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Wood Density of Plantation-grown New Zealand Kauri (*Agathis australis*)

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EXECUTIVE SUMMARY

Growing kauri (*Agathis australis* (D.Don) Lindl.) in plantations for timber has received considerable support over the last decade, particularly with the development of a growth and yield model that indicates better growth and productivity than previously thought possible. The wood properties of heartwood kauri from old-growth forest are well known and highly regarded [1]. Conversely, the wood quality of young, relatively fast-grown timber that will be dominated by sapwood grades at harvest is still largely unknown, apart from an early study from one site [2].

The objective of this study has been to develop an understanding of the wood density of plantation-grown New Zealand kauri and any apparent environmental factors or forest management practices that may influence it. The current study was based on pith-to-bark increment cores and standing-tree measurements from ten planted stands within and outside the current natural range of the species. Stands surveyed represented the majority of areas where kauri plantations are known to be established. The wood quality of planted kauri was also compared with kauri of similar diameter in a natural second-growth stand.

Planted kauri stands were between 14-69 years of age when increment cores were taken. They averaged 51.1 years of age and 31.2 cm diameter at breast height (DBH). Whole-core density averaged 448.5 kg/m^3 for all stands. Wood density was plotted along the length of the core with a small increase in density from pith to bark. Outerwood density was strongly correlated with whole-tree density. Some variation of wood density was noted, both within and between stands. Within-stand variation averaged 81.8 kg/m^3. All planted kauri were within 9.1% of the mean density. Between-stand variation was a maximum of 28.1 kg/m^3. The two stands with the highest density were in Northland, as was the stand with the lowest average density (435.9 kg/m^3).

Whole-core density was not affected by the stand parameters of tree age, diameter and growth rate (DBH MAI), stand density, or any of the environmental factors tested, particularly latitude. It is suggested that kauri can be grown both within and outside its natural range, and planting location will likely have very little impact on wood density.

One natural second-growth stand in Northland was also sampled. Trees from this stand averaged 126 years of age and 26.3 cm DBH (note – a lower DBH at more than twice the age than planted trees). The largest DBH in this stand approached 41 cm, suggesting that some heartwood may have been present in the largest diameter stems. Whole-core density averaged 484 kg/m^3 and within-stand variation was 140 kg/m^3. While the wood density of kauri growing in natural stands was statistically different from planted stands, it is considered of no practical significance.

The study has shown that the wood density of plantation-grown kauri is at least comparable to that found in natural second-growth stands. It has also shown that kauri can be planted on a much greater range of sites, within and outside the current natural range of the species, and that research and management to increase growth rates and harvesting at a comparatively young age (50-70 years), will have no detrimental impact on wood density.

INTRODUCTION

Kauri (*Agathis australis* (D.Don) Lindl.) has a number of natural characteristics that increase the interest in it as a species suitable for commercial forestry plantings. A recent growth model developed for kauri grown in planted forests has shown significant growth improvement compared to kauri grown in natural stands [3]. As a long-lived species, it also has significant potential as a carbon-forestry option. The use of kauri for timber or as a carbon-forestry species is reliant, to some extent, on the wood properties when grown in plantations.

The wood properties of kauri timber from old-growth trees are well known and highly regarded and discussed in numerous publications [4-6]. They are, in the main, based on the significant quantities of heartwood recovered from large diameter stems.

The wood property of kauri in second-growth stands where a high proportion of sapwood was present has also been tested [7-9]. It was presumed to have wood quality lower than that from old-growth stands. A number of small-scale studies of wood properties of second-growth kauri (<200 years old) have been undertaken that either directly compared samples with old growth kauri or compared second-growth kauri with previously published figures for old-growth kauri.

McConchie[10] noted that wood properties are largely age dependent and may be compromised by faster growth rates and shorter rotations. In contrast Whitmore [11] reports that both New Zealand and Queensland plantation-grown trees have been shown to have similar properties to trees from natural forests. Kauri planted on fertile lowland sites typically have growth rates (particularly diameter increment) significantly better than that seen in old growth stands or densely stocked second-growth stands [12]. This leads to the potential for merchantable diameters (40-50 cm) to be achieved within 50-60 years of planting, although the majority of recovered timber grades would be sapwood [13]. Herbert *et al*. [14] noted that there was market acceptance of sapwood, although the working properties and potential enduses for significant quantities of sapwood were not known.

The only study of wood quality of timber from planted kauri was based on one Taranaki site at age 68. The stems selected for the study were the largest diameter trees, therefore the fastest growing element of the stand [2]. Diameters ranged from 31.0-48.1 cm (mean 39.4 cm) with logs predominantly composed of sapwood (80% at ground level, 99% at 10 m above ground). The wood properties of density, stiffness and shrinkage were compared with the same properties from old-growth kauri (heartwood) and second-growth stands (sapwood/heartwood). The wood properties from the study of sapwood from planted kauri were similar to those of old-growth heartwood and second-growth mixed sapwood/heartwood timber for stiffness and shrinkage, but slightly inferior for basic density. The properties were uniform across the width of the stem. The mean annual increment for diameter at breast height (MAI DBH) in this stand was 0.6 cm/yr, and was similar to that of all planted kauri stands (0.62 cm/yr) and substantially better than that in second-growth stands (0.24 cm/yr). This result suggests that the observations of McConchie[10] may not be applicable to kauri, as the growth rates observed did not negatively influence wood quality. The results produced by Steward and McKinley [2] represented only one site and would need to be confirmed with studies of wood properties from other planted stands of kauri.

The cessation of harvesting from crown-owned natural stands in New Zealand has generated wide interest in plantation-oriented production of indigenous conifer species, including kauri. The planting and management of kauri in New Zealand has largely relied on information provided from historic trials that were frequently located on difficult and impoverished sites and suffered from a lack of after-planting care. Consequently the perception for potential growers and investors that growth rates, survival and productivity of indigenous conifers are poor has tended to be reinforced. However, a survey of indigenous tree plantings in the 1980s identified sufficient good stands on high quality, fertile lowland sites where mean diameter increment at breast height exceeded 0.75 cm per annum over 70 years. There are already a number of well-established plantings located throughout New Zealand.

Following the 1980s survey, an Indigenous Plantation research programme was initiated in the early 1990s. The benefits of this research programme, to enhance the productivity of kauri, totara (*Podocarpus totara*) and other indigenous conifers and hardwood tree species, are seen to extend beyond the production of a valuable timber resource to include major contributions to cultural values, water quality, recreation, biodiversity, and carbon sequestration. This view has been represented widely in the community, where an enthusiasm has been shown for the development of sustainable management systems for planted indigenous tree species for timber and non-timber benefits. The programme aims to enhance the economic, social, and environmental welfare of New Zealanders by researching techniques for the development and management of indigenous plantations. Areas of focus include the evaluation of establishment and silvicultural techniques, including uneven-aged silvicultural options, tree improvement, wood quality, and growth and yield modelling utilising information from both plantations and naturally established stands.

Sapwood is less durable than heartwood, and is attacked by a species of wood boring beetle (*Anobium punctatum*)[1]. It decays rapidly when in contact with the ground[15]. Timber from second-growth kauri has a high proportion of sapwood, and until recently its properties were assumed to be inferior to those of heartwood from old-growth trees. When the quality of sapwood from 68-year-old plantation-grown kauri was tested, it was found to be similar to that of old-growth kauri in terms of density, modulus of elasticity, and shrinkage[2]. These findings agreed with those of Hutchins[6], who believed that kauri sapwood was as good as heartwood provided it was used indoors and kept free from borer.

What has been missing from the studies of young kauri stands has been a wider study of the wood properties of kauri grown in plantations, where recovered timber is likely to be entirely or predominantly sapwood. This study aims to provide some of this missing information.

METHODS

Stands

Material for this current study came from ten planted kauri stands and one natural second-growth stand (Figure 1). All stands sampled were previously used to develop growth and yield models for the species [3]. Standing tree measurements of height (m), diameter at breast height of 1.4 m (DBH), height (m), stand density (stems/ha), stand age (years), and variables of elevation (m a.s.l.) and latitude (^{o}S) were also acquired for each stand. Three of the planted stands were located south of the species' current natural range. Wood density in planted stand was benchmarked against one natural second-growth kauri stand where a similar range of diameters was present.

Planted stands ranged in age from 14 to 69 years and were located from near Kaitaia in the north, to Taranaki and Hawkes Bay in the south. The second-growth stand was in Northland, to the south of Russell, and had an estimated average age of 126 years (range 80-161). This age was calculated using the equation developed in one of the growth and yield models for the species [3]. The best performing planted stand observed to date (stand 16) was included in this study and is a standout in terms of DBH MAI (1.84 cm/yr) when compared to all other stands (0.58 cm/yr).

Planted stands have been identified by stand number only. Some owners request privacy on their stands in order to provide protection from disease potentially arising from visitors.

Core Collection and Analysis

Wood density was derived from 5.0 mm pith-to-bark increment cores (Figure 2). It was initially planned to obtain 20 cores per site; however a number of owners gave permission for the removal of only 10 cores. Cores were taken at 1.4 m above ground on the highest side of the tree and labelled for stand number and tree number and DBH immediately on removal. When cores were taken, it was assumed that the pith would be in the physical centre of the tree. However, off-centre piths are not uncommon in kauri. Only one core per tree was permitted, irrespective of whether the core had obtained the pith. Cores were bundled and stored in a domestic freezer until analysis.

For analysis, increment cores were divided into segments from the bark-end of the core into segments of 0-50, 51-80, 81-110, 111-140 and 141-170 mm and tested for basic density using the maximum moisture content method [16]. A whole-core density value was also derived for each core.

Data were analysed within individual stands and as a combined dataset.

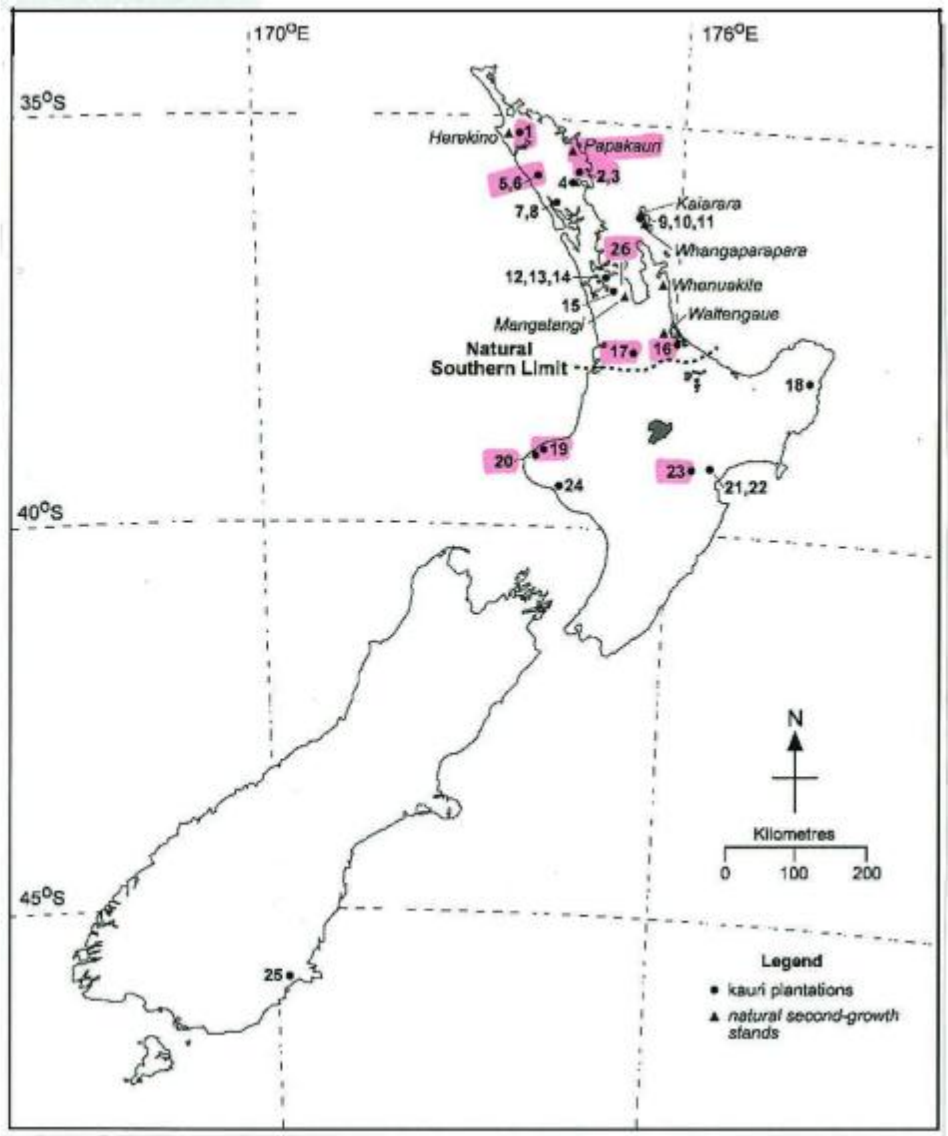


Figure 1. Location of planted and second-growth kauri stands used to develop kauri growth and yield models, from which 10 planted stands and one second-growth stand were sampled for wood density (sampled stands highlighted).

Figure 2. Extracting a 5.0-mm increment core from a 57-year-old planted kauri in Northland.

RESULTS

Planted Stands

The diameters of all planted kauri (N=151) sampled for wood density were plotted and shown to be relatively normally distributed (Anderson-Darling test of normality: P-Value 0.091), and were consistent with the mean DBH of permanent sample plots (PSPs) within individual stands. Stand 16 was the youngest at 14 years when cores were taken, while Stand 20 was the oldest at 69 years. The two Waikato stands had the smallest average diameter (Stand 26), and the largest (Stand 17) (Table 1; Figure 3). Stand density (stems/ha) ranged from 582 to 1099 stems/ha and averaged 824.1 stems/ha. Three stands (Stands 19, 20, 23) were located approximately 140 km south of the species natural southern limit. Elevation of the stands ranged from near sea level (20 m a.s.l.) to 340 m a.s.l. for the Hawkes Bay stand (Stand 23).

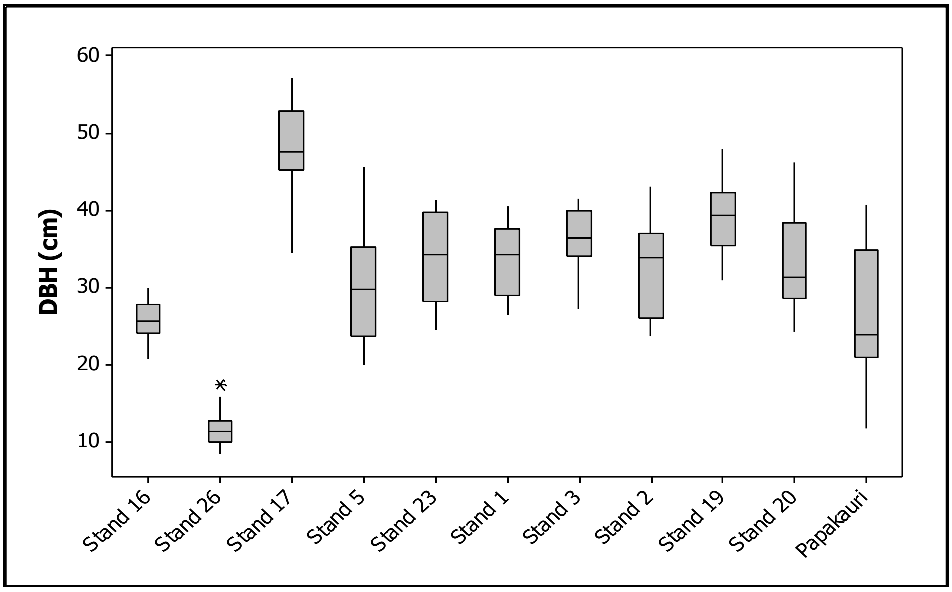


Figure 3. Diameter at breast height of sampled stems in planted stands (youngest to oldest) and one natural stand.

Whole-core density of planted kauri averaged 448.4 kg/m^3 for all sites combined (Table 1), with 2.7% of the sample >500 kg/m^3. Stand 3, a Northland site, had the highest mean whole-core density at 464 kg/m^3, and Stand 2, also a Northland stand, the lowest mean density (435.9 kg/m^3). Within-stand mean whole-core density variation averaged 81.8 kg/m^3, and was as high as 121 kg/m^3 in Stand 5. Between stands, whole-core density varied by 28.1 kg/m^3 from the lowest average density (435.9 kg/m^3) to the highest (464 kg/m^3). All samples were within 9.1% of the mean whole-core density. Outerwood density averaged 436.2 kg/m^3 and varied by 41 kg/m^3 from the lowest to the highest.

Table 1. Planted kauri stands sampled for wood density (stands arranged youngest to oldest).

Stand number *	Region	N	Stand age (years)	Mean DBH (cm)	DBH MAI (cm)	Mean Height (m)	Mean Whole-core density (kg/m^3)	Outerwood density (kg/m^3)	Stand density (stems/ha)	Latitude (°S)	Elevation (m)
16	Bay of Plenty	20	14	25.8	1.84	12.4	445.0	443.2	624	37.66	20
26	Waikato	20	37	11.6	0.31	18.6	441.0	440.1	1000	37.12	150
17	Waikato	10	49	48.1	0.98	19.4	451.8	443.1	582	37.86	340
5	Northland	10	55	30.2	0.55	20.4	460.7	439.9	1099	35.71	200
23	Hawkes Bay	10	56	33.8	0.60	20.8	452.8	442.5	950	39.28	320
1	Northland	10	57	33.6	0.59	16.8	441.8	402.2	825	35.16	100
3	Northland	20	57	32.8	0.57	21.6	464.0	441.1	823	35.39	120
2	Northland	11	62	36.0	0.58	23.0	435.9	410.1	860	35.40	120
19	Taranaki	20	68	39.4	0.58	24.3	451.4	442.8	647	39.06	60
20	Taranaki	20	69	33.1	0.48	25.3	441.5	435.8	831	39.08	60
	Mean		**52.4**	**32.4**	**0.71**	**20.3**	**448.4**	**436.2**	**824.1**	**-**	**149**
	Min.		**14**	**11.6**	**0.31**	**12.4**	**435.9**	**402.2**	**582**	**-**	**20**
	Max.		**69**	**48.1**	**1.84**	**25.3**	**464.0**	**443.2**	**1099**	**-**	**340**

*Planted stand numbers relate to the stands in Figure 1.

Table 2. Papakauri natural second-growth stand in Northland sampled for wood density.

N	Stand age (years)	Mean DBH (cm)	DBH MAI (cm)	Mean Height (m)	Mean Whole-core density (kg/m^3)	Outerwood density (kg/m^3)	Stand density (stems/ha)	Latitude (°S)	Elevation (m)
20	126	26.3	0.20	28.1	483.6	464.7	365	35.36	100
Range	*80-161*	*11.7-40.7*	*0.15-0.25*	-	*437-577*	*405-551*	-	-	-

Data from individual stands were compared using Analysis of Variance (ANOVA), which showed no significant difference for whole-core or outerwood density. The youngest and fastest growing stand (Stand 16; 14 years) had an average whole-core density similar to that of the oldest stand (Stand 20; 69 years) (Figure 4).

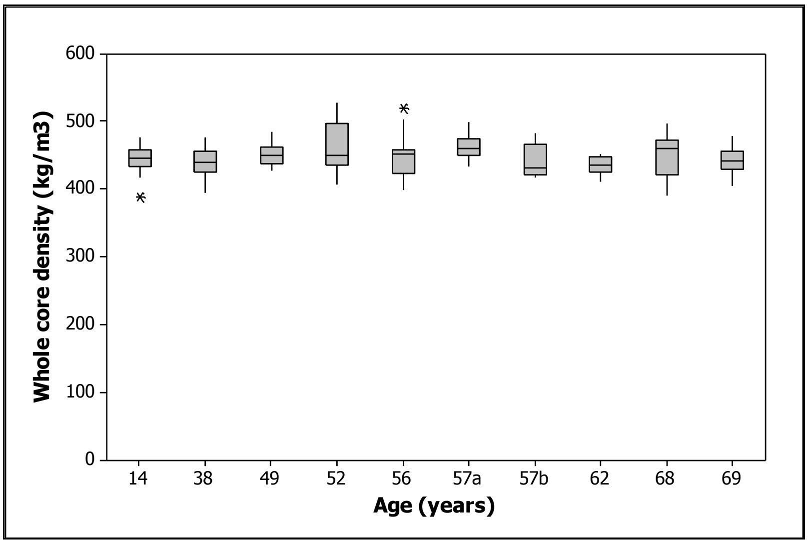


Figure 4. Whole-core density (kg/m3) at breast height of kauri in planted stands between 14-69 years of age.

Whole-core density was plotted against DBH, DBH MAI, stand density, elevation, latitude and rainfall (Figures 5 and 6). No relationship was found between whole-core density and any of these kauri growth or stand parameters (stand density R^2=0.000; elevation R^2=0.0015; latitude R^2=0.0045, rainfall R^2=0.002).

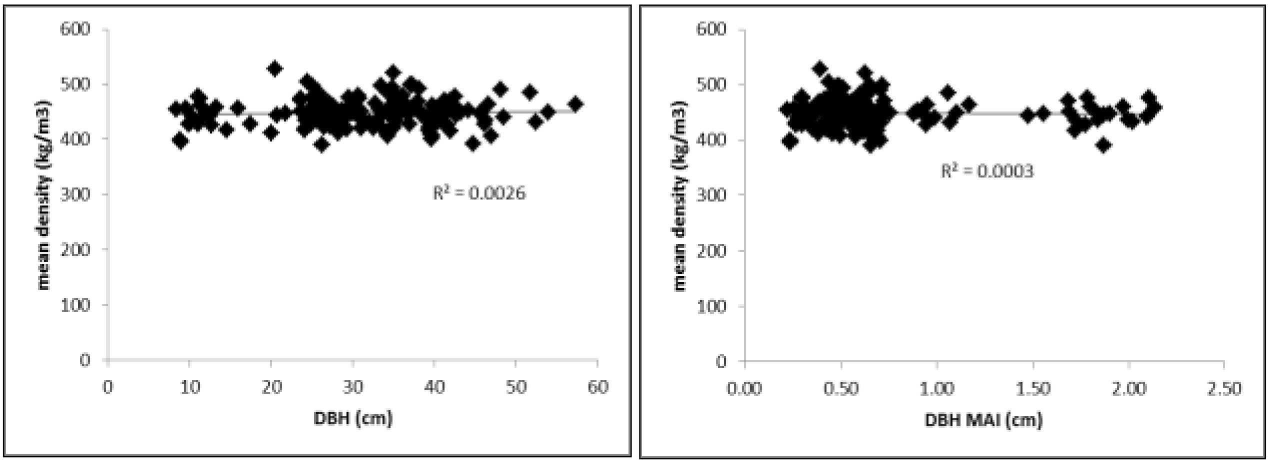
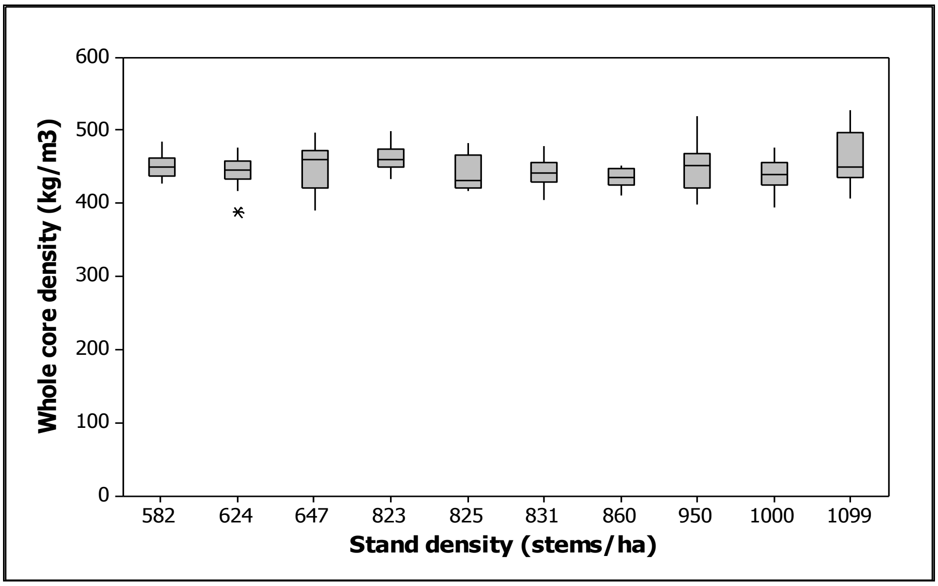
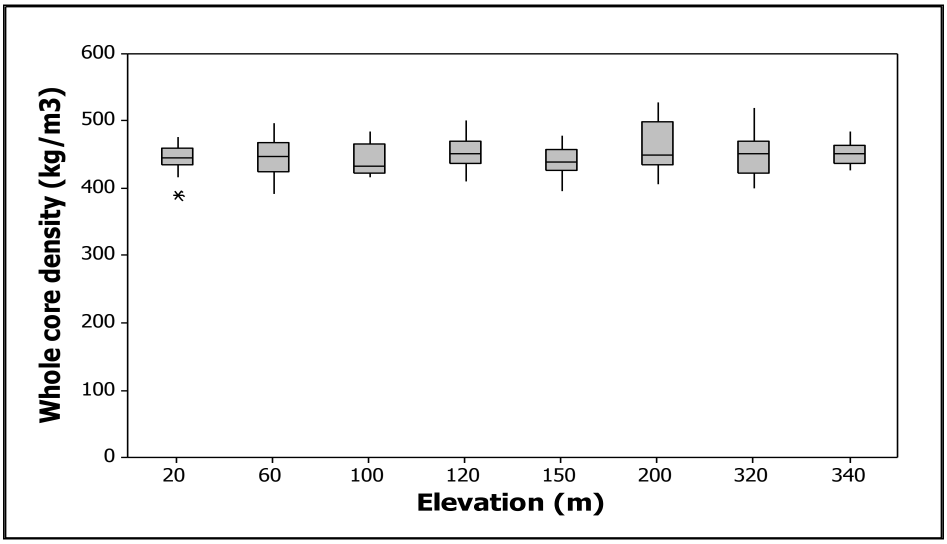


Figure 5. Whole-core density plotted against DBH and DBH MAI for kauri in planted stands. No relationship was identified.





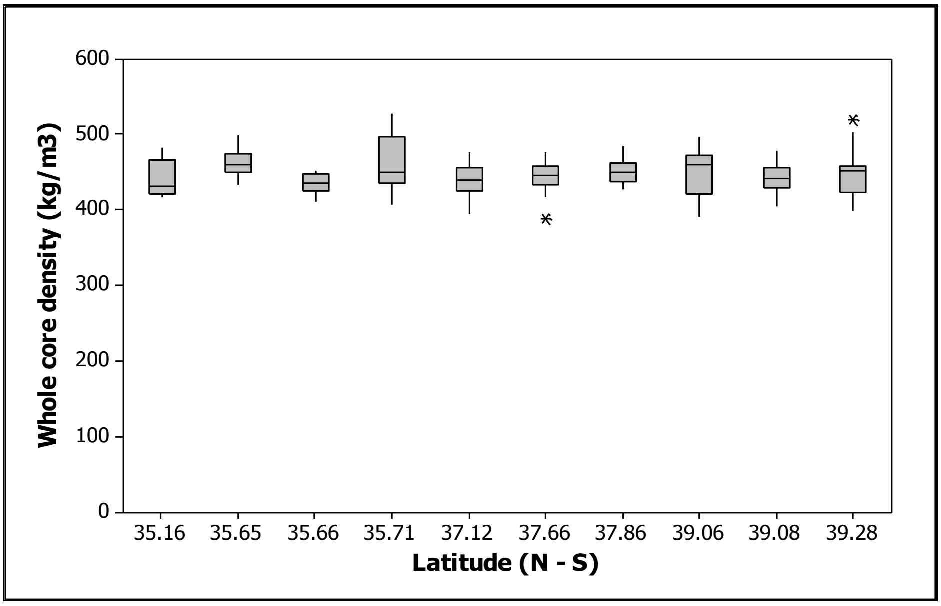


Figure 6. Whole-core density at breast height against stand density, elevation and latitude within individual planted kauri stands.

Whole-core density was correlated with outerwood density of samples from planted stands and was found to be strongly related (Figure 7). Outerwood density was on average 3.2% less than the whole-core density. Outerwood density cores (0-50 mm from bark end) would be sufficient to predict whole-core density.

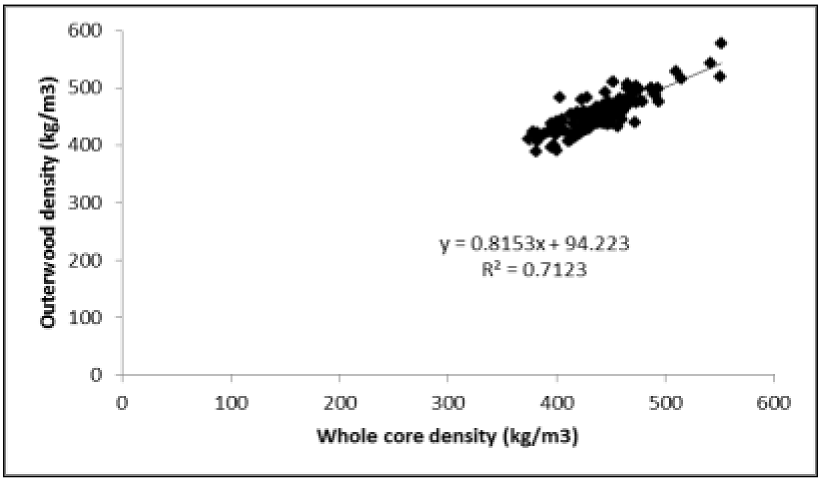


Figure 7. Relationship of outerwood density to whole-core density for individual kauri in planted stands - Pearson correlation 0.838 (P-Value = 0.000).

Comparison between Planted and Natural Stands

Kauri in the natural second-growth stand (N=20) had an estimated mean age of 126 years (range 80-164 years) and a substantially lower stand density (365 stems/ha) (Table 2) than for any of the planted stands. The mean DBH of the natural second-growth stand was lower than, but consistent with, all the planted stands (32.4 v. 26.3 cm) as was average DBH MAI (0.71 v. 0.2 cm/yr) (Figure 8). Applying the heartwood model of Steward and Kimberley [13] indicates only minimal heartwood content in the largest diameter stems, and none in the smaller stems.

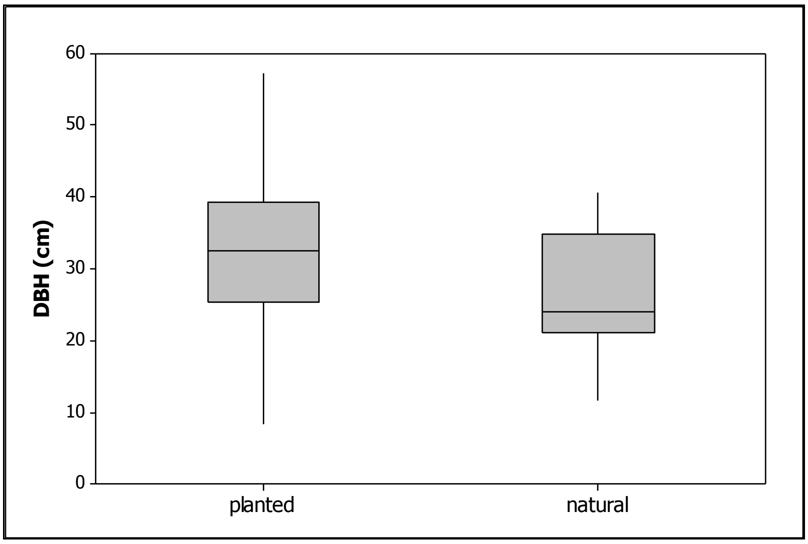


Figure 8. Diameter distribution of kauri sampled in a natural second-growth stand compared with kauri sampled in planted stands.

Whole-core density was correlated with outerwood density in samples from the natural second-growth stand and was found to be strongly related (Figure 9) - Pearson correlation 0.869 (P-value = 0.000). This relationship is slightly stronger in the natural second-growth stand than in the planted stands, but it follows a similar trend.

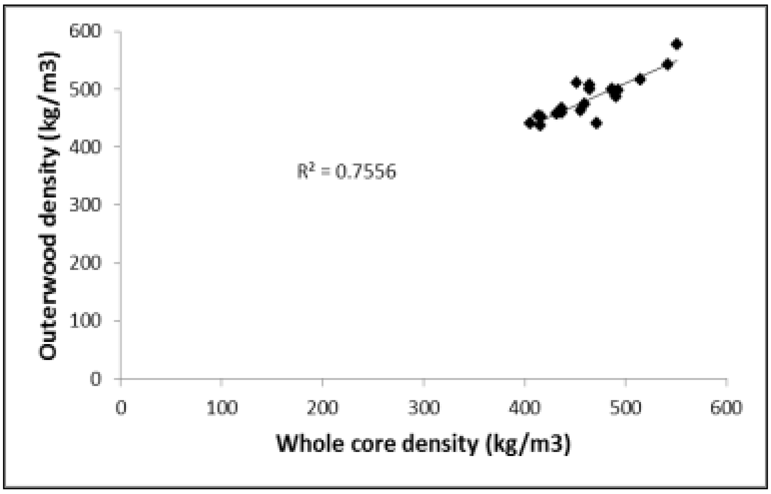


Figure 9. Relationship of whole-core density with outerwood density for individual kauri in one natural second-growth stand.

Whole-core density in the natural second-growth stand averaged 483.6 kg/m^3 (range 437-577 kg/m^3). When compared (ANOVA) with the planted stands, the whole-core density of second-growth kauri was significantly higher than for planted kauri (*F = 30.26, p* = 0.000). The difference between means of the two groups was 35.2 kg/m^3, while the difference in the means of the individual planted stands was 29 kg/m^3. For the second-growth stand, the whole-core density range was 120 kg/m^3. The whole-core densities for all planted kauri were combined and plotted against data from the second-growth stand (Figure 10). As only one second-growth stand was surveyed, it is suggested that the difference identified is of no practical significance.

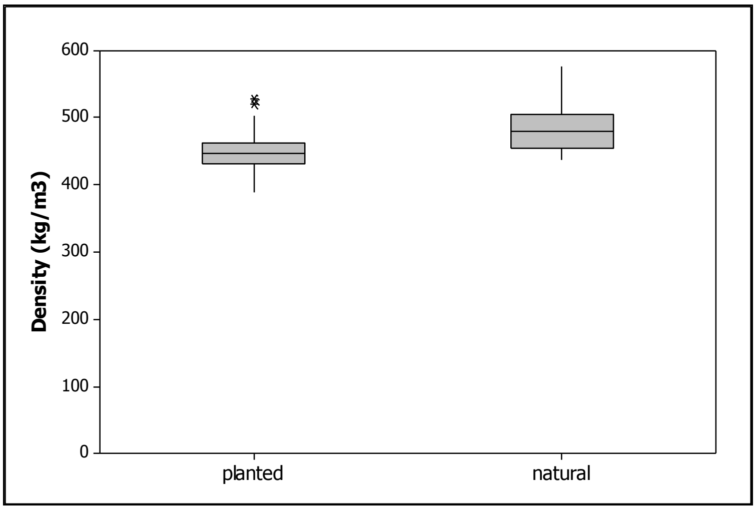


Figure 10. Comparison of whole-core wood density in planted and second-growth kauri stands.

Increment cores were divided into segments from the bark-end of the core into segments of 0-50, 51-80, 81-110, 111-140 and 141-170 mm, and the density of each segment was determined. For planted and second-growth stands a mean density was calculated for each measurement point and plotted. There is a similar trend for increment density to increase with distance from the bark in the planted stands and the second-growth stand (Figure 11). The difference between the planted stands and the second-growth stand was never greater than 11.5 kg/m^3 at any point on the core. The difference between outerwood and innerwood was 53.7 kg/m^3 for planted stands, and 58.3 kg/m^3 for the second-growth stand.

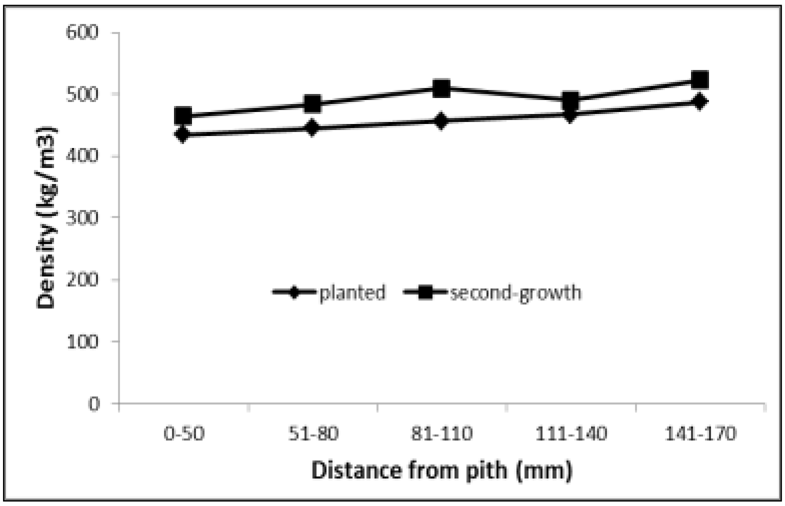


Figure 11. Radial-density pattern of kauri in planted stands and a second-growth stand at breast height.

CONCLUSION

- Wood density of kauri in planted stands has been found to be consistent across sites within and outside the current natural range of the species. The mean density of 448.4 kg/m^3 was similar to that reported by Steward and McKinley [17] (451 kg/m^3) from one stand surveyed in 2003, but higher than that used by Steward in 2011 [3] to calculate carbon in planted stands (435 kg/m^3). The carbon predictions made by Steward [3] are therefore shown to be conservative.

- The DBH range of kauri in both planted and second-growth stands suggests that the majority of the wood tested for density was likely to be sapwood. Steward and Kimberley [13] produced a heartwood model for kauri in planted and natural stands, and found heartwood content strongly linked to DBH, and secondly age. The model indicates that a DBH greater than 30 cm would be required to contain useable quantities of heartwood. With average DBH of 32.4 and 26.3 cm, only a small fraction of the wood tested in this study would be heartwood. Heartwood density is reported as 520 kg/m^3[1, 17]. For individual trees in both planted and natural stands, the whole-core density in this study was not dissimilar to, or in some cases exceeded, the density figure quoted for heartwood.

- There was a general trend for an increase of density from pith to centre, although in practical terms it was no greater than the variability in either whole-core or outerwood density. Outerwood density (outer 50 mm from the bark) was found to be highly related to whole-core density. This suggests that for future studies of wood density of kauri, and where ages are known, only outerwood cores will be required.

- This study shows that there is no practical difference between the wood density of kauri in planted and natural stands where similar diameters are present, and where the majority of wood tested is sapwood.

- The results indicate that kauri can be planted for timber production, and planted kauri will have similar wood density properties irrespective of where they are planted (north to south), and how fast they have grown, or how they have been managed. Stand 16 in the Bay of Plenty is the fastest growing stand observed to date. Its diameter increment is over twice that of the average planted stand and over nine times that of the natural second-growth stand. Whole-core density for this stand is within 4 kg/m^3 of the average for planted stands and 39 kg/m^3 of the natural second-growth stand.

  The within-stand variation of wood density suggests that any future selections for inclusion into a breeding programme should include those trees of superior growth that have higher than average wood density.

- These data will be added to the kauri growth model and further develop the case for growing this species in plantations for a timber outcome.

ACKNOWLEDGEMENTS

The author thanks the landowners for permission and assistance to remove increment cores from their kauri for inclusion into this study. Also thanks to Russell McKinley for analysing cores.

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