve (Fig. 5) were both developed based on the predicted growth of six totara plantations that had a comparable stand density of around 1000 stems/ha. Plotting individual stands against the mean curve shows large variation in performance and reflects the major differences in site and climatic types and stand management histories described earlier. Initial growth is slow, particularly for volume, but begins to increase from about age 40 years onwards. An 80-year-old stand has a basal area approximately 100 m^2/ha (Fig. 4) with overall volume at 80 years exceeding 800 m^3/ha (Fig. 5).

Predicted growth of stands at a density of 1000 stems/ha was calculated based on the 13 stands (Table 6). Predictions for basal area and volume beyond about 80 years may be excessive as the model does not take into account mortality that may have occurred since planting. Because stands had not been monitored regularly and information on stand maintenance was largely anecdotal, it would be difficult to determine when trees died and the rate of mortality. However, there is lack of evidence of major recent self-thinning in the

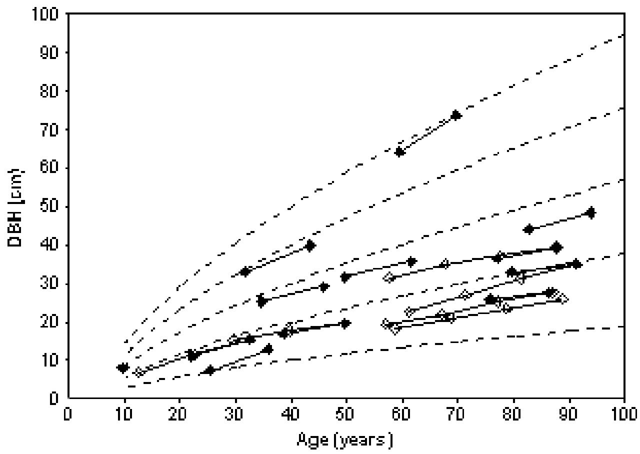

FIG. 3–Diameter measurements of 13 planted totara stands. The growth record was extended back using ring width measurements from increment cores for 20 or 30 years prior to the last measurement for seven of the stands; one ring was assumed to represent 1 year of growth. Dashed lines give fitted dbh/age curves for mean diameters at age 40 years of 10, 20, 30, 40, and 50 cm. Planted seedlings were assumed to be 5 years old before diameter at breast height (1.4 m) could be measured.

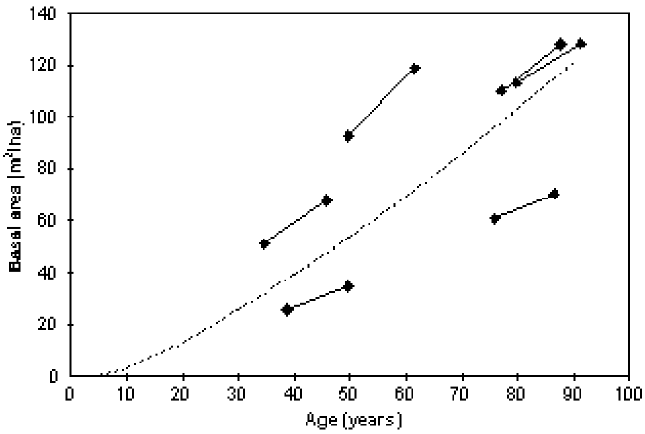

FIG. 4–Basal area measurements for totara derived from six planted stands with comparable stand densities of around 1000 stems/ha. The dashed line shows the predicted basal area corresponding to the estimated mean 22.3-cm dbh at age 40 for these stands.

stands assessed. Most mortality may have been during early years and not the result of competition between planted trees. At 80 years, mean height is predicted to be over 17 m with a mean 36 cm dbh. Basal area and volume over the same period are predicted to be 103 m^2/ha and 803 m^3/ha, respectively, with a mean annual volume increment of almost 10 m^3/ha.

Site index and diameter at age 40 years

In order to allow more useful comparisons between the performance of the 13 totara stands that span a wide range of sites and ages, height and diameter at 40 years of age were

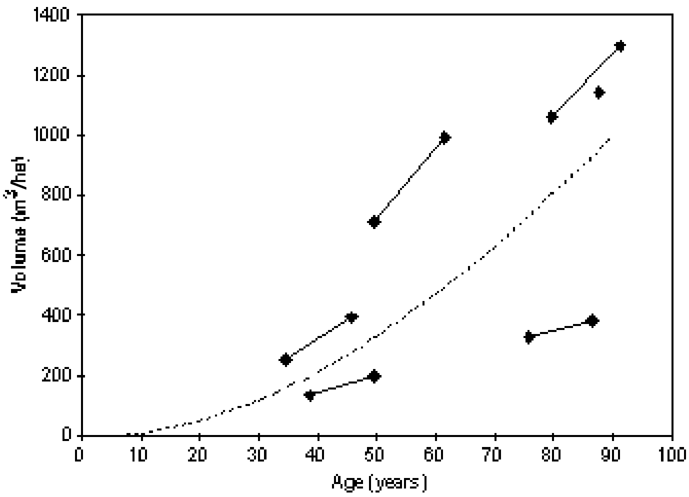

FIG. 5–Volume assessed for totara derived from six planted stands with comparable stand densities of around 1000 stems/ha. Five stands were measured twice and one stand did not have an earlier height measurement. The dashed line shows the predicted volume for these stands based on total stem height and a volume equation for kauri pole stands (Ellis 1979) as there is no volume equation for totara.

TABLE 6–Predictions of stand growth for totara at 1000 stems/ha based on assessments of six plantations with comparable actual stand densities located on a range of sites. Volumes are based on total tree heights and the volume equation for kauri pole stands (Ellis 1979) as there is no volume equation for totara.

Age (years)	Mean height (m)	Mean diameter (cm)	Basal area (m^2/ha)	Volume (m^3/ha)	Mean annual increment (m^3/ha)	Current annual increment (m^3/ha)
10	3.7	6.4	3.3	6.1	0.6	0.6
20	6.7	13.0	13.3	43.1	2.2	3.7
30	9.3	18.0	25.4	111.5	3.7	6.8
40	11.5	22.3	39.1	208.0	5.2	9.7
50	13.4	26.2	53.8	328.9	6.6	12.1
60	14.9	33.1	69.5	470.4	7.8	14.2
70	16.2	35.7	86.0	629.3	9.0	15.9
80	17.3	36.3	103.3	802.9	10.0	17.4
90	18.2	39.3	121.2	988.8	11.0	18.6

predicted for each stand. A more convenient form of the height/age equation can be obtained in which site index (SI) replaces the asymptote parameter in Eq. [3]:

$$H = 0.5 + (SI - 0.5) \times e^{7.69\left(\frac{1}{40^{0.403}} - \frac{1}{T^{0.403}}\right)} \quad [5]$$

where H is height, SI is the site index, and T is stand age. An equation for estimating site index from height measurement at a known age can be obtained by rearranging this equation:

$$SI = 0.5 + (H - 0.5) \times e^{7.69\left(\frac{1}{T^{0.403}} - \frac{1}{40^{0.403}}\right)} \quad [6]$$

As for site index, a more convenient form of the diameter/age equation can be obtained with diameter at age 40 replacing the site parameter:

$$\text{dbh} = \text{D40} \times \left(\frac{T-5}{36}\right)^{0.790} \quad [7]$$

where D40 is diameter at age 40, and T is stand age. An equation for estimating diameter at age 40 from a diameter measurement at a known age can be obtained by rearranging this equation:

$$\text{D40} = \text{dbh} \times \left(\frac{36}{\quad}\right)^{0.790} \quad [8]$$

Estimated site indices and diameter at age 40, using the above equations for each of the study stands, are given in Table 7. Estimated heights at age 40 years vary from 7.3 m at Purau to 16 m in the younger shelterbelt at Kamo. Estimated diameters range from 14.9 cm for the dense stand at Puhipuhi to 50.4 cm in the low-stocked stand at Cornwall Park. The poorest performing stands in terms of diameter growth are the dense stand at Puhipuhi and the most southern stand at Purau, and the best performing are open-grown stands at Cornwall Park and the shelterbelts at Kamo. Average height and diameter for totara across all stands at age 40 are estimated at 12.3 m and 25.8 cm, respectively.

TABLE 7–Estimated site index (SI, stand height at age 40 years) and diameter (dbh) at age 40 years (D40) for the 11 totara stands based on the latest stand measurements for height and increment core measurements for diameter. The underplanted stand at Kaingaroa and the young stand at Tapapakanga were excluded. Actual stand density of plantations is also given.

Stand	Estimated SI (m)	Estimated D40 (cm)	Stand density (stems/ha)
Holt's Forest	10.8	18.1	1975
Kamo	16.0	38.7	–
Glenbervie	11.2	27.0	975
Te Karaka	10.4	17.2	1100
Pukekura	14.1	27.6	1078
Cornwall Park	14.4	50.4	–
Purau	7.3	16.6	1100
Prior	11.6	25.5	1000
Puhipuhi (1925 stems/ha)	12.7	14.9	1925
Puhipuhi (1275 stems/ha)	14.4	20.1	1275
Kamo (older)	12.5	27.4	–
Average	12.3	25.8	
Range	7.3–16.0	14.9–50.4	

DISCUSSION

Growth and Yield

This study presents the first attempt at producing growth and yield equations for totara. The growth predictions are relatively crude as they were based on data from a small number of stands that cover a wide range of ages and site types, and where care of stands after planting had been variable. Total stem volume growth is slow over the first 50 years, but yield increases significantly over the following 50 years (Fig. 5). A mean basal area of about

100 m^2/ha and mean volume of 800 m^3/ha are predicted at age 80 years, based on six stands with a density of approximately of 1000 stems/ha (Table 6). Current annual volume increment is less than 7 m^3/ha at age 30, increasing to 14 m^3/ha at age 60, although no allowance has been made for mortality.

From the growth prediction equations, height growth of totara in the planted stands assessed in this study is most rapid over the first 25–30 years (Fig. 2) with estimated heights for the better-performing stands approaching 25 m by 100 years. Diameter growth follows a more linear pattern with estimated diameters ranging from 20 cm to almost 1 m after 100 years, reflecting the wide range of stands sampled (Fig. 3). Although average diameter increments can exceed 1 cm/year, these growth rates generally occur either in widely spaced plantations such as Cornwall Park or in shelterbelts. For plantations established on reasonable sites at around 1000 stems/ha (e.g., Glenbervie, Pukekura) mean annual increments 40–50 years after planting are around 6 mm for diameter and up to 30 cm for height (Table 4). This is similar to earlier assessments of growth rates for planted totara (Pardy *et al.* 1992). The stands used in this analysis were young compared to totara in old-growth forest where trees are often estimated to be several centuries old. Mature trees in natural forest are up to 30 m high, with breast-height diameters up to 2 m (Allan 1959). Although trees in the planted stand in this study were approaching the top heights of trees in natural forests, they had considerably smaller stem diameters.

Site Differences

The performance of totara described in this paper is based on stands that are widely scattered from Puhipuhi in Northland to Purau on Banks Peninsula. In addition to obvious differences in site and climate among stands, various factors have clearly influenced performance including the type of stand (e.g., shelterbelt *vs* plantation), tree age, stand density, and management history. The slower-growing stands located at Te Karaka, Kaingaroa, and Purau (Table 4) illustrate some of the complex of factors that are likely to influence growth. Te Karaka has a warm but dry climate; Kaingaroa, where totara was planted within a stand of *P. ponderosa*, is a cold upland site and there has been severe competition from the pines as well as blackberry and fern ground cover; the stand at Purau, Banks Peninsula, with a cool dry climate, has been adversely affected by the damage caused by cattle trampling exposed root systems over many years. Among the faster-growing stands are Cornwall Park and the younger shelterbelt at Kamo where trees were established on well-drained, fertile and sheltered sites at low density, allowing development of large crowns. The young Tapapakanga stand is also achieving good growth on a fertile, ex-pasture, lowland site where trees have been kept free of weed competition during the early establishment phase.

Comparison with Other Species

Average growth of totara in this study is similar to growth rates of other podocarps planted in early Forest Research Institute trials on cool upland sites of the North Island (Beveridge *et al.* 1985). However, average height increment for totara is less than the 40 cm/year generally reported for kauri (Ecroyd *et al.* 1993) and beech (*Nothofagus* spp.) (Wardle 1984).

Productivity of the 62-year-old Pukekura stand in Taranaki (Table 4) was similar to two 60-year-old neighbouring kauri stands (Herbert *et al.* 1996). For the kauri stands, average stand density was 1375 stems/ha and estimated volume was 804 m^3/ha; the totara stand, which had a slightly lower density of 1078 stems/ha, had an estimated volume of 992 m^3/ha. Tree heights for the kauri stands were slightly greater than for the totara stand (21.1 m *vs* 18.6 m) while diameters were slightly smaller (29.8 cm compared to 35.6 cm). However, productivity at this site was well above average, as the average volume at age 60 years was predicted to be 470 m^3/ha for the six sites of similar stand density in this study (Table 6).

Average diameter growth rates of nearly 5 mm/year and height of 25 cm/year were found for totara in an 80-year-old natural podocarp pole stand in the upland central North Island, regenerating on land formerly cleared and burnt by Maori for cultivation (A.Katz unpubl. data). In that stand totara had a total basal area of 71 m^2/ha compared to 103 m^2/ha predicted for planted totara stands in this study.

Growth rates of totara are much slower than those of the two most widely planted exotic conifers in New Zealand, *Pinus radiata* D.Don and *Pseudotsuga menziesii* (Mirb.) Franco. Predicted total tree volume of 112 m^3/ha for totara at 30 years (Table 6) is only a fraction of the typical total volume yields for *Pinus radiata* which range from 400 to over 900 m^3/ha in 25–30 years, depending on the management regime and site (Maclaren 1993). Growth rates of totara are less than half those of *Pseudotsuga menziesii*. The average mean annual increment of recoverable volume for *P. menziesii* in New Zealand is 16 m^3/ha at 60 years of age compared to 7.8 m^3/ha predicted for total tree volume of totara at the same age (Table 6). Like totara, *P. menziesii* exhibits relatively slow early growth until about 30 years of age (Miller & Knowles 1994), although it is considerably faster growing overall.

Plantations of cypress (*Cupressus macrocarpa* Gordon and *C. lusitanica* Miller) in New Zealand have, like totara, generally suffered from widespread silvicultural neglect, particularly lack of thinning (Miller & Knowles 1992). Mean annual volume increments of late-thinned cypress stands range from 6 to 15 m^3/ha. Unthinned stands older than 40 years show wide variation in total volume yields from 200 m^3/ha for stands on poor sites to over 1000 m^3/ha on exceptional sites. The poor-site growth is similar to that predicted for totara plantations at a similar age (Table 6).

Stand Density

Although growth of plantations was clearly influenced by site and history of stand maintenance, some differences were due to stand density. Average stem diameter predicted for each stand at age 40 years shows a trend of decreasing diameter with increasing stand density (Fig. 6). The two shelterbelts and the widely-spaced Cornwall Park plantation have been assigned a nominal stand density of 100 stems/ha. These plantings were virtually open-grown and had average diameters of over 35 cm at age 40 compared to 20 cm for trees at around 1000 stems/ha and only 15 cm for stands at around 2000 stems/ha. There was no clear relationship between stand density and height growth (Fig. 7).

As reported by Pardy *et al.* (1992), stand density has also had a significant effect on the form of totara. The dense untended stand at Puhipuhi had a high proportion of single-leadered stems many with clear boles over 10 m in height, compared to coarsely low-branched trees in the shelterbelts and at wide spacing at Cornwall Park.

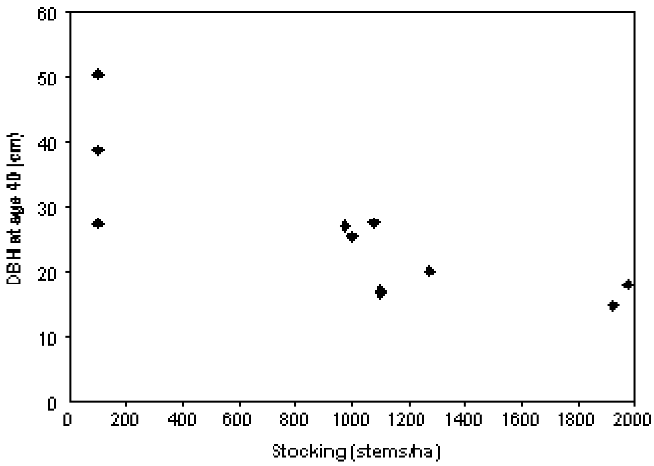

FIG. 6–Estimated diameter at age 40 *vs* stand density for 11 planted totara stands. The underplanted stand at Kaingaroa and the young stand at Tapapakanga were excluded. A nominal stand density of 100 stems/ha was assigned to the two shelterbelts at Kamo and the wide-spaced stand at Cornwall Park.

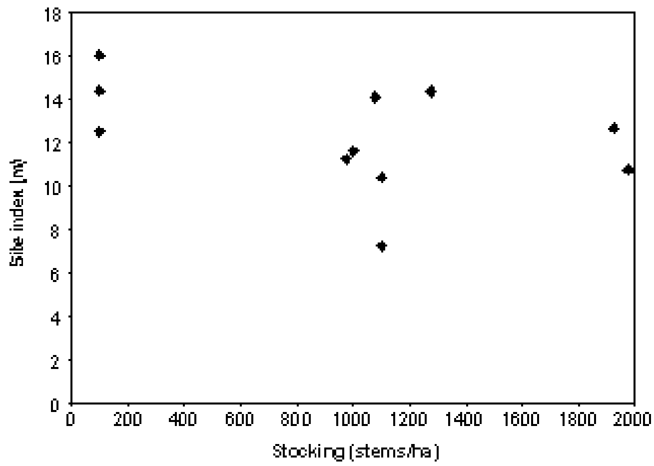

FIG. 7–Estimated site index (height at age 40) *vs* stand density for 11 planted totara stands. The underplanted stand at Kaingaroa and the young stand at Tapapakanga were excluded. A nominal stand density of 100 stems/ha was assigned to the two shelterbelts at Kamo and the wide-spaced stand at Cornwall Park.

Implications for Management

Records indicated that management of the stands used in this study varied considerably and this is consistent with assessment of a large number of indigenous conifers planted in trials and larger-scale stands throughout the country (Bergin 2003). Most had received little after-planting care with consequent poor early growth. Furthermore, some stands were located on poor or inappropriate sites. Considerably better growth can therefore be expected on good-quality lowland sites and where seedlings are kept free of weed competition in early years.

Optimum stand density for the planting of totara will depend on the plantation establishment objectives and the resources available. Planting totara at an initial density of 2500 stems/ha on the warm, lowland, fertile site at Tapapakanga has resulted in canopy closure within 10 years, with faster-growing trees over 5 m high and 10 cm in diameter. Within the next 10 years growth will become severely affected by competition, although good stem form will be enhanced by the early high stand density as occurred in the densely stocked 91-year-old Puhipuhi plantation. The other extreme of planting at low density is exhibited by the Cornwall Park stands where lack of competition between planted trees has resulted in fast diameter growth and the development of multi-leadered trees with very large crowns. It is likely that little or no inter-tree competition occurred in this stand for at least the first 20 years after planting; once canopy closure occurred, poor tree form had been set in place. Therefore, planting and management of totara for timber production requires a compromise between an initial density sufficient to achieve good stem form but, at the same time, a wide enough spacing betwen trees to save on establishment costs and to maintain good diameter growth.

The average growth rates of the highly variable plantations assessed in this study are not likely to be reflecting optimum performance of totara. Considerably better growth can be expected where it is planted on good-quality lowland sites, where seedlings are kept free of weed competition in early years, and where judicious thinning in later years promotes continued growth without compromising good stem form.

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