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HEARTWOOD CONTENT IN PLANTED AND NATURAL SECOND-GROWTH NEW ZEALAND KAURI

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ABSTRACT

A comparison of planted and natural second-growth stands of kauri (*Agathis australis* Salisb.) in the North Island of New Zealand identified stem diameter as the principal factor for predicting heartwood presence and quantity. Age was a secondary factor, with older smaller stems from natural stands having disproportionately more heartwood than would be predicted from their stem diameter. Heartwood was found in kauri with diameters as small as 10.3 cm in natural trees and 15.8 cm in planted trees, although it represented less than 4% of total stem volume, and it was present in all trees above 35 cm diameter at breast height (dbh). Usable quantities of heartwood did not appear until breast height diameters reached 60 cm when mean heartwood volumes exceeded 0.5 m^3 in the bottom 6-m log. Kauri with diameters in excess of 90 cm are predicted to contain a minimum of 1.9 m^3 of heartwood per tree in the bottom 6-m log. Diameter increments in the best-performing planted stands in this study suggested that an average diameter over bark of 90 cm would be achieved in 120–150 years. Maximum sapwood width occurred at 40–50 cm dbh for planted kauri and 80–90 cm dbh in natural stands, and stabilised at an average value of 13 cm. In this study sapwood width was less than 15 cm in 93.7% of the kauri. The results of this study will facilitate the prediction of heartwood quantity in planted or second-growth stands using easily obtained diameter over bark measurements.

Keywords: heartwood; sapwood; productivity; *Agathis australis*.

INTRODUCTION

"The noble kauri trees, the most valuable production of the [North] Island"
— Charles Darwin (1835)

Although harvesting of kauri from Crown-owned land in New Zealand ceased in the 1980s, there is still a considerable demand for the timber in the furniture and tourism markets. As the remaining old-growth forest and the majority of second-growth natural stands are in Crown ownership and unavailable for harvesting, there is an increasing interest in planting kauri to produce valuable high-quality timber. However, one of the key factors influencing value recovery from plantation-grown kauri is the amount of heartwood produced within these stands.

Studies of recovered timber grades of kauri from naturally regenerated second-growth stands showed that, for comparatively young stems, there was little or no usable heartwood content. Gibson (1983) found that in (estimated) 120-year-old kauri in Russell Forest less than 1% of recovered boards were graded as heartwood and Barton (1983) reported that larger diameter logs from the Hunua Ranges produced better conversion rates than smaller diameter logs. Observations based on stem cross-sections and increment cores from young (less than 80 years old) planted kauri suggested a similar trend. Although there is market acceptance of sapwood kauri (Herbert *et al.* 1996) it is probable that a major price differential between sapwood and heartwood kauri could emerge. Certainly in terms of appearance (including colour), working properties, and natural durability, heartwood has intrinsic and market-recognised advantages over sapwood (Clifton 1990).

Pardy *et al.* (1992) reported on the performance of a range of indigenous tree species in a study of native plantations of which over half were dominated by or contained kauri. A significant finding was that kauri planted on good-quality sites (lowland, moist, fertile, and free-draining soils) had growth rates almost double that of natural stands despite the frequent lack of after-planting maintenance. These plantings clearly identified the potential of kauri as a high-value forestry species. Prior to 1973, 227 ha of kauri had been planted by Government agencies, with over 150 ha being established in the 1950s (Halkett 1983). Subsequent inspections showed 15% of those plantings had failed and half of the remainder were inadequately stocked. By 1983 a further 782 ha had been established with reported early survival between 65% and 90%. Although the objectives of these plantings were to restore disturbed (selectively logged) forest or to enrich regenerated scrubland, the possibility of future timber production was retained as a management option.

Various authors (e.g., Erne Adams 1973; Lloyd 1978; Halkett 1983) have estimated the area of well-established second-growth kauri in New Zealand to be between 60 000 and 100 000 ha. Approximately 5000 ha of this developing resource were silviculturally treated in two major areas (Russell Forest and Great Barrier Island) with the aim of shortening succession time by releasing seedlings and saplings (Whitmore 1977). Included in this silvicultural treatment were a series of thinning trials, undertaken between the late 1950s and the 1970s, that were an attempt to reduce competition and improve the performance and quality of retained stems.

Potential growers of kauri need to be aware of the outcomes in terms of wood characteristics before committing to managing second-growth forest or establishing plantations that may be required to produce timber. Therefore there was a need to confirm whether the trends of heartwood content observed were the norm and whether there were identifiable factors influencing heartwood formation. The objective of this study was to quantify the pattern of heartwood formation by comparing similar diameter classes in planted stands and in natural second-growth stands.

METHODS

Seven planted and four natural second-growth kauri stands were identified and assessed in the North Island of New Zealand (Fig. 1). The natural second-growth stands located at Great Barrier Island, Coromandel, and the Kaimai Ranges were on Crown-owned land administered by the Department of Conservation, while the Mangatangi stand in the Hunua Ranges was administered by the Auckland Regional Council. The planted stands were located on Crown-owned conservation land, and in local authority and Trust reserves on the northern flanks of the Maungataniwha Ranges in Northland, Great Barrier Island, and

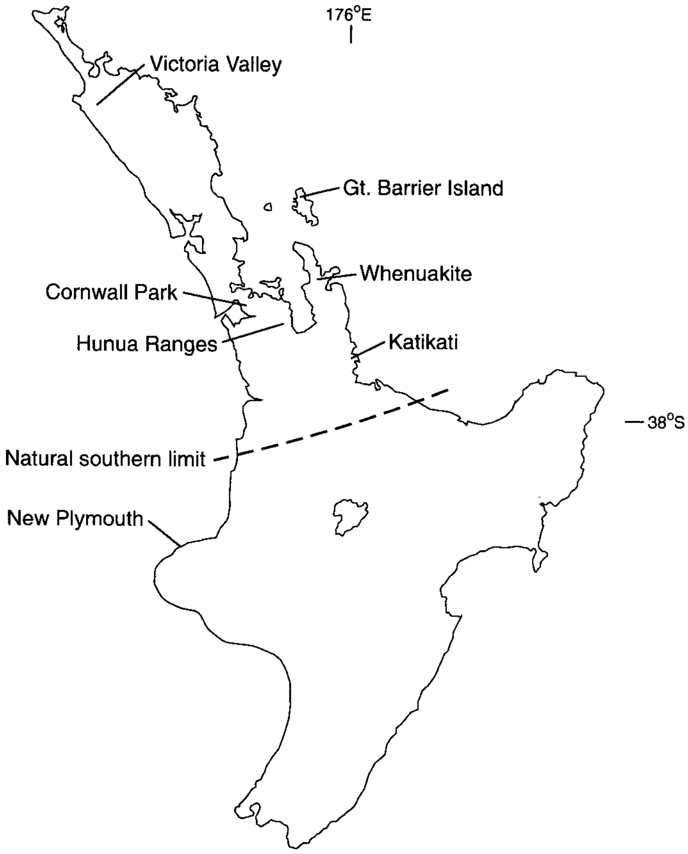

FIG. 1–Location of study sites in the North Island of New Zealand (dotted line indicates natural southern limit of kauri in New Zealand).

Cornwall Park in Auckland and at New Plymouth. The two New Plymouth stands were approximately 120 km south of the natural southern limit of kauri in New Zealand (Fig. 1 and Table 1).

Kauri exceeding 10 cm dbh (diameter at breast height, at 1.4 m above ground) were sampled for heartwood content by the extraction of a single 5-mm cross-sectional (pith-to-bark) increment core. In natural stands, 10-cm-diameter classes were established and 10–15 cores/diameter class were extracted depending on stand size and diameter distributions. Stems over 90 cm in diameter were not sampled as coring equipment long enough to reach the centre of the stem was not available. In planted stands, 20–30 cores covering the range of diameters in the stand were extracted, except in two stands where fewer cores were collected because of the small size of the stands. The colour of kauri heartwood has been described (e.g., Cockayne & Phillips Turner 1928; Salmon 1980; Clifton 1990) as a light biscuit (yellow brown) to rich reddish brown with a characteristic speckle, while the sapwood is a very light brown. As there is no chemical test to identify the kauri heartwood/ sapwood boundary, visual differences between heartwood and sapwood were used to identify any heartwood zone within the core. Where immediately identifiable, the boundary between sapwood and heartwood was marked as cores were extracted from stems. Cores were kept intact and prepared for ageing, final definition of the sapwood/heartwood boundary, and measurement of heartwood content by mounting them on wooden holders. A flat surface was then sanded over the length of the core, sufficient to give a good visual definition of the wood and annual rings.

To determine the heartwood content, the width of the sapwood zone and the radius of the full core (pith to bark) were measured. Where the pith was not included in the core, an overlay chart of concentric circles on clear film was used to assist in estimating the approximate location of the pith in relation to the core (following the technique of Applequist 1958). To estimate the age of trees from natural stands where the pith was missing from the core, the missing-distance-value was multiplied by the mean annual diameter increment obtained from the same part of cores from similar-sized stems in the same stand, where the core passed through the central pith. All planted kauri were of known age. Complete growth ring counts on cores from these known-age trees typically resulted in under-estimation of the known age by about 5%. For the purposes of this study it was assumed that the same error would apply to the cores taken from naturally regenerated stands. Therefore, ages for kauri from natural stands had 5% added to the age obtained by counting annual rings on the core.

To determine stem and heartwood zone taper (to formulate heartwood volumes), stem diameter measurements and cross-sectional increment cores were taken at 1.4 m and 4 m above ground level for stems greater than 50 cm dbh in the natural stand at Whenuakite. Using these measurements, a tapered cone equation (Equation 1) was used to determine heartwood volumes for all other stands (e.g., Kern & Bland 1948):

$$HV = \frac{\pi L}{3}\left(r_1^2 + r_2^2 + r_1 r_2\right) \qquad (1)$$

where HV = heartwood volume (m^3)
r_1 = large end radius (cm)
r_2 = small end radius (cm)
L = log length (6 m)

Regression models were derived for predicting diameter of heartwood. The following basic regression model was fitted:

$$\begin{aligned} HD &= a(dbh - dbh_0), && \text{when } dbh > dbh_0 \\ &= 0, && \text{when } dbh \leq dbh_0 \end{aligned} \qquad (2)$$

where HD is heartwood diameter (cm) and dbh is diameter at breast height (cm). Values for dbh_0 and a were estimated using the SAS procedure NLIN (SAS Institute 1989). Dbh_0 is the mean dbh at which heartwood begins to form, and the coefficient, a, determines the relationship between heartwood diameter and dbh once heartwood begins to develop. Because the equation is restricted to be always positive, it was necessary to use a nonlinear regression procedure, rather than a simple linear regression. This model was fitted using data from the plantations, and from natural stands that had not been thinned or treated with fertiliser.

Several variations of the above model were also fitted using nonlinear regression. Firstly, to determine whether the heartwood relationship varied significantly between stands, separate dbh_0 parameters, and separate a parameters were fitted for each stand. F-tests were used to test the significance of the improvement in fit of this model, and provided an indication of differences in the HD *vs* dbh relationship between stands. Secondly, for natural stands, individual tree age was included as an extra variable in the regression. Thirdly, to determine whether the relationship between HD and dbh might be nonlinear, the following variation to the above model was fitted:

$$HD = a(dbh^c - dbh_0^c), \text{ when } dbh > dbh_0 \\ = 0, \quad \text{when } dbh \leq dbh_0 \qquad (3)$$

In this model the extra parameter, *c*, allows for a nonlinear relationship between HD and dbh.

RESULTS

Dbh and Height

Dbh of individual trees (natural and planted) ranged from 10.3 to 93.3 cm (mean 34.8 cm) and height ranged from 8.9 to 32.0 m (mean 21.3 m). Mean age and diameter for natural kauri in second-growth stands (n =233) were 146 years and 31.7 cm, respectively. In planted stands (n =199) mean age and diameter were 59 years and 36.7 cm, respectively. Characteristics of the individual stands surveyed in this study are summarised in Table 1.

Heartwood Percentage

Heartwood was identified in 92.9% of all stems, with heartwood width strongly correlated with diameter at breast height. Stems with no identifiable heartwood did not exceed 35.0 cm dbh. Heartwood was identified in stems with diameters from 10.3 cm in natural stands and 15.8 cm for planted kauri, although at this size it represented only 8.7% and 17.7% respectively of the total radial length. Second-growth natural stems had more heartwood than similar-sized planted trees for diameter classes between 20 and 60 cm (Table 2). Above 60 cm dbh, heartwood content was similar for both types. Small quantities of heartwood were present in older (>200 years) smaller diameter (10–30 cm dbh) stems from natural stands.

Sapwood Percentage

Sapwood radial width was longer in planted stands than in natural stands in diameter classes up to 50–60 cm (Table 2). Maximum sapwood radial width occurred at 40–50 cm dbh for planted kauri and 80–90 cm dbh in natural stands (Fig. 2). At 40–50 cm diameter, sapwood width averaged 13.3 cm and 10.0 cm, and represented 59.4% and 46.0% of the radial width, for natural and planted kauri respectively. Once diameters reached 60–70 cm, sapwood width from trees in natural stands had increased to a mean of 12.3 cm, and in planted stands sapwood width averaged 12.2 cm and made up similar proportions (36.3% and 39.7% respectively). In this study 93.7% of kauri had sapwood radial width <15 cm. Of those trees with sapwood width >15 cm the majority were in planted stands.

Prediction of Heartwood Diameter

The regression model (2) was fitted, and showed that the relationship between HD and dbh was statistically highly significant. However, there were significant differences between stands in the dbh_0 parameter, the stem diameter at which heartwood begins to form ($F_{8,379}$ = 21.34; $p < 0.0001$). The parameter *a* did not differ significantly between stands ($F_{8,371}$ =

TABLE 1–Summary of individual stands

Type	Location	Treatment	N	Mean stand age	Mean dbh (cm)	dbh M.A.I. (cm)	Mean height (m)	Height M.A.I. (m)	Mean stems/ha
Planted	Victoria Valley (Northland)	Nil	14	43	28.5	0.66	18.0	0.42	825
	Great Barrier Island	Nil	23	44	33.2	0.75	19.2	0.44	545
	Cornwall Park - Stand 6 (Auckland)	Nil	14	50	45.8	0.92	16.4	0.33	500
	Brookland Park (New Plymouth)	Nil	30	61	31.0	0.51	19.6	0.32	1286
	Fred Cowling Reserve (New Plymouth)	Nil	56	62	33.2	0.54	18.7	0.30	1463
	Cornwall Park - Stand 4 (Auckland)	Nil	30	70	44.8	0.64	19.6	0.28	320
	Cornwall Park - Stand 3 (Auckland)	Nil	32	70	53.8	0.77	22.1	0.32	500
Natural	Whenuakite (Coromandel Peninsula)	Nil	92	120	40.8	0.34	28.8	0.25	713*
	Great Barrier Island	Nil	65	137	27.1	0.20	17.6	0.13	1254*
	Mangatangi (Hunua Ranges)	Nil	28	136	27.4	0.20	19.4	0.15	2755*
	Katikati (Kaimai Ranges)	Nil	48	218	27.2	0.13	21.4	0.10	1470*

*For stems >5 cm diameter at breast height only

TABLE 2–Mean heartwood volume, and heartwood and sapwood width at 1.4 m above ground, in kauri trees from planted and natural stands

Type		Diameter classes (cm)							
		10–20	20–30	30–40	40–50	50–60	60–70	70-80	80-90
Planted	N	4	43	72	27	24	3	-	-
	sapwood width (cm)	7.3	10.5	11.4	13.3	13.1	12.2	-	-
	heartwood radius (cm)	1.5	2.4	5.8	9.0	13.7	18.6	-	-
	heartwood volume (m^3)*	0.006	0.016	0.067	0.132	0.298	0.540	-	-
Natural	N	46	62	45	31	16	13	2	1
	sapwood width (cm)	5.7	7.1	8.8	10.0	10.9	12.3	12.3	13.3
	heartwood radius (cm)	1.9	5.5	8.4	12.1	16.7	20.0	25.1	28.2
	heartwood volume (m^3)*	0.009	0.052	0.121	0.234	0.446	0.639	1.003	1.273

* In 6-m butt length

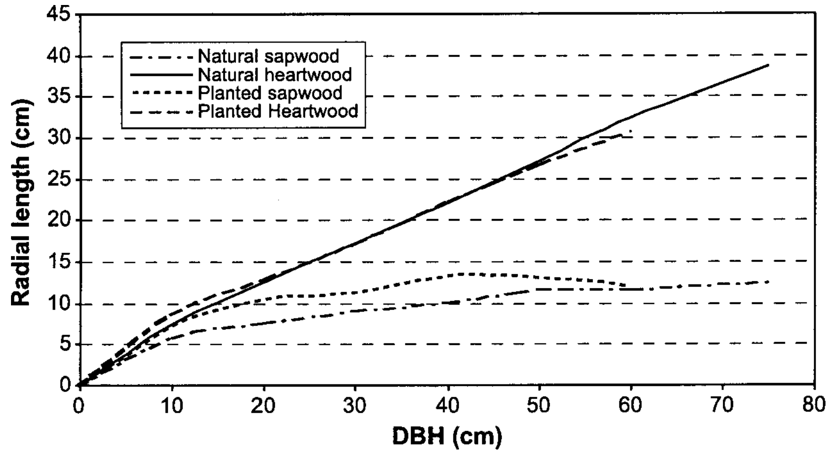

FIG. 2–Development of sapwood and heartwood in planted and natural kauri.

0.41; p = 0.92), and was estimated at 0.768. The analysis also proved that there was no significant relationship between individual tree age and HD in natural stands after allowing for dbh ($F_{1,377}$ = 0.01; p = 0.91). Also, the parameter *c* in Equation (3) did not differ significantly from one ($F_{1,378}$ = 1.46; p = 0.23), indicating that the HD *vs* dbh relationship is essentially linear once heartwood has begun to develop, at least over the range of stem diameters in the study. There was also no significant difference between stand margin trees and inner trees. Dbh_0, the stem diameter at which heartwood begins to develop, was quite strongly dependent on stand mean age (Fig. 3), and was fitted well using a logarithmic regression. Incorporating this into Equation (2) produced the following model:

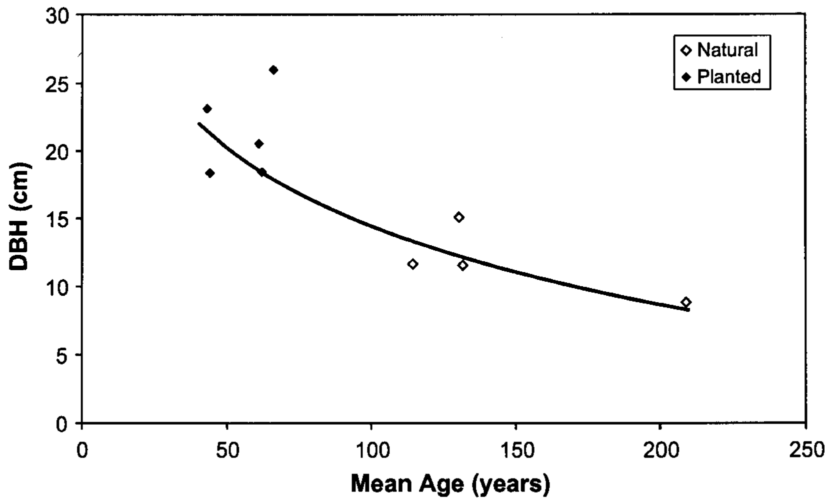

FIG. 3–Diameter (dbh) measurement at which heartwood begins to form (dbh_0) *vs* mean stand age.

$$HD = 0.768(dbh - (52.8 - 8.33\ln(Age))), \quad \text{when } dbh > 52.8 - 8.33\ln(Age)$$
$$= 0, \quad \text{when } dbh \leq 572.8 - 8.33\ln(Age)$$

This model is illustrated in Fig. 4, and indicates that, although heartwood diameter is primarily related to dbh, there is a tendency for it to be slightly less for a given dbh in younger stands. This will generally be the case with planted stands, which usually achieve much faster dbh growth than do natural stands.

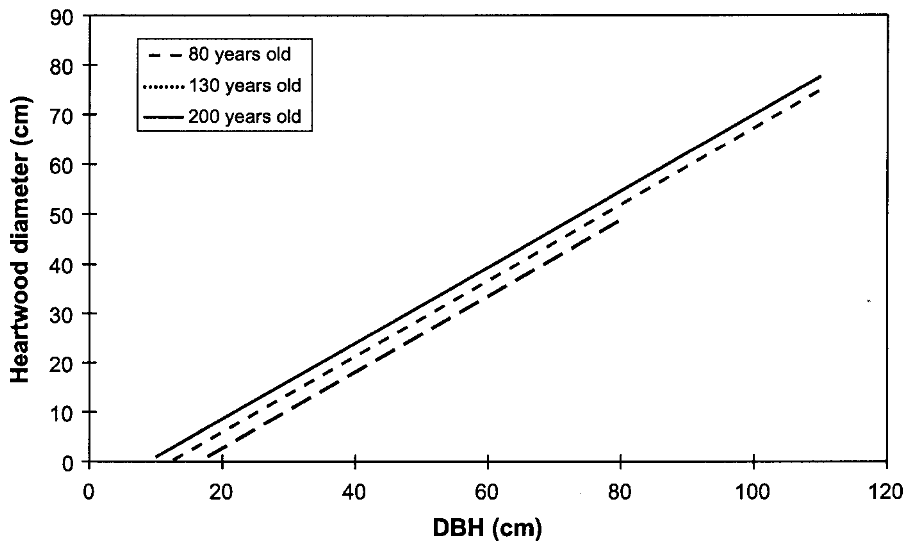

FIG. 4–Predicted relationships between heartwood diameter and dbh for stands of various mean age.

Note also that the age term in the model accounts for the slight flattening of the sapwood width relationship with dbh (Table 2, Fig. 2). Without it, the model will predict that once heartwood begins forming, the relationship between dbh and sapwood width is linear. However, once the age term is included in the model, it will predict a flattening relationship if dbh growth slows, as generally happens in older trees.

Heartwood Volume

To calculate true heartwood volume, the within-stem (heartwood) taper was assessed in 25 kauri trees exceeding 50 cm dbh in one natural stand. Diameters were measured and cores extracted at 1.4 m and 4.0 m above ground level. The mean external diameter at 1.4 m above ground was 65.2 cm, and it was 61.6 cm at 4.0 m (5.5% reduction). Mean heartwood radius at 1.4 m was 20.3 cm, reducing to 19.1 cm at 4.0 m. It closely followed the external taper. Heartwood radial width at 6 m was extrapolated using the internal and external taper rates to derive a mean radial width of 18.1 cm (i.e., 89.2% of the 1.4 m radius).

While heartwood was present in some trees with diameters 10–20 cm dbh, it represented on average only 8.8% of the total log volume of what would be a 6-m bottom log (0.009 m^3).

Once diameter reached 80–90 cm, heartwood (1.273 m^3) was 42.9% of the total log volume. For any given diameter class, kauri in natural stands had more heartwood content than similar stems in younger planted stands (Fig. 5 and Table 2). At diameters of 20-30 cm, planted kauri have only 39.6% of the heartwood volume of natural kauri of similar diameter; however, once diameters reach 60–70 cm, planted stands have 79.4% of the natural kauri volume. Indications are that once diameters in planted kauri reach 90-100 cm they will have ≈ 90% of the volume of heartwood found in natural stands.

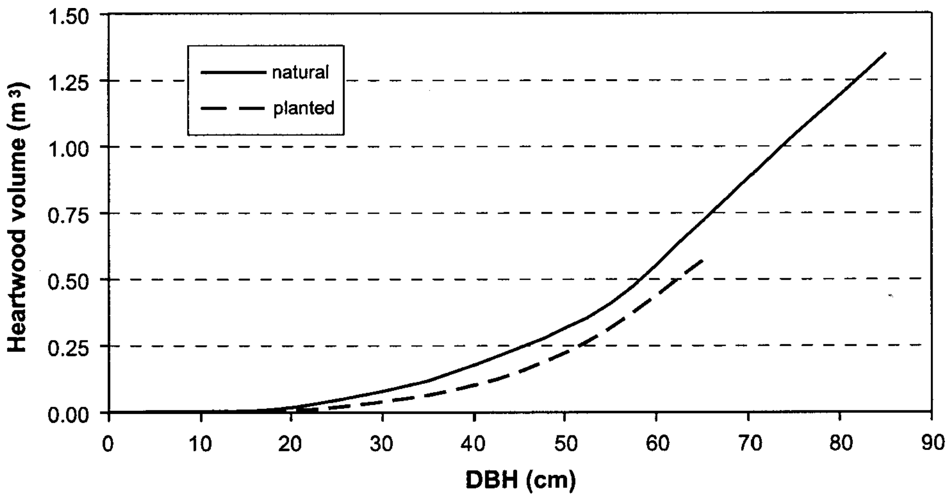

FIG. 5–Mean heartwood volume in planted and natural kauri by diameter classes (based on a 6-m butt log).

DISCUSSION

Stem Uniformity

Numerous authors (e.g., Hutchins 1919; Reed 1953; Hinds & Reid 1957) indicated that amongst the most significant features of kauri is its uniform and almost circular and defect-free stem which has little, or even occasionally reverse, stem taper. In this study, cores taken at 1.4 m showed the heartwood zone to be predominantly centrally located within the stem and most easily identified immediately on extraction of the core. The mean distance by which the increment borer missed the pith was only 1.3 cm when aiming for the physical centre of the stem, and so it is apparent that the pith is generally centrally located. As over 93% of kauri with heartwood had sapwood with width less than 15 cm, it seems the random removal of a single increment core at 1.4 m over a range of diameters in a stand is a suitable method for the assessment of heartwood content and age in kauri. The quantity of heartwood in New Zealand kauri in planted and natural stands identified in this study is similar to that reported for hoop pine (*Araucaria cunninghamii* Ait. ex D.Don) logs from Queensland, Australia. Smith (1980) reported that hoop pine logs, assumed to be from virgin forest, with mean diameter of 75 cm dbh had a mean heartwood diameter of 45 cm (i.e., 15 cm radial width of sapwood).

Wood Properties

McConchie (1999) noted that heartwood, and many other wood properties, are largely age dependent and may be compromised by faster growth rates and shorter rotations. In contrast, Whitmore (1977) reported that both New Zealand and Queensland plantation-grown trees have similar properties to trees from natural forest, although in this instance it appears that Whitmore used the term "plantations" to refer to managed second-growth rather than planted stands. A number of small-scale studies have been undertaken that either directly compared wood properties of samples from second-growth and old-growth kauri, or compared second-growth kauri with previously published figures for old-growth kauri (Table 3). C.M.Colbert & D.L.McConchie (unpubl. data) assessed wood samples obtained from butt discs and cut timber and noted some reduction in values for second-crop kauri compared to old-growth heartwood. Parker (1983) tested clears of second-crop and mature heartwood kauri and *Pinus radiata* D.Don in a comparison of alternatives for boat building. This study, amongst other findings, reported that second-crop kauri clears were equivalent in strength and ease of bending to mature heart kauri. Briscoe (1981, *in* Gibson 1983) reported on thinnings taken from a silvicultural trial and noted 10% lower density and up to 16% lower strength in the green condition; however, in the dry condition the strength was similar to that in published figures for old growth. Stiffness of second-crop kauri was lower by 26% and 17% in the green and dry conditions. It is likely that, in the future, timber obtained from planted kauri stands will have physical properties at least similar to second-crop kauri.

TABLE 3–Comparisons of some physical and mechanical properties of old-growth (heartwood) and second-growth kauri (at 12% moisture content).

Type	Density (kg/m^3)	Shrinkage (%)			Strength	
		Radial	Tangential	Volumetric	Modulus of rupture (Mpa)	Modulus of elasticity (Gpa)
Old growth*	511.0	–	–	–	96.6	10.6
Old growth†	560.0	2.3	4.1	6.6	88.0	9.1
Second growth‡	468.3	–	–	–	97.0	10.8
Second growth§	605.0	2.6	3.9	6.4	–	–
Second growth*	468.3	–	–	–	97.0	10.8

* Parker (1983)
† Clifton (1990)
‡ Briscoe (1981)
§ Colbert & McConchie (1981)

Merchantable Timber Recovery

Herbert *et al.* (1996) suggested in an economic evaluation of a planted kauri stand that merchantable recovery rates of 80% could be obtained, but Barton (1983) and Gibson (1983) reported only a minimal percentage of boards (<1%) graded as clean heart from small-diameter logs from thinning trials in second-growth forest. The model based on the data collected in this study indicates that to achieve a uniform heartwood zone of between 60 and 66 cm diameter a log would need to be 89.2–98.1 cm dbh and be from a tree between 121 and 161 years old, depending on diameter mean annual increment (Table 4). Indications from

TABLE 4–Predicted age and stem diameter (at breast height) required to achieve a heartwood diameter of 60 or 66 cm.

	MAI 0.6 cm		MAI 0.75 cm	
Heartwood dbh (cm)	60	66	60	66
Stem dbh (cm)	89.2	96.4	91.0	98.1
Age (years)	148	161	121	131

sawmillers are that larger diameter logs, from older and presumably slower-growing stems, rarely have a sapwood width that exceeds 15 cm. The prediction for continued increasing sapwood width with increasing age and diameter, above 90 cm dbh, is getting beyond the range of data that the model was fitted to and therefore predicted volumes may be understated. "Live sawing" (White 1973) of this internal heartwood core into 50-mm-thick boards would see a recovery rate of 86.3% of clean heart grade with minimum width boards of 33 cm (Fig. 6). Previous helicopter thinning trials in second-growth stands recovered mainly small-diameter (<50 cm dbh) stems because of either the limited lifting capabilities of the machinery, or the age and diameter distribution of stems available in the stand. In one thinning trial there was an emphasis on maintaining long lengths (12 m) predominantly for the boat-building industry (Gibson 1983). Where bigger diameter logs were recovered, they were either split in half or quartered lengthways to enable lifting by helicopter. Usually this log breaking was done through the centre of the stem, thereby reducing the recoverable width of the heartwood zone. Consequently, milled boards of any significant width would have contained some element of sapwood, which downgraded their use potential and value. Although there is market acceptance of treated kauri sapwood, any future recovery operation should be focused on maximising heartwood recovery. In the same way, to maximise potential recovery (value and timber volume) from natural stands, where recovery is restricted by weight limits, stems which contain usable quantities of heartwood should have the outer sapwood slabbed off leaving the majority of the heartwood core intact. Halkett (1983) and other commentators (e.g., R.C.Lloyd, in Barton 1974) described a minimum diameter limit of ≈100 cm as a guideline when kauri were being selected for felling in mature

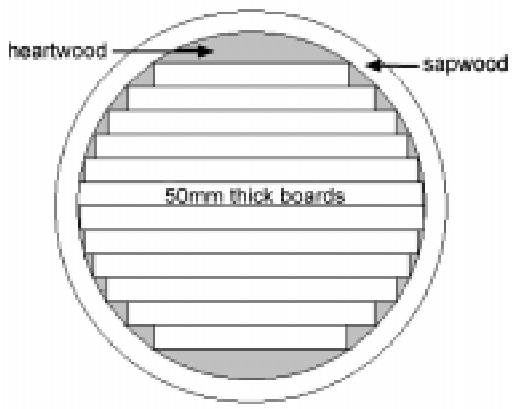

FIG. 6–Sawing pattern for 66-cm-diameter heartwood zone "live sawn" into 50-mm boards from a log with diameter at breast height between 96.4 and 98.1 cm. Conversion rate is 86.3%, including allowance for kerf.

forest, except where the felling was required silviculturally (thinning). For planted stands, recovery of suitable amounts of heartwood is likely to occur when stems are left until they reach a minimum diameter of 90 cm.

Productivity of Planted and Natural Stands

The study reported here identified significant differences between the performance and productivity of planted and natural stands based on growth rates and age. Herbert *et al.* (1996) suggested that this difference is probably due to natural second-growth kauri often being located on poor-quality sites while better-performing planted stands are on good-quality lowland sites. Hinds & Reid (1957) noted that "in natural stands growth rates vary exceedingly with the site and amount of competition with other vegetation, therefore in plantations and enrichment operations, a rotation of 200–250 years is anticipated for production trees of mean diameter 30 inches [76.2 cm]". It is unlikely in the current political and social climate that significant commercial harvesting of second-growth kauri on conservation land will be permitted. Therefore, planting of kauri as a means of establishing a sustainable resource is the likely future option.

The best diameter increments in this study were recorded in three planted stands with stockings of 500–550 stems/ha. Diameter increment in these planted stands was 0.79 cm annually since planting (compared with 0.22 cm for all natural stands). In other recently measured planted stands with similar stocking rates, annual diameter increments between 0.8 and 0.9 cm (unpubl. data) have been recorded in stands 43–71 years old, but it is unlikely kauri would maintain this rate of diameter increment to a mean 90 cm dbh, even in moderately stocked stands. Hutchins (1919) suggested natural stocking rates of 150–200 stems/ha, while Halkett (1983) reported a mean 85 stems/ha in old-growth forest. At a mean dbh of 90 cm and a final stocking of 80–100 stems/ha, basal area would be between 50.9 and 63.6 m^2.

Therefore, one potential scenario for plantation kauri could involve establishing at 500 stems/ha within either a natural or artificially established nurse crop. The stand would then be thinned over time to 80–100 stems/ha, which would yield at final felling 154.5–193.1 m^3 of heartwood and 132.8–165.9 m^3 of sapwood per hectare, for 6-m butt logs at a mean 90 cm dbh. Thinning operations (at a stand mean 40 cm and 60 cm dbh) prior to final felling might yield a further 137.6 m^3 and 323.3 m^3 of heartwood and sapwood respectively. To achieve a mean dbh of 90 cm would require between 120 and 150 years (at a mean annual diameter increment of 0.6–0.75 cm) from planting.

An alternative to clearfelling at 90 cm dbh would be felling within small coupes and careful extraction of logs, or timber milled onsite. However, a possible problem with felling kauri at age 100+ is that they will have lost the monopodial "ricker" form of younger trees and developed the more massive spreading crown typical of mature trees (Halkett 1983). These spreading crowns are considerably more difficult to fell without damaging surrounding stems intended for further development or to act as seed trees.

Herbert *et al.* (1996) suggested wholesale sawn timber prices for second-growth kauri, depending on grade and dimensions (width), of NZ\$1,200–\$3,500/m^3 (in 2002, prices up to \$7,000/m^3 have been reported to one author). While the initial analysis of heartwood yields was based on a standard 6-m butt log, this study found merchantable butt log lengths (branch free) averaged 10.8 m (range 7.0–15.0 m). Therefore the prediction of volume yield using 6-m butt logs only is conservative. Allowing the development of greater diameters, achieving longer recoverable log lengths or identifying an ability to maintain a higher stocking capacity without loss of diameter increment would increase the yield, as would recovery of sapwood grades.

The current study has developed a method for predicting heartwood content within kauri from planted and natural second-growth stands. Although over 93% of sampled trees had sapwood radial width less than 15 cm, it was seen that even within the same stand there was a range of heartwood content from trees with similar ages and/or diameters. Harding (1990) reported in a study of wood properties for species from two genera (*Araucariaceae* and *Pinus*) that "in general, wood properties are under a higher degree of genetic control than growth traits". Therefore there appears to be an opportunity to identify individual trees that contain above-average amounts of heartwood. As heartwood formation in kauri is likely to have high heritability, it will be possible (using sapwood radial measurements) to select families that are known to have superior heartwood formation for inclusion into a breeding programme. In addition, breeding programmes and improved nursery techniques have the potential to produce better quality and faster growing seedlings that will lead to substantial improvements in the first 10–15 years of growth, with subsequent reductions in rotation length, improving the returns to growers and investors.

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