GROWTH AND YIELD OF NEW ZEALAND KAURI (*AGATHIS AUSTRALIS* (D. DON) LINDL.)

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by

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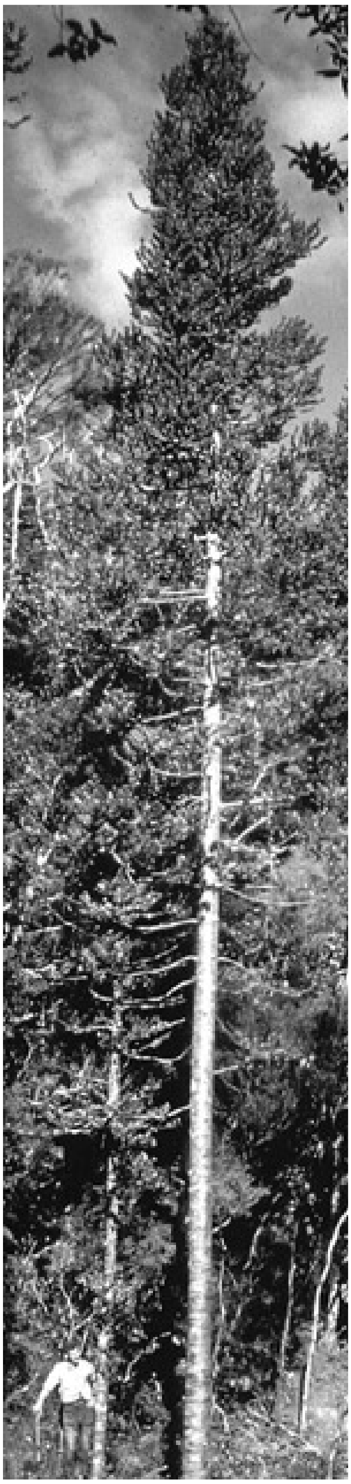

"...for many years a few of us have been urging that some attention should be given by the foresters of the Dominion to the regeneration and cultivation of the New Zealand native forests. For the most part this advice has fallen on deaf ears, although it has been shown repeatedly by scientific men such as the late Sir David Hutchins and Thomas Cheeseman that most kinds of indigenous trees respond quickly to the protection necessary to give them a start in the world. Even the kauri grows more rapidly here than the oak does in Europe. Someday, let us hope, there will be a reconstruction of present afforestation methods in the direction of planting native timbers largely, instead of relying wholly on exotics, as at present...".

J. Cowan (1936)

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Dr Euan Mason, my senior supervisor, was hugely supportive through this whole process. From the time I nervously emailed my proposed topic and received such a positive response to this and every conversation we had; I have changed some of my thinking, re-enforced some, and learnt a lot - in more directions than I expected to.

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I am indebted to those people and organisations who took what must have seemed to be an act of faith to plant kauri, and for making those developing stands available for measurement and inclusion in this study. Some of those individuals are now deceased, but in a large sense they live on through what appears to be the simple act of planting trees. This thesis would not have been possible without their vision for the future of kauri and New Zealand. I would also like to thank the numerous members of the New Zealand public whom I have spoken with over the years about kauri forestry, your enthusiastic response gives me hope that people do actually care for our native trees.

This thesis is also, in some part, an acknowledgement to the people who recorded the history, for better or worse, of kauri. Fortunately, those same individuals also often identified and promoted the potential of the species for the future environmental, financial and cultural well-being of New Zealand. Many of those individuals have been cited in this thesis.

To Diane, my thanks and love for your support and tolerance.

ABSTRACT

The growth and productivity of kauri (*Agathis australis* (D. Don) Lindl.) in even-aged single-species planted stands and mixed-aged second-growth natural stands has been studied. Stand-level models of height, basal area and whole-tree volume were developed. Kauri growth and productivity in planted stands up to 83 years old were compared to that of natural stands that were up to 196 years of age. Within natural stands, the effect of thinning treatments on growth and productivity was also assessed.

Models of growth and productivity were initially developed for each of the three different kauri stand types independently (planted, second-growth unthinned and thinned). Combined data sets allowed for the development of single models that were able to fit all stands. A Schumacher equation with local slope parameter and asymptote bounded at 45 m gave the best fit for height growth, while a von Bertalanffy-Richards equation in difference form with local slope parameter gave the best fit for basal area growth. Kauri in all stand types were found to be slow to establish with little height growth in planted stands for the first five years after planting, and for the first 25 years in natural stands. Similar trends were observed for basal area and whole-tree volume development. Models developed in this study are relevant only to kauri in the "ricker" or monopodial form irrespective of age, and for stands from 320-2000 stems/ha.

Kauri growth and productivity in planted stands was substantively better than that in second-growth stands. Planted kauri had height increment of 0.4 m/yr for periods of up to 30 years. At age 50, planted kauri was predicted to be 20 m in height, over twice the height of kauri in natural stands, and to be 28.1 m by 100 years. Basal area at age 50 averaged 64.9 m^2/ha for all planted stands, and was predicted to be 98.2 m^2/ha at age 100. Whole-tree volume was predicted to increase by 11.7 m^3/ha/annum for all stands, but was as high as 20.6 m^3/ha/yr in one 70 year old stand. The maximum productivity of kauri was observed in one high-performing young kauri planted stand where whole-tree volume increment in excess of 30 m^3/ha/yr were predicted for a period from age 15-30. Carbon sequestration was calculated from the volume model and predicted to be 316 t C/ha and 1168 t CO_2/ha at age 100.

Mortality of kauri in planted stands was as high as 3.9%/yr for individual stands, over their entire rotation to date. For all stands, mortality averaged 0.56%/yr. The highest mortality occurred in the years before the first assessment and averaged 0.64%/yr for all stands. From the first to the last assessment mortality averaged 0.30%/yr. Where mortality in individual stands was above the average rate the dominant cause was drought.

The growth and productivity of kauri in second-growth stands was only marginally improved by thinning to reduce competition. The volume removed in thinning operations had not been replaced in the (up to) 50 years since thinning treatments were applied. At age 150, the predicted height of kauri in unthinned control and thinned stands were identical at 25.9 m. Basal area at age 150 was 64.5 m^2/ha in unthinned stands and 52.6 m^2/ha in thinned stands. Whole-tree volume was predicted to be 681 m^3/ha in unthinned and 549 m^3/ha in thinned stands. Volume increment peaked at 5.2 m^3/ha/yr in unthinned stands and 4.7 m^3/ha/yr in thinned stands.

This study has shown that the worst growth and productivity of kauri in planted stands was better than that of the best natural stands. The difference in performance between plantation and second-growth kauri was most likely a result of a combination of lower site quality characteristics (soil type and fertility), stand structure and within-stand competition of natural stands.

The data for planted kauri came from 31 permanent sample plots located in 25 planted stands. These stands ranged in age from 14-83 years at the last assessment, and ranged in stand density from 218-1800 stems/ha. The overall number of planted stands and plots from which data was available to develop models was small in comparison to many exotic forest species datasets. The majority of the planted stands were not silviculturally treated after planting, and considerable variation in establishment methods was recorded. The results of productivity from the models developed for planted kauri should therefore be considered to be conservative.

The results of this study indicate an opportunity to grow kauri in plantations on good quality sites for the production of high quality sapwood timber over rotations of 60 years or less. They also indicate that second-growth stands will produce usable volumes of timber, but only over extended periods of time.

To ensure that kauri in planted stands can meet the potential observed during the development of these models, a series of well-managed stands on a range of sites is urgently required where the effects of timely silviculture, including initial stand density, can be assessed, quantified and reported on. Further research on selection and breeding for the species would improve the early establishment and growth of planted kauri resulting in a reduced rotation length. Research on long-term management strategies that include continuous cover forestry may make the species an attractive proposition for carbon forestry and/or for the production of high quality, naturally durable heartwood. The dataset compiled for this study was the best data available. While it cannot as yet be used to develop prescriptions for the establishment and maintenance of planted kauri stands, it does provide clues and directions that should be pursued in further research, however.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The history and story of kauri (*Agathis australis*) is almost like that of no other New Zealand native tree species and, to a large degree, reflects the history of the settlement of New Zealand. From its first use by Māori and the way it was woven into oral tradition, through to the national and international recognition of the species. The logging of kauri and the quest for its gum was a story of great ingenuity and resourcefulness, but also one of great waste, bordering on a national tragedy. The degree of forest clearance that occurred over *c.* 1000 years in Europe and *c.* 250 years in North America was achieved in only 100 years (or less) in New Zealand. Arguably the saviour of the last remnants of mature kauri forest, and other native timber trees, was the rapid development of an exotic forest industry from which, over time, New Zealand foresters and researchers gained a well-deserved reputation for forest development and management. However, where early New Zealand forestry was initially based on a range of native species from different genera, it quickly became reliant on one species, radiata pine (*Pinus radiata* D. Don). In the early stages of the 21st century it is timely for that expertise to be applied in greater amounts to New Zealand's native timber trees, not only as a means of developing new resources and options, but also to restore these species to the New Zealand landscape. As kauri was the principal species on which the forestry industry and early economy for New Zealand was based, it should be one of the first to be considered when New Zealanders look back to their own native resources.

Observations of the ecology and extent of the kauri resource lagged considerably behind the initial exploitation by Europeans. Many of those original observations, and latterly those of growth rates, were contradictory and pessimistic. This was probably the main reason why kauri was generally not established in large-scale afforestation projects. An early, and erroneous, assumption was that native trees would have to be grown to the same or similar dimensions as trees in old-growth forest (Hutchins, 1919), over periods of growth commonly assumed to be in the hundreds, if not a thousand years (Laing & Blackwell, 1907). The basis for this assumption was the perceived need to replicate native forest and presumably to recover large quantities of clean heartwood. McKinnon (1946a) summarised this position when he wrote that "in the case of kauri the interval between sowing and reaping is a long one, upwards of 200 years…..the fully developed forest crop, will resemble to no small extent the primitive forest …". Consequently only a small number of kauri were planted with any sense of replacing the rapidly disappearing resource.

During the mid-20th century the various forms of New Zealand forestry, and other land-managing organisations, began disjointed planting programmes that incorporated indigenous species. These were often undertaken and promoted by enthusiastic individuals rather than following any particular policy or established guidelines. Regrettably, many of the records of these plantings and their performance languished in files that remained unpublished or in a situation where they could not be accessed by future potential growers. Happily, this situation changed with a review of kauri forest management (Halkett, 1982) and, in the mid 1980s, a comprehensive survey of plantings of a range of native species and their performance (Pardy, et al., 1992). The survey of Pardy et al. (1992) identified kauri as one of the species most commonly planted, and became the basis for the development of a database of plantings and performance.

Growing native species in plantations for a range of outcomes, including timber, has become increasingly popular, but it has been constrained by a lack of quantitative information on growth and productivity (Forest Research Institute, 1997). Bergin (2001) identified totara (*Podocarpus totara* D. Don) as a future plantation species, and produced a preliminary growth and yield model based on a limited number of planted totara stands (Bergin & Kimberley, 2003). Wardle (1984) reviewed the ecology, utilisation and management of the New Zealand beeches (*Nothofagus* spp.) that followed an earlier economic review of Cockayne (1921). Kauri, totara and the beech's are the indigenous forestry species in the New Zealand flora whose growth has been most frequently assessed.

Kauri timber, highly valued for its appearance and working properties, is now difficult to obtain. Exploitation of the species, described as a forester's dream (Whitmore, 1977), left a mature natural resource of only 7500 hectares, predominantly in the conservation estate (Halkett, 1982). Various estimates of the extent of natural second-growth stands arising since land clearing indicated a resource of approximately 60 000 hectares (Lloyd, 1978; Halkett, 1982). Only a third of this was classified as having the potential to be managed for timber production (Halkett, 1982). The majority of the second-growth resource is now in widely dispersed populations on difficult or atypical sites. A depleted and protected natural kauri forest has left the New Zealand timber market with continued interest in kauri timber, but largely without a supply.

While volume tables have been produced for old-growth (Lloyd, 1978) and second-growth kauri (Ellis, 1979), and a preliminary productivity and economic case study was developed for planted kauri (Herbert, et al., 1996), all were based on only a few or atypical stands. Since the survey of Pardy et al. (1992) and the demise of the New Zealand Forest Service (NZFS) in 1987, records of other planted kauri stands and trials within second-growth natural stands have come to light. Many of these are now held by the New Zealand Forest Research Institute Ltd. (Scion). Trials that could be relocated and reconstructed were reassessed and results were added to the database. A pattern began to emerge, indicating faster growth than was previously considered possible on sites within and outside the species natural range. It is time to draw the numerous threads of kauri growth together in order to develop robust models of kauri growth in even-aged plantations.

1.2 OBJECTIVES

This study aimed to test hypotheses about the growth and productivity of New Zealand kauri growing in planted and in natural second-growth stands.

The study had three hypotheses in relation to kauri growth.

1. that kauri grow faster and are more productive in even-aged planted stands than in natural second-growth stands.
2. that thinning of natural second-growth stands improves growth and productivity compared to comparable stands that are unthinned.
3. that kauri can be planted and grown in rotations for timber recovery as short as 60 years.

The development of stand-level models for height, basal area and standing whole-tree volume would allow the comparisons to be made between the different stand types. Such models allow:

- Comparison of the growth and productivity of planted kauri stands with those of naturally regenerated kauri stands.
- Identification of the potential timber volume yield of kauri grown in even-aged planted stands and the management options that would maximise it.
- Identification of differences in the performance of kauri grown in planted stands with natural second-growth stands.

Specific Tasks

1. Undertake a review of current knowledge about kauri and the existing kauri resource.
2. Create growth and yield models for kauri using data from planted stands.
3. Apply the models developed in (2) above to natural stands, and identify any bias/disparity.
4. Compare growth and productivity of kauri in planted stands with kauri in natural second-growth stands.

1.3 SCOPE OF THE STUDY

The study incorporated assessments of stands of kauri on private, crown-owned and District Council land. These included 25 planted stands and seven natural second-growth stands.

1.4 OUTLINE OF THESIS

An outline of the thesis is given below. Some chapters have been or are in the process of being published in peer-reviewed journals. This has led to some unavoidable repetition within the text.

Chapter two is the principal review of the species and sets out the history of the description and nomenclature of kauri over which there has, and continues to be, some confusion. It contains the geographical history and distribution of the species; a review of its ecology; the various attempts at determining growth, age, and management relevant to managing the species in planted stands. There has been considerable published material on age and growth of kauri dating back to the mid-1800s, much of it is contradictory, some of it, including some well known and often cited authors, was not based on actual measurements or arose from unsubstantiated assumptions. The review highlights the over-exploitation during the early settlement of New Zealand by Europeans, and describes the species in detail. It identifies that the old-growth kauri resource, from which the species gained its deserved reputation, largely no longer exists. It also serves as the literature review for the species, exploring as many of the early references to kauri as possible. It looks at the waste of a species which today, with a different history, could have been sustainably managed for the benefit of the forests and the people of this country. The review was also the first chapter to be published.

Chapter three reviews the development of growth and yield modelling in forestry. It describes what a growth and yield model is, and also describes and defines some of the commonly used modelling types. Chapter four describes the individual study sites, their locations and history. Chapter five describes the methods of data acquisition. Chapters six and seven give a general description and analysis of the data from planted and second-growth natural stands. Chapter seven also describes the effects of thinning on second-growth kauri stands that arose after the early land clearance and kauri logging. This chapter will offer a basis for which to compare the performance of kauri in planted stands. Chapter eight develops the models of height and basal area and gives predictions for volume yield. It also makes comparisons between the stand types. These chapters highlight the opportunity for kauri to become a true forestry species managed solely for its timber production. Chapter nine discusses the results of the study and draws some conclusions from the reviews and development of the models.

CHAPTER 2

[1]REVIEW OF KAURI

2.1 INTRODUCTION

Kauri is New Zealand's only representative of the Araucariaceae (Henkel & W. Hochst.). This ancient family of coniferous trees consists of three genera: *Araucaria*, *Wollemia* and *Agathis* (Setoguchi, et al., 1998). The genus *Agathis* (Salisb.) consists of 21 species (Farjon, 2001). Its range extends west to Sumatra; north to the Philippines; east to Fiji; and south to New Zealand (Hooker, 1867; Kirk, 1889; Whitmore, 1977). The greatest representation of the genus (five species) occurs in New Caledonia (Whitmore, 1977). They are highly prized for their fine-grained, uniform timber (Whitmore, 1977, 1980a).

The correct nomenclature for kauri is *Agathis australis* (D. Don) Lindl. in Loudon, as presented by Franco (1949). Earlier references attributing the binomial *Agathis australis* to Salisbury (1807) are incorrect. Salisbury described the genus *Agathis,* but did not describe *A. australis*.

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[1] This review follows that of Steward, G. A., & Beveridge, A. E. (2010). A review of New Zealand kauri (*Agathis australis* (D.Don) Lindl.): its ecology, history, growth and potential for management for timber. *New Zealand Journal of Forestry Science, 40*, 33-59. The paper was written as the kauri review chapter for this thesis. Mr Beveridge, the co-author, is a retired NZFRI scientist and was a mentor in the early part of my career. His co-authorship of the paper is an acknowledgement of that mentoring role. His input to the published review paper was (estimated) 5-7% of the paper. This chapter is a summarised version of the published paper. It includes only the relevant sections, and some minor inclusions, pertinent to this study and thesis.

2.2 BOTANICAL FEATURES OF NEW ZEALAND KAURI

Kauri is monoecious. Male and female reproductive structures may be borne on the same branch (Morrison, 1950) (Figure 2.1). Viable pollen, produced from as young as six years of age in open grown planted trees, is shed during September-October. Female cones ripen in late summer. Trees usually begin to produce viable seed when they are 25-40 years of age (Halkett, 1982). However, Ecroyd (1982) reported formation of seed on 15-year-old trees, and female cones and viable seed have been observed on planted trees as young as 6 years old (M. Sutton, pers. comm. 2009). Viable seed is produced on trees planted outside of the species natural range and have been found as far south as Hokitika and Mosgiel in the South Island. Seed crops are annual but vary in terms of quantity and viability. Seed-bearing cones disintegrate on the tree in late summer and early autumn, approximately 18 months after initiation (Hutchins, 1919; Lloyd, 1960; Ecroyd, 1982). Under moist, warm conditions, germination occurs soon after shedding. Seed viability is lost after only a few months on the forest floor (McKinnon, 1937a; Whitmore, 1977).

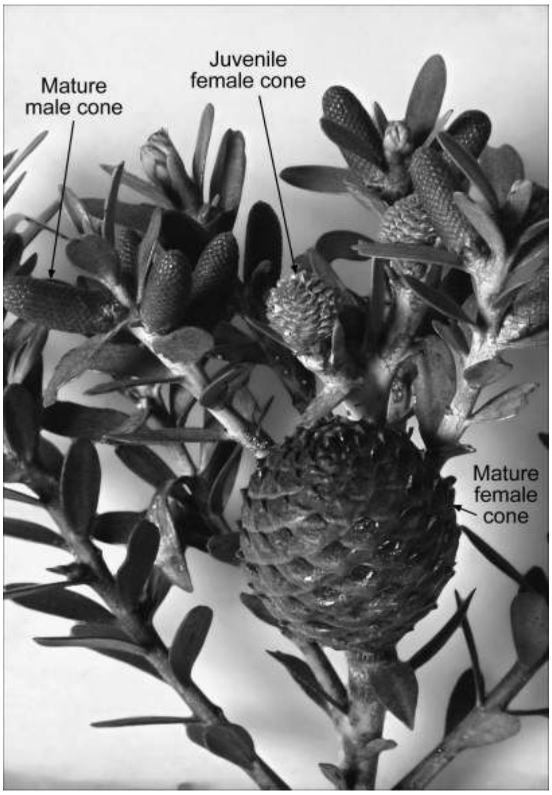


Figure 2.1. Kauri is monoecious; male and female cones are carried in close proximity on the same branch which raises the potential for self-fertilisation (note mature and immature female cones). (*Image No. 019601 - copyright to Scion*).

Leaves are usually dull olive-green, with adult leaves functional for 3-6 years (Ogden & Ahmed, 1989), and some remaining on the tree for up to 15 years (Silvester & Orchard, 1999). Budburst occurs in September-October when average daily maximum temperature starts to exceed 17 °C (Bieleski, 1959). Growth and stand productivity have been linked to leaf/shoot architecture, efficiency of light capture being shown to decrease with increasing tree age and size (Niinemets, et al., 2005).

Figure 2.2. Branch abscission is a useful feature of kauri, and can be induced by pruning and leaving a branch stub of 40-50 mm in length. The split in the bark indicates abscission occurring.

In natural stands, the lower branches abscise cleanly from the stem from the sapling stage (Hutchins, 1919; Licitis-Lindberghs, 1956). There is no lasting damage to the bark and no knots form in the stem. This mode of abscission is a valuable characteristic leaving few of the defects in the timber usually associated with branch development (Kirk, 1889; Hutchins, 1919; Bergin & Steward, 2004). Branch abscission was able to be induced in 6-8 year-old trees in a tightly-stocked natural stand (10 000 stems/ha) (Wilson, 1995; Wilson, et al., 1998b, 1998a). When a 40-50 mm branch stub was left after pruning, almost all of the stubs were shed within six weeks. Unpruned branches remained attached over the same period. Advantages of pruning kauri when grown in low-density plantations (625 stems/ha) where branch abscission was not occurring naturally, have also been identified (G.A. Steward unpubl. data). Branch stub abscission was initiated in 70% of pruned branches if pruning was carried out before branches reached 4 cm in diameter, leaving a stub 40-50 mm in length (Figure 2.2).

The root system of mature trees is extensive, with lateral roots often reaching beyond the crown. Deeply-penetrating "peg" roots descend from the laterals, giving firm anchorage. Kauri are generally wind-firm until senescence sets in or rot develops. Few incidences of wind-throw in natural stands are recorded, and none in planted stands. Young kauri have a well-developed taproot, and it is possible that penetration and exploitation of free-draining soils is important for optimum growth (Morrison & Lloyd, 1972). Fine feeding roots are superficially-distributed in layers of raw humus and litter. They bear nodule-like beaded rootlets which contain vesicular arbuscular mycorrhizal endophytes. Potted or bare-rooted kauri seedlings do not form balanced fibrous root systems (Morrison & Lloyd, 1972; Bergin & Steward, 2004). Slow development of roots may account for the slow establishment of naturally-established and planted seedlings. Root grafting, presumed to occur in this species (Beddie, 1941), was confirmed by observation (Hillary, 1944).

Mature kauri trees have straight, untapered, cylindrical stems averaging 12-25 m in length. The stems have flaking bark and are typically free from branches or epiphytes (Figure 2.3). Crowns of emergent trees are massive with upward-arching branches producing flat or slightly rounded tops (Anonymous, 1868). Total height generally reaches 30-50 m, and occasionally 60 m (Hooker, 1867; Allan, 1961). Stem diameter of trees aged 400-800 yr is commonly 1-2 m, but in living giants are 3-5 m. Massive stems with diameters exceeding 6-7 m were recorded during logging and burning for land clearing carried out by early settlers.

Figure 2.3. The monopodial growth habit (A) of younger kauri is referred to as a ricker; typical mature kauri approximately two metres in diameter with upward arching branches and uniform stem (B); the massive diameter (5.2 m) of older kauri that may be 1500-1700 years of age (C). (*Image copyright to Scion*).

The wood of kauri has been shown to become mature at approximately 70 years of age. The heartwood of mature kauri has the reputation of being one of the finest softwoods in the world (Hochstetter, 1867; Cheeseman, 1914; Clifton, 1990). The timber has a light honey to rich reddish-brown colour, with a distinctive silvery speckled lustre (Clifton, 1990). Average values for density (560 kg/m^3), strength (modulus of rupture 88 MPa, modulus of elasticity 13.0 GPa), and shrinkage (tangential 4.1 percent, radial 2.3 percent) are given by Hansson (1924) and Hinds & Reid (1957). Kirk (1874) and Campbell (1891) indicated a service life for building, construction and maritime use of more than fifty years. A computer model designed to estimate the amount of heartwood present in planted and second-growth natural kauri stands was developed by Steward & Kimberley (2002). Stem diameter was identified as the principal factor for predicting heartwood presence and quantity. Age was found to be a secondary factor, the older, smaller stems in natural stands having more heartwood than the amount predicted from stem diameter.

Sapwood is less durable than heartwood, and is attacked by the wood boring beetle (*Anobium punctatum*) (Clifton, 1990). It decays rapidly when in contact with the ground (Kirk, 1874). 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 (Steward & McKinley, 2005). These findings agreed with those of Hutchins (1919), who believed that kauri sapwood was as good as heartwood provided it was used indoors and kept free from borer.

2.3 AGE

Cheeseman (1914) reviewed early attempts at defining the longevity of kauri. Estimates of 1300-2000 years made by Laslett (1875) in the early 1840s were more accurate than later suggestions of 3600-4000 years by Kirk (1889). Stewart (1905) showed that growth rings in planted kauri were annual, and could be used to assess growth rates and tree age. Growth rings are usually clear and can be counted with little trouble (Hutchins, 1916; Steward & Kimberley, 2002) (Figure 2.4). Using growth measurements from sections removed from a number of large kauri logs, Cheeseman (1914) estimated that stems approximately 2.5 m in diameter were 465 years old, while those with diameters up to 6.5 m were “not in excess of 1280 years”. Enright & Ogden (1995) suggested typical longevity of 600 years for trees in old-growth stands, and a maximum estimated longevity of 1679 years. Ahmed & Ogden (1987) examined cores from trees of different diameter classes in 25 stands covering the geographical range of kauri. They derived the age of large trees by adding ages of the average-sized tree in each diameter class, and concluded that trees 2 m in diameter average 1100 years, while 3 m diameter trees are approximately 1700 years old.

Estimates of maximum age of kauri show considerable divergence. It has been assumed that larger stem diameter indicates greater age. Highest estimates have rarely been based on a complete count of growth rings in cut stumps or logs. The assumption that maximum age is associated with large diameter may be unfounded. Most of the few surviving trees with stem diameter 3-5 m are known or assumed to be hollow; this will prevent accurate determination of age (Beveridge, et al., 2009). The wide range of diameter growth observed in natural stands suggests that large dimensions may simply be the result of above-average growth rate sustained over long periods of time. Wood decay fungi are found in natural forests under the climatic conditions in which kauri grows (McKenzie, et al., 2002). Individual trees growing for more than 1000 years would almost inevitably have experienced some damage to the crown or stem from storms, falling trees, insects and/or fungi. When variable growth rate is taken into account, it can be assumed that the maximum age for kauri is not likely to be more than 1500-1700 years.

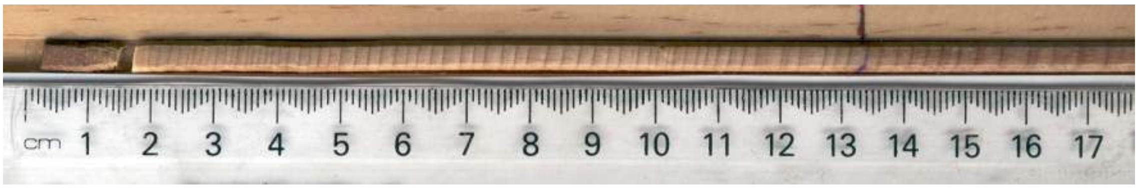


Figure 2.4. Increment core of kauri from a natural second-growth stand. Annual rings are clearly visible and can be used to accurately age individual trees. The mark at approximately 13.5 cm indicates the sapwood/heartwood boundary. The study of Steward & Kimberley (2002) rarely found sapwood width >15 cm.

During the juvenile or “ricker” stage, kauri trees have narrow, tall, tapering crowns with a strong monopodial (orthotropic) habit (Figure 2.3). In natural forests this form may persist for 150-200 years, when stems reach 50 cm diameter and the crowns start to spread. From data collected from several forests, Ahmed & Ogden (1987) estimated a mean age of 127 years for trees 10-20 cm in diameter and 231 years for those in the 50-60 cm diameter class. Individuals with a full spread of healthy emergent crown were likely to be 250-350 years old. These estimates agree with those of Steward & Kimberley (2002) who calculated a mean stand age of 120-218 years for 27-40 cm diameter trees in natural, second-growth stands.

2.4 NATURAL DISTRIBUTION

2.4.1 Distribution in prehistoric times

The genus *Agathis* first appeared in New Zealand during the Cretaceous period. Its members were very similar to modern kauri (Barton, 1983a). *Agathis australis* appeared during the Oligocene epoch (Fleming, 1979). Molecular sequence data was in favour of kauri having survived the

Oligocene drowning of New Zealand, and indicated it as the oldest living species of the genus (Stöckler, et al., 2002). Kauri was widespread in New Zealand until the Pleistocene epoch (400 000-14 000 years BP), when glaciation caused retreat to the northern half of the North Island. Kauri was uncommon within its present geographical range during the mild, moist conditions of early post-glacial periods. It became more prominent from 7000 BP (3000 BP in the southernmost parts of its present range).

2.4.2 Present distribution

Hochstetter (1867), Sando (1936a), and Hinds & Reid (1957) all considered that the current natural range of kauri is confined to the northern part of the North Island of New Zealand, latitude 34-38 ^{o}S. The species is most common on the Northland and Coromandel peninsulas. It is found from sea level to altitudes of approximately 360 m (Cockayne, 1928); although a few stunted trees exist at 800 m on Mt. Moehau on the Coromandel Peninsula (Anonymous, 1868; Hutchins, 1919; Cranwell & Moore, 1936). Kauri also occurred on the small islands east of the mainland. On Great Barrier Island and Little Barrier Island some old-growth forest remains and second-growth forest has established on sites from the initial logging (Bergin & Steward, 2004). Factors limiting expansion of kauri from existing stands include low seed germination rate and low rate of subsequent establishment as a shade-tolerant but slow-growing seedling under natural forest conditions (Barton, 1983a).

2.5 ECO-PHYSIOLOGY

2.5.1 Climatic tolerance

The effects of climate on kauri growth have been reviewed by Ogden & Ahmed (1989). Lowlands within the geographical range generally have warm summers, mild winters, evenly-distributed rainfall and mean annual temperatures of 13-16 ^{o}C. Typical kauri habitats have a mean annual rainfall of 1000-2500 mm, a mean maximum temperature in the hottest month of 28 ^{o}C and mean minimum temperature in the coldest month of 3 ^{o}C. Frosts are few and light in Northland and in coastal localities but more frequent and severe inland and near the southern limit. Sakai & Wardle (1978) found that kauri twigs were not affected until temperatures dropped to -7 ^{o}C. Barton (1982, 1985) reported frost damage in cotyledonary seedlings exposed to temperatures below -1 ^{o}C. For 18-month-old seedlings, damage occurred below -2 ^{o}C, although severely damaged, seedlings were able to survive temperatures of -6 ^{o}C. There are no records of frost damage in planted kauri or young trees in sheltered localities, even those located near Dunedin at latitude 45 ^{o}S (Bergin & Steward, 2004).

2.5.2 Soils and nutrient cycling

Prior to European colonisation in the 1840s, kauri grew on a wide range of terrain and soils (Anonymous, 1868; Hansson, 1924; Hinds & Reid, 1957). Gibbs et al. (1968) listed these soil types as strongly leached and podsolised northern yellow-brown earths, podsols, strongly leached brown granular clays, and brown loams of very low fertility. Kauri is often found on soils of low fertility, making them even less fertile (Beveridge, 1975).

Kauri makes efficient use of nitrogen and phosphorus. Biomass and nutrition studies of kauri in a 130-year-old pole stand in the Hunua Ranges (Madgwick, et al., 1982) confirmed earlier work of Peterson (1962) and Silvester (1978) who suggested that levels of both nitrogen and phosphorous needed for maximum growth were low. The availability of nitrogen may be a limiting factor for growth of *Agathis*.

2.5.3 Water relations

Bieleski (1959) found that waterlogging decreased both root length and stem branching of kauri at the seedling stage. Conversely, drought increased root development at the expense of stems (Bieleski, 1959). Stephens et al. (1999) measured isotope carbon ratios in trees growing on ridge crests and valley sites and concluded that kauri may make more efficient use of water than many other species. This would contribute to its relatively high productivity on dry, infertile ridge crests. Verkaik et al. (2007) reported that young kauri seedlings growing beneath a kauri canopy compete successfully with other plant species under conditions of low soil moisture and fertility. Observations in a natural stand at Huapai showed that diameter growth of trees 31 cm or less in diameter was limited by soil moisture over the summer period, while peak growth was observed in trees with diameter greater than 31 cm (Ferguson, 1997). Of the three seasonal variables investigated (mean temperature; maximum temperature; soil moisture deficit), mean temperature was shown to have the closest relationship with diameter growth in medium-sized (31.0-41.0 cm DBH) and large kauri. Growth of smaller trees was not affected.

2.6 STAND DYNAMICS

2.6.1 Associated tree species

Cockayne (1908) recognised six types of forest containing kauri in Waipoua Forest. Hansson (1924) classified kauri forest over its entire range into two types; kauri-dominated and kauri-taraire (*Beilschmiedia tarairi* (A.Cunn.) Benth. & Hook.f.). Nicholls (1976) divided kauri forest into three classes and 22 types. Class A comprised five types in the limited areas in the north of the North Island where kauri was abundant. It included remnant dense old-growth and the more numerous areas of abundant pole and ricker stands. Class B comprised twelve types in kauri-softwood-hardwood mixes in forests of the Waikato, Bay of Plenty and Coromandel. Class C comprised five types where hard beech (*Nothofagus truncata* (Colenso) Cockayne) and silver beech (*Nothofagus menziesii* (Hook.f.) Oerst.) were found with kauri-softwood-hardwood mixes. The relationship between kauri and hard beech has been investigated in forests of the Waikato Region (Collins &

Burns, 2001). Age structure of the stands indicated that both species establish in forests initiated by disturbance, rather than reciprocal replacement where either species acted as a nurse crop.

2.6.2 Regeneration

Conditions favouring kauri seed germination and seedling establishment were summarised by (Barton, 2000). Germination occurs at temperatures above 11 °C, but rates are higher between 19-27 °C. Regeneration is most prolific in secondary forest, scrub or grassland invaded by small-leaved species such as manuka (*Leptospermum scoparium* J.R.Forst. & G.Forst.) or the taller-growing kanuka (*Kunzea ericoides* (A.Rich.) Joy Thomps.). It has been observed on disturbed sites near the present southern limit of the species (Beveridge, et al., 2009). Mirams (1957) and Bieleski (1959) showed that in terms of light, temperature and thin litter layer, secondary forest was more favourable for the establishment of kauri seedlings than old-growth forest. Enright et al. (1993) observed that seedlings grew very slowly when the degree of canopy closure was more than 90%. According to Bieleski (1959) and Barton (1982), small seedlings are shade-tolerant, while saplings and young trees require full overhead light for vigorous growth. In natural stands, substantial mortality results from root competition and the desiccation of humus layers during prolonged dry periods unless seedling root systems have penetrated to the A1 soil horizon (McKinnon, 1945).

Although female cones and viable seed have been produced by kauri trees planted as nursery–raised seedlings in many locations south of the natural range, regeneration is rare. Two examples of persistent natural regeneration have been recorded south of latitude 38 ^{o}S; one in New Plymouth and the other in Wellington (Steward, et al., 2003). It has also been observed in the Hawkes Bay on two sites.

2.7 GROWTH

2.7.1 Early estimates

Under natural conditions, kauri growth rates vary widely at all stages of development. Many of the early assessments of diameter growth were made from individual cut stumps and logs. Data were not presented in the context of forest composition, the place of individual trees within a forest structure, or stage of development (i.e. ricker or mature form).

Matthews (1905) considered that the rate of kauri growth was too slow for timber culture, a view supported by Laing & Blackwell (1907). Conversely, the species was considered to be eligible for “industrial culture” and naturalisation in New South Wales and Victoria, Australia (Mueller, 1881, 1888). It was also named among 20 New Zealand tree species considered to be of economic importance (Zon & Sparhawk, 1923; Forbes, 1932).

Hutchins (1919) estimated that the timber volume of mature kauri in Puhipuhi Forest averaged 700 m^3/ha. Hansson (1924) developed a stand table representing a typical acre (0.404 ha) of mature kauri forest of the kauri/taraire type from Waipoua Forest. Diameters and stem counts for kauri from 20-279 cm in diameter indicated a stand density of 116 stems/ha (423 stems per hectare for all species), and a volume of 400 m^3/ha.

2.7.2 Diameter growth

Cheeseman (1914) agreed with Laslett's (1875) early assessments of mean diameter growth (2.5 mm/yr) after counting growth rings in sections taken from felled trees 1 m or more in diameter (Silvester & Orchard, 1999). Kirk (1889) recorded growth of 1.9-3.6 mm/yr in free-growing trees. A study of kauri from 25 sites over the range of the species led Ahmed & Ogden (1987) to conclude that stems 10-140 cm in diameter grew at a mean rate of 2.3 mm/yr. Mature trees were found to grow for long periods at a rate of 5.0 mm/yr. Slocombe (1921) assessed more than 250 cut stumps at sites located throughout the natural range and estimated diameter growth rates of 3.6-6.1 mm/yr in trees 250-500 years of age. From measurement of increment cores taken from kauri poles and saplings in a range of diameter classes at Omahuta Forest, McKinnon (1940) reported a maximum rate of 6.3 mm/yr in 76 cm diameter trees, although the average for 37 stems approached 4.0 mm/yr. Burns & Smale (1990) found that the maximum rate in a 100-200 yr old second-growth stand (4.3 mm/yr) on the Coromandel Peninsula occurred in sub-mature trees 25 cm or more in diameter. Most of these were still at the ricker stage, but the crowns of larger diameter trees were beginning to spread. Although there were large numbers of tanekaha (*Phyllocladus trichomanoides* D.Don) trees in the stand, most of the basal area increment (0.6 m^2/ha/yr) was attributable to kauri. Large kauri trees suppressed all other vegetation, including smaller kauri. Steward & Kimberley (2002) reported diameter increment values of 1.3-3.4 mm/yr in four 120-218 yr-old natural second-growth stands that had been monitored over periods of up to 35 years.

Hutchins (1919) suggested that natural stand density reaches 150-200 stems/ha, while Halkett (1982) reported an average of 85 stems/ha in old-growth forest. At a mean diameter of 90 cm and stand density of 80-100 stems/ha, basal area would be 50.9-63.6 m^2/ha. Basal area increment of kauri in two thinning × fertiliser trials in natural second–growth stands was measured annually between 1967 and 1972. Basal area increased by approximately 0.3 m^2/yr in control plots, 0.1-0.4 m^2/yr in thinned plots, and 0.3-0.8 m^2/yr where trees were thinned and fertiliser was applied. Some of the increment was attributable to recruitment as well as to growth of selected trees (Anonymous, 1974). Barton & Madgwick (1987) found that application of fertiliser increased mean annual diameter increment to 5.1 mm from an unstated average for control trees. Data derived from stems removed from thinned plots indicated that an increase in diameter growth brought about by earlier thinning in or about 1900-1912 had been sustained for at least thirty years. In a later thinning ×

fertiliser trial in a second-growth kauri stand estimated to be 130 years old, reduction of the number of stems/ha by 75% (and basal area by 55%) had a negligible effect on basal area increment after five years (Barton & Madgwick, 1987). Addition of nitrogen fertiliser doubled basal area growth after five years to 1.0 m^2/ha/yr.

Ferguson (1997) found that stand density was the best predictor of basal area increment in a natural kauri stand at Huapai. Chikumbo & Steward (2007) developed a basal area model for kauri, using data obtained from 13 plantations in the North Island. Predicted basal area values of 60 m^2/ha at age 40, and 95 m^2/ha at age 80 were considerably lower than the 116 m^2/ha predicted by Herbert et al. (1996) for stands of the same age. Some of the data used in both models were derived from stands located outside the natural range of the species.

2.7.3 Height growth

Hutchins (1919) observed a few planted specimens around Auckland. He estimated that kauri was "decidedly faster in height growth than the European forest trees". Kauri is shade-tolerant only when seedlings are small. Annual height growth of seedlings under favourable light conditions is usually 10-25 cm. Shaded seedlings may stagnate or grow very slowly for 50 years or more. Suppressed saplings in a stand that was probably in existence since pre-European times had a mean age of 40 years and a mean height of 1.4 m (Burns & Smale, 1990). As saplings emerge into full overhead light, height growth increases and rates of 30-40 cm/yr are common in rickers in uncrowded stands (Beveridge, et al., 2009). At Waipoua, height increments of 22-30 cm/yr were recorded in kauri saplings measured over a period of 11 years (McKinnon, 1940). In second-growth stands located in Northland, Great Barrier Island, Hunua and Kaimai Ranges, height increments of 10-25 cm/yr were observed (Steward & Kimberley, 2002).

2.7.4 Growth of planted kauri

Kauri is known to grow faster than second-growth stands when planted on moist, fertile soils (Beveridge, et al., 2009). Cameron (1959) suggested that sites usually occupied by larger-leaved mesophytic species are the most suitable for kauri planting. In some plantations average annual diameter growth has exceeded 10 mm for periods of up to 40 years. Height increments of 1 m/yr have been recorded for individual trees (Ecroyd, et al., 1993). In a survey of planted indigenous trees, annual growth of kauri was found to average 7 mm in diameter and 36 cm in height (Pardy, et al., 1992). Using data from a wide range of sites with different stocking rates and management history, Pardy et al. (1992) predicted a mean annual height increment for planted kauri of 44 cm at 20 years, reducing to 26 cm at 80 years. This rate was among the highest for the eight major indigenous conifers surveyed. Predicted annual diameter increment in kauri, measured at 1.4 m above ground level, was 6.9 mm for stands less than 100 years of age. Growth of trees planted at

Rotorua was equivalent to that of planted trees further north. While growth of young planted kauri has been enhanced by careful site selection and management, this does not necessarily imply that early rates will be sustained or that growth rates of more mature planted trees will differ from those in natural stands.

2.7.5 Volume increment

McKinnon (1946a) compared several methods used to calculate wood volume in kauri stems in natural stands. Results from the "centre-girth" method (based on girth-over-bark at breast height, estimated log height, and estimated centre girth-over-bark) were compared with those derived from the actual diameter and length of 164 felled stems. The centre-girth method was found to underestimate standing volume by 7.1%. Actual log measurements were then used to construct a local log volume table. Tables based on measurements from a number of stands have been produced for old-growth (Lloyd, 1978) and second-growth (Ellis, 1979) kauri. McKinnon (1946b) also calculated an individual tree merchantable volume and increment table from measurements obtained from 50 trees from Omahuta and Waipoua forests. Periodic annual increment culminated between the 250th and 300th year (0.04-0.05 m^3), while mean annual increment culminated in the 350th year (0.03 m^3). Volume increment (mean annual increment) in mature kauri forest was found to be in the order of 1-3 m^3/ha/yr. This estimate was based on limited data and did not take the influence of stand composition and structure into account (Halkett, 1983). Estimates of total stem volume increment (periodic mean annual increment) in second-growth kauri stands were 2.8-8.8 m^3/ha/yr (untended) and 4.1-9.9 m^3/ha/yr (thinned), and were dependent on stand density (Halkett, 1982, 1983) (Table 2.1).

Table 2.1. Total stem volume increment (periodic mean annual increment) in untended and thinned natural second-growth kauri. Data from Halkett (1982).

	Volume increment (m^3/ha/yr)	
Stand density (stems/ha)	Untended stands	Thinned stands
<200	2.85	4.16
200-400	4.83	6.45
400-600	7.65	9.90
>600	8.85	9.80

A preliminary stand productivity and economic case study, based on data from two 60-year-old unthinned kauri plantations at New Plymouth (96 km south of the natural range limit), predicted tree height of 25 m and diameter of 34 cm at age 80 years (Herbert, et al., 1996). At this age, total wood volume in stands containing 1300 stems/ha was predicted to be 1103 m^3/ha. According to Steward & Kimberley (2002), only a small proportion of this volume would be heartwood.

2.8 HEALTH

Until recently, pathogens and pests were considered to be of low or local importance for kauri that had developed beyond the seedling stage. However, with changes in climate and the entry into the country of new diseases may see a change in this situation.

2.8.1 Fungi

Species of fungi causing local damage to kauri were listed by Ecroyd (1982). McKenzie et al. (2002) presented a checklist of fungi found on kauri and this was amplified by Gadgil (2005) who indicated their relative importance. Fungi known to cause damage in living kauri trees are:

Armillaria limonea and *A. novaezelandiae*: root rot disease in young trees. Recently found on planted kauri in New Plymouth.

Fomes hemitephrus: white heart rot.

Ganoderma applanatum: white heart rot extending to the sapwood when the heartwood is completely rotted.

Heterobasidion araucariae: sap rot.

Pestalotiopsis funerea: a facultative parasite, invading damaged leaf tissue.

Phaeolus schweinitzii auct.: destructive red-brown cubical rot in mature trees.

Phytophthora cryptogea, Pythium irregulare, Pythium ultimum, Rhizoctonia solani: damping off and seedling root rot.

Phytophthora nicotianae: Isolated from stem lesions on a 20-year-old tree.

Phytophthora cinnamomi: associated with mortality of trees (evidence doubtful).

Phytophthora heveae: isolated from basal cankers on dying trees on Great Barrier Island and shown to be pathogenic to *A. australis* seedlings (Gadgil, 1974). Recent molecular analysis has indicated that this fungus cannot be identified on morphological characters alone, and it is now known by the temporary name "*Phytophthora* taxon Agathis". It has been isolated from dying trees in the Waitakere Ranges and from Northland. It may be one of the causes of death and ill-thrift in regenerating kauri stands on poorly drained sites (Beever, et al., 2007).

Four pythiaceous fungi, *Phytophthora cryptogea*, *P. cinnamomi*, *Pythium irregulare* and *P. ultimum* were found to be the cause of rootlet rot in kauri seedlings grown on heavy, poorly-drained soils by Newhook (1959) and Robertson (1973). *Phytophthora cinnamomi* and *P. nicotianae* have been associated with stem lesions on older kauri trees, causing minor damage

(Brien & Dingley, 1959; Newhook, 1959). Johnston et al. (2003) considered that *P. cinnamomi* may have had a significant impact on regeneration of kauri, and could have a greater impact if weather patterns change. Podger & Newhook (1971) described death and dieback of kauri and other species in two small areas of 80-100 year-old kauri regrowth in the Waitakere Ranges. *Phytophthora cinnamomi* was isolated from roots of kauri and other plants, and the authors discussed a possible link between the presence of the fungus and damage to the vegetation occurring under conditions favourable to the fungus. Zentmyer (1985) showed that *P. cinnamomi* grows best in mild temperate or subtropical regions. It does not survive at soil temperatures below 6 °C or above 34 °C. Optimum temperatures are in the range 21-27 °C. It does not tolerate low soil moisture conditions.

2.8.2 Insects

Insect species causing local damage have been listed by Ecroyd (1982). Those found on living trees (Miller, 1984) are:

Acrocerops leucocyma (Lepidoptera: Gracillariidae): leaf miner
Planototrix excessana (Lepidoptera: Totricidae): leaf roller.
Platypus apicalis (Coleoptera: Curculionidae): pin hole borer.
Xenocnema spinipes (Coleoptera: Curculionidae): short nosed weevil, following attack by *P. apicalis.*

A number of wood borers not listed by Ecroyd (1982) have been found on kauri, but are not considered to be important (J. Bain, pers. comm. 2009).

2.9 USE AND EXPLOITATION

2.9.1 Use by Māori

The straight, branch-free stems of kauri growing beside harbours or near rivers were once used to make large sea-going canoes (Dieffenbach, 1843; Best, 1925). Some of these, constructed from a single stem, were 30 m long and 4.5 m wide (Reed, 1953). The wood was also valued for carving (Anonymous, 1868; Clifton, 1990). Prior to European settlement, it is likely that only limited numbers of easily-accessible trees were used, since the stone tool and fire method of felling required the expenditure of considerable amounts of effort and time (Maning, 1863; Best, 1941).

2.9.2 Use by European Settlers

Marion du Fresne was the first European to harvest kauri when his vessels *Mascarin* and *Marquis de Castries* sought shelter in the Bay of Islands in 1772. By 1794, kauri on Great Barrier Island was being felled for ship spars (New Zealand Forest Service, 1975).

The initial extraction of kauri logs for spars was not straight forward. Trees for spars had to be sought further inland once suitable trees had been harvested close to harbours (Campbell, R. D., 1955). Away from harbours, kauri often existed on rugged and precipitous terrain making the manual extraction of large, heavy logs difficult. An early discovery was that kauri logs would float (Polack, 1838). Trees were felled directly into or alongside waterways and logs rolled into the bed of the watercourse. Subsequent storm and flood events would carry logs down to harbours for collection and milling, however this was an unreliable method. From 1837, dams were constructed, frequently in series into the upper catchments (Reed, 1953). Logs were driven on more substantive bodies of water to major river confluences or harbours. It was estimated that upwards of 60% of all kauri timber was driven from the forest using this method. The ability of kauri logs to float gave it a preference for logging over all other timber species, even within mixed forest types (Campbell, R. D., 1955). This, in turn, drove the exploitation of the species.

For nearly 100 years, until the early 20th century, large quantities of high-class timber were extracted from kauri forests. Matthews (1905) reported a 1900 prediction that "in only thirteen years the kauri forests would be exhausted at the present rate of conversion, not including losses caused by fire". Output reached a peak in 1907, when production of approximately 1.2 million m^3 of sawn kauri timber was reported (Roche, 1990). In 1909 an estimated 1.1 million m^3 of kauri remained from all sources (State Forest Service, 1909).

A considerable quantity of timber was used to construct dams, sluices, chutes, "rolling roads" and tramways to facilitate the transport of logs (Kirk, 1889; Sale, 1978). Rapid development of the colony of New Zealand increased the demand for timber and resulted in the use of kauri without appropriate drying or workmanship. Application of appropriate drying and grading procedures increased recognition of the usefulness of kauri timber (Kirk, 1889; Reed, 1953). Resistance to decay and dimensional stability under moist conditions made it eminently suitable for ships spars and masts, boat building (both commercial and recreational), bridging, railway sleepers, mine props, roof shingles, churns and vats, railway carriages, fence palings and road pavers (Hochstetter, 1867; Kirk, 1874; Barlow, 1888; Cyclopedia Company Limited, 1897; Cheeseman, 1914). It was also used for house construction, including panelling, doors, flooring and weather boards; also for furniture, mouldings, and decorative carving (Reed, 1953, 1964; Sale, 1978; Clifton, 1990). Timber was exported in great quantities with approximately 77 300 m^3/yr exported during the period 1904-1909 (State Forest Service, 1909).

Logging in Crown kauri forests ceased in 1981. Since then, sustainable timber production from old-growth or secondary forest has been carried on by private landowners operating under the Forest

Amendment Act (1993). Currently, only a few hundred cubic metres are used each year for production of high-class furniture and musical instruments, turned items and craft work. Other sources of wood are ancient logs recovered from swamps (Clifton, 1990) and the old kauri heads and high stumps left behind after logging (Beveridge, et al., 2009). Recycled kauri timber from old buildings is also used for cabinet-making. Little new timber is being produced for the market.

2.10 FOREST POLICY AND MANAGEMENT OF KAURI

Concern about the decline of the kauri resource was expressed in the 1830s with calls to Governor Hobson for the appointment of a conservator of kauri forests (Roche, 1990). Under the prevailing view that one blade of grass was worth more than two trees (Masters, et al., 1955), decline of the resource continued. Hursthouse (1857) prescribed the felling and burning of all trees less than one metre in diameter during conversion of forest to pasture. Fire was used to kill large trees and recovery of timber was not a priority. By 1873, the kauri resource had been reduced by 70% (Masters, et al., 1955). It was not until 1877 that a Lands Act prohibiting unlicensed harvesting of kauri passed into law (Jourdain, 1925).

Legislation and forest policy applied from earliest European settlement until the mid 1900s have been reviewed by Jourdain (1925) and the New Zealand Forest Service (1964). Emphasis was placed on development of pastoral farming through the clearance of forest and the draining of swamps. Prior to 1853, sale or disbursement of forested lands was controlled by the New Zealand Government Act (1846), the Crown Lands Ordinance (1849), and the Constitution Act (1852). The Waste Lands Act of 1854 was the first of a series that followed later. Between 1853 and 1876 much of the regulation became provincial and there was considerable divergence in its application (Jourdain, 1925). The first Forests Act (1874) established the position of Conservator of Forests and a second Forests Act in 1885 created a Forestry and Agriculture branch of the Department of Lands with a Chief Conservator. In 1893 the Minister of Lands was appointed as Commissioner of State Forests. The New Zealand Forest Service was established under the Forest Act of 1921-22.

Opportunities for preservation of the kauri resource existing in the mid-1800s (Firth, 1874; Hutchins, 1919) were lost through destruction and wastefulness that continued into the 1920s. In a review of Government policy specific to the management of kauri forest, Barton (1975) observed that research evidence obtained between 1800 and the early 1970s was insufficient to support policy for kauri management. Various working plans for management of State-owned kauri forest were developed between 1935 and the mid-1900s. The 1946-51 plan included provision for reservation and production through selective harvesting. Kauri exceeding 90 cm diameter could be harvested at an average rate of 2360 m^3/yr, the equivalent of 250-300 trees (7.87-9.44 m^3/tree).

Long-term management plans covering the whole of the resource were not developed until the final years of State Forest logging in the 1970s and 1980s. In the 1960s and 1970s a number of thinning trials had been undertaken in natural second-growth stands in Russell Forest, on the Hunua and Kaimai Ranges, and on Great Barrier Island (Lloyd, 1978) (Figure 2.5). These stands contained up to 7000 stems/ha of kauri greater than 5 cm diameter. In the late 1970s, the New Zealand Forest Service was responsible for the thinning and milling of kauri in a 120-year-old ricker stand in Northland (Halkett, 1979, 1980; Gibson, 1985; Ecroyd, et al., 1993). Less than 1% of the boards were classified as heartwood and recovery of clear timber was 37%, only half that expected from mature kauri logs.

Figure 2.5. Thinning treatment applied to a natural second-growth stand in Russell Forest. Thinning reduced the stand from an estimated 400 stems per hectare to a near final stocking of 200 stems per hectare. (*Image copyright to Scion*).

Barton & Madgwick (1987) recorded a moderate diameter growth response to thinning and fertiliser application in ricker stands south of Auckland. In other projects, kauri regeneration on

Great Barrier Island and also in the Russell and Herekino Forests was managed by felling or ring-barking overstorey vegetation (mainly kanuka) to release developing kauri saplings (Sando, 1936b; Lloyd, 1960, 1963; Halkett, 1983). Small-scale, partial-logging operations in several kauri forests were permitted until 1979. Following the prohibition of logging in old-growth forests, helicopters were used to extract logs during the thinning of dense stands of sub-mature kauri. This caused little apparent damage to residual trees in Russell Forest (Halkett, 1982) or in the Hunua Ranges (Barton & Madgwick, 1987).

A further aim of modern kauri management is forest restoration through the widespread planting of nursery-raised seedlings. The New Zealand Forest Service started experimental plantings of kauri in Waipoua Forest in the 1940s and carried out supplementary or enrichment planting in tall scrub and partially-logged forest until the demise of the Service in 1987. By this time, hundreds-of-thousands of nursery-raised kauri had been planted over a total area of 1000 ha (Halkett, 1982; Halkett & Sale, 1986), mainly on sites formerly occupied by kauri forest. Only cursory attention has been paid to evaluation of these results. Newly-planted kauri seedlings are vulnerable to drought, and survival in exposed sites on open and compacted ground or in short scrub was generally poor. Improved survival was noted beneath an intact tall canopy but there was little height growth for many years.

Morrison & Lloyd (1972) considered that soil texture and condition were major factors affecting kauri seedling establishment. Growth rates were usually enhanced in soils with a loose, friable structure, while nutritional characteristics had a smaller effect. Best growth of planted kauri has been observed in fertile, sheltered sites such as those chosen for plantations established by the New Zealand Forest Service in Northland and Great Barrier Island (Halkett, 1982). Other vigorous plantations have been established in urban parks in Whangarei, Auckland and New Plymouth, and small stands have been planted by private landowners (Pardy, et al., 1992). Some of these now exceed 80 years old. Many with high stocking rates (in excess of 1000 stems/ha) show a decrease in growth rate and some mortality as competition becomes more intense (Herbert, et al., 1996). In general, the objectives of kauri plantation establishment or enrichment planting have not been clearly stated, and “kauri policy” was not applied consistently. Strong arguments were put forward for management of second-growth kauri and some planted stands for wood production (Barton & Horgan, 1980). Recognition of the effects of kauri exploitation in the past and continued veneration for the small remnants of old-growth forest have stimulated support for the planting of kauri and for promotion of natural regeneration of the species.

2.11 CONCLUSION

Kauri is the only species of *Agathis* native to New Zealand. Forests containing kauri have been greatly reduced in area, especially since European settlement over the past 200 years. Kauri timber was cut from as early as 1772. The harvesting of kauri was driven by the demands of supplying timber for the new colony, the clearance of land for pastoral use, and developing a local economy. By 1873 the kauri resource had already declined by 70%. Restriction on the export of native timbers was imposed by the Commissioner of State Forests in 1918. At the same time D.E Hutchins, an early colonial forester, gave proposals for the sustainable management of the kauri resource. The policy to restrict the export of native timbers (particularly kauri) came as the first national forest inventory in 1921-23 found that remaining kauri comprised only 0.6% of the available milling resource. At this time, New Zealand began to plant exotic timber species in replacement of the natural forest. A move that prompted D.E. Hutchins to comment that "for reasons which have never been satisfactorily explained, it has been thought to replace the valuable native forest of New Zealand by artificial plantations of exotics – a quite unusual proceeding in forestry". By 1920 kauri logging had declined, and in 1981 logging on Crown land had ceased entirely. The management of New Zealand's native forests became the responsibility of the new Department of Conservation in 1987, at which time less than 1% of kauri forest remained. Management of kauri is now focussed on ensuring the species long-term survival despite a severely altered population and in the presence of new diseases.

The disease causing kauri dieback (*Phytophthora* taxon Agathis) in the Northland and Auckland regions poses a threat to the long-term survival of kauri at the local and national level, and also to those proposing to plant kauri in plantations. While management options have been proposed to limit the spread of the disease, further investigation into this *Phytophthora* spp. and its relationship with kauri is required to ensure that kauri continues to exist in New Zealand's forests and landscapes.

Kauri grows slowly in its natural habitat, but under favourable conditions it is one of the faster-growing indigenous conifers. Although seedling growth is slow in logged areas, there is considerable evidence that regeneration takes place in old-growth forests. Trees surviving for many years as suppressed saplings assume a faster growth rate when gaps form in the forest canopy.

Climatic changes during the Quaternary period are likely to have been responsible for restriction of the natural range of the species to areas north of Latitude 38 °S. Vigorous growth is possible if trees are established artificially on fertile, free-draining soils in sheltered areas south of the current natural range. When young, kauri is easily suppressed by other plant species. Its efficient use of water and nutrients probably accounts for competitive advantage on relatively infertile sites.

Emphasis has shifted from destructive exploitation to conservation, and more recently to expansion of the national kauri resource. The current research focus on improvement of establishment techniques and enhancement of early growth rate offers good prospects for the widespread planting of kauri for amenity and cultural purposes, and for timber production on appropriate sites. Planting of kauri in New Zealand will continue, and the rate is likely to increase, especially within the natural range of the species.

Numerous historical and contemporary references indicate that kauri has a potential role in the development of New Zealand’s economic well-being. Careful management is likely to allow the production of a very desirable timber over much shorter rotations than were previously thought to be possible. Those wishing to plant kauri for future timber production will require more information about best-practice regimes and potential yield. Continued development of techniques and growth models is likely to accelerate the expansion of a unique national resource.

CHAPTER 3

REVIEW OF GROWTH MODELLING

3.1 INTRODUCTION

Growth modelling has a long history in forestry (Dzierzon & Mason, 2006), with mensurational yield models being used from the early 1850s (Peng, 2000). Fries (1974) referred to the development of growth models as an important part of the research into growth and yield since the end of the last century (19th century). Robinson & Ek (1998) observed that individual tree-based growth models had been under development since the 1960s, and in that time several dominant modelling themes had emerged. Apart from graphical yield tables, the first generation of mathematical modelling did not occur in New Zealand forestry until 1966, with later generation models appearing in the 1970s, for example the Kaingaroa Growth Model (KGM1) (Goulding, 1986). Forest growth and yield modelling has been reviewed by numerous authors (Fries, 1974; Goulding, 1979, 1986; García, 1988; Vanclay, 1994; Vanclay & Skovsgaard, 1997; Peng, 2000; Pinjuv, et al., 2006; Mendoza & Vanclay, 2008) and individually and collectively are a useful chronological record of the progress and development in the area.

Growth models are important for forest management planning to forecast the growth and yield of individual trees, stands or species (García, 1988; Berrill, et al., 2007), to provide estimates of future timber harvest (Mendoza & Vanclay, 2008) and to plan silvicultural operations or develop forest policy (Vanclay, 1994). Clutter et al. (1983) suggested that the relationships of standing timber volume to age, site quality, and stand density could be used by forest managers to make informed decisions on the manipulation of forest stands using the controllable stand variables. Much of the growth and yield modelling in New Zealand has been conducted on even-aged, single-species plantations (Vanclay, 1994; Twery, 2004).

3.2 WHAT IS A GROWTH MODEL?

The meaning for the term growth and yield model can be derived from the definition of the individual words where **growth** is an increase in size or value, **yield** is the amount produced, and **model** is a description or representation of a process or system to assist calculations or predictions (Sykes, 1982). Therefore, the abbreviated term “growth and yield model” is commonly used to describe a system of equations that are used to predict the growth and yield of a forest stand under a variety of conditions through time (Vanclay, 1994; Twery, 2004). In its simplest form, a growth and yield model is also referred to as a “set of mathematical equations that predict the development of tree crops over time" (Goulding, 1986), and as an abstraction of the natural dynamics of a forest stand that may encompass growth, mortality, and other changes (Vanclay, 1994; Peng, 2000). Robinson & Ek (1998) suggested that such models could be divided into components that deal with different aspects of tree or forest processes. These models are either distance dependent (spatial) or distance independent (aspatial), where spatial models consider the relationship and location of individual trees within a plot

3.3 TYPES OF GROWTH MODELS

There is a wide range of forest growth modelling approaches available (Figure 3.1). They differ in complexity and the detail in which they describe the systems under consideration. At one end of the range are the traditional empirical models based on periodic measurements, which make no attempt to measure all factors that may affect tree growth. At the other end are the complex process-based models, these include the mechanisms intrinsic to tree growth. The selection of a modelling approach is driven mainly by current or potentially available data, and the objectives for which the model is to be constructed (Alder, 1995). Vanclay (1994) noted that there is no one best method for forest growth models.

A model should provide information that is sufficiently accurate and detailed to suit the intended purpose. Bunnell (1989) recommended that users of growth and yield models should distinguish between models for understanding, and models for prediction. Models which are unnecessarily complicated may incur extra costs, loss in precision of estimates, and difficulty in understanding and assessing the utility of the model (Vanclay, 1994). He also stated that growth and yield models are of limited use on their own and require additional data to provide valid information. This additional information may be in the form of:

1. forest area estimates
2. inventory data (stand-level)
3. growth and harvesting models based inventory data

A model may be deterministic or stochastic. A deterministic model gives an estimate of the expected growth of a forest stand; given the same initial conditions the model will predict the same outcome each time. A stochastic model attempts to illustrate the natural variation by providing different predictions, each with a specific probability of occurrence. A stochastic model needs to be run multiple times to give a good indication of expected growth, but also to look for variability (Vanclay, 1994).

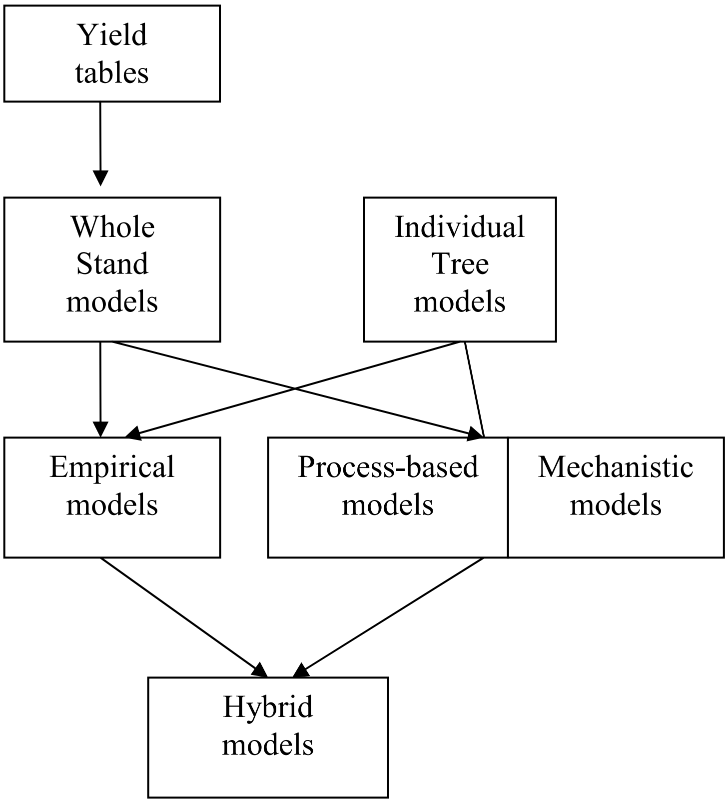


Figure 3.1. Relationship and development of Growth and Yield modelling.

3.3.1 Yield Tables

Yield Tables persisted as the status quo for yield modelling until the 1950s (Peng, 2000). Twery (2004) believes they are still adequate for managers who are interested primarily in timber volume production. A yield table is defined as a table showing the expected timber yields by age of an even-aged stand, usually by site index classes, and typically including quadratic mean diameter (DBH), height, number of stems per unit area, basal area, and standing volume per unit area; yield tables may also include volume of thinnings, current annual increment (CAI), mean annual increment (MAI), and other data (Vanclay, 1994; Society of American Foresters, 2008). A yield table may be expressed graphically as a series of curves represented by age and volume, or it may also be expressed as an equation (Vanclay, 1994). More complex models may include spatial elements and timber quality. The main purpose of yield tables is to provide estimates of present yield and future increment and yield. There are three main types of yield table: normal, empirical and variable density. These are discussed below.

3.3.1.1 Normal Yield Table

A normal yield table is based on two independent variables, age and site (species constant), and applies to fully stocked (or normal) stands (Society of American Foresters, 2008). Normal yield tables originated before the ability to analyse more than two independent variables existed (Husch, et al., 2003). It depicts relationships between volume and unit area together with other stand parameters and independent variables. As only two independent variables are involved, normal yield tables are typically presented by graphical means (Husch, et al., 2003). The density variable is held constant by attempting to select sample plots of a certain fixed density assessed as full (or normal) stocking. Because it is difficult to describe precisely and recognise full stocking, generalised subjective descriptions are used which leave much to the judgment of the individual in choosing samples. The data presented in normal yield tables are averages derived from many stands considered to be fully stocked at the time they were sampled. In North American usage, normal-yield tables were usually developed from one-time measurements in unmanaged stands of natural origin; in European usage, normal-yield tables do not necessarily represent stands of natural origin only and are often based on remeasured plots, sometimes with low thinning (Society of American Foresters, 2008).

3.3.1.2 Empirical Yield Table

In contrast, empirical yield tables are based on average stockings rather than fully stocked stands and other statistics in relation to age and (sometimes) site index classes as they are found in the existing forest (Husch, et al., 2003). This simplifies the selection of stands for sampling. The resulting yield tables describe stand characteristics for the average stand density encountered during the collection of field data. Empirical yield tables are of limited usefulness today as existing older stands do not reflect the effects of changing management practices applied to younger stands (Society of American Foresters, 2008).

Normal and empirical yield tables essentially have the same limitations, namely:

- the difficulty of locating fully stocked stands or representative average stocked stands from which to collect the basic data;
- stocking may not have always been 'fully stocked' or 'averaged';
- the problem of selecting correction factors to apply to stands of density other than normal or average.

3.3.1.3 Variable Density Yield Table

Yield tables that include three independent variables (stand density, site index, age) are known as variable density yield tables, and were developed as a result of the limitations of normal and empirical yield tables (Society of American Foresters, 2008). Variable density yield tables are particularly useful for abnormal stands (e.g. early establishment problems, insect and fungal attack, drought, fire, fluctuating demands for produce). However, they still have limitations (which apply also to normal and empirical tables), namely:

- no confidence limits are attached to trends;
- extrapolations are made outside and beyond thinning regimes and ages sampled;
- volume functions used are mostly two-dimensional and of regional application;
- volumes are computed for normal trees only and no account is taken of malformation and other such factors affecting recoverability;
- usually, no account is taken of the pruned component of a stand.

3.3.2 Empirical Models

Of the two basic types of empirical models (whole-stand and individual-tree models), whole-stand models are generally used when dealing with even-aged, single-species stands (García, 1988, 1993; Vanclay, 1994). Empirical models represent a good compromise between generality and accuracy of the estimates.

Whole-stand models characterise the state of the stand by means of a small number of variables, such as basal area, mean diameter, volume per hectare, stand density, average spacing or top height (García, 1993). These types of models require few details for growth simulation. However, they provide rather limited information about the future stand, in some cases only stand volume (Vanclay, 1994), but may include stand volume equations and branching models. Single-tree models are one of the most detailed approaches to modelling, and may be complex (Vanclay, 1994). Tree-level models include individual tree growth models, tree volume equations (Ellis, 1979), taper equations (Ellis, 1982), and branching models (Grace & Pont, 1999; Watt, et al., 2000).

Mathematical models usually used in forestry to predict stand growth and yield are typically statistically-derived and empirically-based (Clutter, et al., 1983; Campion, et al., 2005). An empirical model is based only on data and is used to predict, not explain, a system, as in process-based models. Data for this type of model is collected from permanent sample plots (Ellis & Hayes, 1991) that are located over the range of site conditions that the species is planted, preferably with a wide range of stand ages. Data are crucial for an empirical model. Data are used to develop the model, to estimate its parameters, and for testing the model. An empirical model consists of a function that captures the trends of data. Sometimes it is difficult or impossible to develop a mathematical model that explains a situation. However, if data exist, they can be used as the sole basis for an empirical model. The trend line of the function goes through the data points approximately. Although empirical models are normally more than adequate, their accuracy is limited to the species and the site conditions for which they were originally developed (Landsberg, 2003). Such models cannot simulate changes in growth and yield due to changing environmental or management conditions (Battaglia & Sands, 1997, 1998).

3.3.3 Difference Equations

While some predicted forest outcome and value using yield tables, others made predictions based on developing growth models. Clutter et al. (1983) combined the two approaches into one entity, and laid the foundation for modelling with difference equations in forestry, where future yield is expressed as a function of existing yield (Pinjuv, et al., 2006). Scheid (1968) described difference equations as a relationship between the values of y_k of a function defined on a discrete set of arguments x_k. Difference equations are used to calculate the value of a function recursively from a given set of values. These equations are useful in numerous settings and forms including biological fields (Kelley & Peterson, 2001).

3.3.4 Process-based Models

The process-based modelling approach involves the simulation of stand growth by the underlying physiological processes or mechanisms that regulate tree growth (e.g. light interception, photosynthesis, respiration, carbon allocation, foliage mortality, temperature, soil nutrients etc) and the way the processes are affected by the site conditions (Vanclay, 1994). This allows process-based models to be applied to sites, ages and situations beyond the original data sets. A number of process-based models have been developed in the last 20 years including FOREST-BGC (Running & Gower, 1991), BIOMASS (McMurtrie & Landsberg, 1992), PnET (Aber & Feberer, 1992), G'DAY (Comins & McMurtrie, 1993), and CABALA (Battaglia, et al., 2004). These models require a large number of parameters which many can be only be obtained with intensive and expensive measurements.

Process-based modelling is an alternative, albeit difficult, approach to empirical-based modelling. Individual modelling approaches are often assumed to be separate or discreet; however, Korzukhin et al. (1996) suggested that process-based and empirical models were on a continuum, rather than existing as pure entities. Johnsen et al. (2001) indicated that the term process-based models specify a level of resolution, usually for growth models. Mäkelä et al. (2000) stated that "process-based models are seldom used as practical tools in forest management as they embody too many uncertainties and to require too many poorly-known parameters". Despite this, there is much interest in the use of process-based models in forest management (Landsberg & Waring, 1997). Mäkelä et al. (2000) also suggested that progress in this area was more to do with incorporating process-based thinking into management models to make better use of empirical observations.

3.3.5 Hybrid Models

Hybrid growth models are a developing area for the prediction of forest growth and yield. Dzierzon & Mason (2006) define hybrid modelling as the combination of classical growth and yield modelling and physiological process or site information. They have been advocated as the most expeditious way to provide forest managers with forest growth information since the 1990s (Battaglia, et al., 1999). Models that combine a mix of elements from empirical and process-based models can, to some extent, avoid the shortcomings of both (Husch, et al., 2003; Pinjuv, et al., 2006). A comparison and validation of empirical, process-based and hybrid models were made on a New Zealand radiata pine dataset. In this comparison, the hybrid model CanSPBL(water) achieved a better prediction based on historical data using water balance and soil type as site variables than was achieved by the models 3-PG, CANTY, and CanSPBL(1.2) (Pinjuv, et al., 2006).

3.4 MODEL VALIDATION

The use of a model that does not fit the data well cannot provide useful or appropriate answers. Therefore, an important process in the development of a model is its validation or testing (Alder, 1995). Until validated, a model can be viewed as still being a hypothesis. Validation of the model can be both an ongoing and terminal activity. Ongoing validation occurs during the development of a model, and later as more data is added, while terminal validation seeks to define the limits of the models ability to predict. Model validation has been discussed by numerous authors e.g. (Marcus & Elias, 1998; Sargent, 1998; Palomo del Barrio & Guyon, 2004; Buranathiti, et al., 2006; Abdul-Aziz, 2007). Several methods are available for model validation, and their individual use is dependent on the type of data, and modelling approach.

When developing and testing growth models it is normal to divide the data into two independent data sets; one for the development of the growth model (the training set), and another for validation of the model (the test set). Called the hold-out method, this can result in a high variance, depending on which data points end up in the training set and which end up in the test set. Cross-validation is a method for testing models where datasets are too small to divide into training and test sets, and can be used for estimating prediction error (Efron & Tibshirani, 1993). The cross-validation method is an in-built feature to the statistical package SAS (SAS Institute Inc, 2006). Two methods of cross-validation are described.

***K*-fold cross-validation.** The data set is divided into a number of roughly equal subsets (*k*). Each time, one of the *k* subsets is used as the test set and the other *k*-1 subsets are put together to form a training set. The average error across all *k* trials is then calculated. In this method, it matters less how the data gets divided. Every data point gets to be in a test set exactly once, and gets to be in a training set *k*-1 times. The variance of the resulting estimate is reduced as *k* is increased (Efron & Tibshirani, 1993).

One-at-a-time cross-validation is *k*-fold cross-validation taken to its logical extreme, with *k* equal to N (the number of data points in the set). That means that N times, the model is run on all the data except for one point and a prediction is made for that point. As with the *k*-fold method, the average error is computed and used to evaluate the model e.g. (Stone, 1974; Stone & Brooks, 1990; Efron & Tibshirani, 1993; Voet, 1994).

3.5 SUMMARY

Growth and yield models are important for forest management and planning, and to provide estimates of future timber harvest and profitability. There is a wide range of forest growth and yield modelling approaches available. They differ in complexity and detail, from traditional empirical models based on periodic measurements to complex process-based models, which include the mechanisms intrinsic to tree growth. The use of a model that does not fit the data well cannot provide useful or appropriate answers. Therefore, important processes in the development of a model are the selection of the modelling approach, driven mainly by the available data and the objectives for which the model is to be constructed, and its validation or testing. Until validated, a model can be viewed as still being a hypothesis. Importantly, there is no one best method for forest growth modelling.

In this thesis, empirical stand-level models will be developed as the data available was variable for stand age, initial stand density, establishment methods and location (latitude). The data set was not sufficient in size to create a training and a test set, therefore model validation will use the one-at-a-time cross-validation method to test the models developed. These models will provide the basis for further testing and model development as more data becomes available. They will facilitate early predictions from which investment and management decisions can be made for kauri forestry.

CHAPTER 4

STUDY SITES

4.1 INTRODUCTION

This study has used both planted, and second-growth natural stands to identify and compare the performance (growth and productivity) of kauri. Individual stand histories, site descriptions including climate, latitude, sunshine and rainfall for both planted and second-growth stands are presented in this chapter.

4.2 PLANTED STANDS

Twenty five planted stands were used for this study (Table 4.1). Twenty four of the stands were located in the North Island. Eight stands were planted south of the current natural southern limit (38 ^{o}S) described for kauri (Figure 4.1). One stand was located in the South Island at latitude 45.83 ^{o}S. Site descriptions are given below. Soil descriptions are from New Zealand Soil Bureau (1968) and Hewitt (1998) (Table 4.2), with measurement details (Table 4.3), and environmental parameters (Table 4.4). Climate data is from the New Zealand Meteorological Service (1983).

Where seed source was known, it has been recorded. Where the seed source was not recorded, but where the New Zealand Forest Service (NZFS) undertook the planting, it was assumed that seed was sourced from the Waipoua Forest seed-tree programme. Experimental planting of kauri began in Waipoua Forest during the 1940s. Seedlings were raised from seed collected from mature kauri spread throughout the forest. From this planting programme a complementary project to identify superior seed trees was developed. The NZFS identified kauri (60-70 cm diameter) in Waipoua that produced regular crops of seed cones (Halkett, 1982). Over time the selection of seed-trees was refined to include only those trees that produced better than average seed crops, and in subsequent observations, better than average seedlings. Seedlings were raised in Government owned nurseries near Kaitaia in Northland, and near Cambridge in the Waikato region. These seedlings, and some seed, were widely dispersed in NZFS and private kauri plantings throughout New Zealand up until the dissolution of the NZFS in the late 1980s.

The majority of planted stands observed in this study represent stands that were established without the aid of a nurse crop or over-storey species as described by Bergin & Gea (2007). Where a vegetative cover existed at establishment, the developing stands were expected to have received only minimal, if any, benefit from the existence of the cover on the individual sites.

The growth and performance of many of the planted stands was first measured in 1986 (Pardy, 1987; Pardy & Bergin, 1987c, 1987a, 1987b; Pardy & Steward, 1987b, 1987a; Pardy & Williams, 1987a, 1987b; Pardy, 1988).

Table 4.1. Number of planted kauri stands and Permanent Sample Plots in this study, by site and region.

Region	**No of Planted Stands**	**No. Permanent Sample Plots**
Northland	8	10
Auckland	3	4
Great Barrier Island	4	4
Waikato	1	1
Bay of Plenty	1	2
East Cape	1	1
Taranaki	3	5
Hawkes Bay	3	3
Otago	1	1
Totals	**25**	**31**

4.2.1 Stand and site descriptions

Many of the planted stands observed in this study were privately owned. The owners requested confidentiality of their data and/or the location of their stands. To meet these obligations, all planted stands are identified only by region and were given an individual stand number.

Stand 1, Northland – A small stand of approximately 0.5 ha that was established by the NZFS in 1955. It is located on the northern flanks of the Maungataniwha Ranges, to the south of Kaitaia. The stand received no silvicultural operations since planting. Soils are described as Weathered Fluvial Recent Soils (RFW) (Hewitt, 1998). Regeneration of kauri has established within the stand.

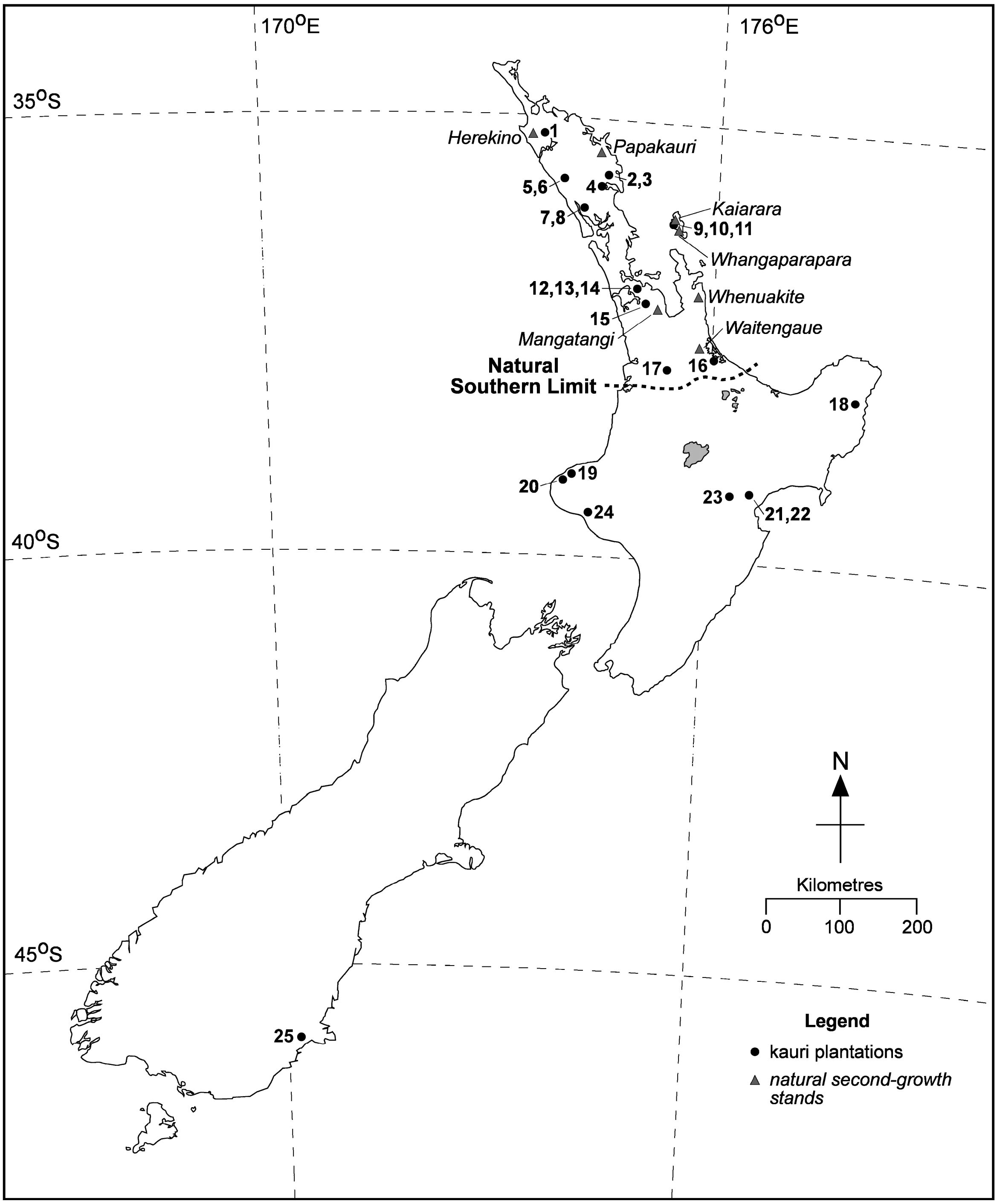


Figure 4.1. Location of planted and natural second-growth kauri stands used in this study of growth and productivity. Eight of the planted kauri stands were established south of the species current natural limit.

Stands 2 & 3, Northland – This exotic forest, to the east of Whangarei, contains three planted stands of kauri established by the NZFS. These stands cover approximately 5-7 hectares. The two 1950s stands were included in this study. The third and youngest stand was similar in initial stand density to the two older stands, but had no history of measurement, and was therefore excluded from this study. The 1950 stand was established at 5 × 2 m spacing and the 1955 at 4 × 2 m spacing (Figure 4.2). The 1955 stand contains two permanent sample plots (PSP). At both sites pre-planting vegetation was dominated by bracken fern (*Pteridium esculentum* (G.Forst.) Cockayne), gorse (*Ulex europaeus* L.) and other ground ferns, and was burnt before planting. Early mortality occurred through drought and suppression by regrowth of bracken and gorse despite some early releasing of seedlings from competing vegetation being undertaken for the first five years. The soils are Mottled Orthic Brown Soils (BOM) (Marua clay loam hill soil, derived from greywacke) of low to medium natural fertility (Hewitt, 1998). Regeneration of kauri has established within the stands.

Figure 4.2. Stand 3. At age 55 this stand was 21.5 m MTH and 32.7 cm DBH and averaged 541 m^3/ha. Note the small branches, which were abscising.

Stand 4, Northland – A small stand (0.2-0.3 ha) established in 1945 within an urban reserve on the outskirts of Whangarei. The stand was regularly released during its early growth, but had received no pruning or thinning since. Soils are described as Typic Orthic Allophanic Soils (LOT) (Ohaewai silt loam, derived from basalt) of medium to high fertility (Hewitt, 1998). Regeneration of kauri has established within the stand.

Stands 5 & 6, Northland – This forest is located to the south of Waipoua Forest, and had several plantings (estimated to cover 3-5 hectares) established over a number of years by the NZFS. Planted stands established in 1955 and 1960 were assessed for this study. No details of the site at planting, or follow-up maintenance, were available. The sites received no silvicultural operations since planting. Soils are described as Typic Oxidic Granular Soils (NXT) of low fertility (Hewitt, 1998). Regeneration of kauri has established within the stands.

Stands 7 & 8, Northland – This site consists of two young planted stands established in 1992 (1.0 hectare) and 1996 (1.5-2.0 hectares) on privately owned retired farmland. It is located to the south-east of Dargaville (Figure 4.3). **Stand 8** (planted 1996) contains two PSPs. Kauri seedlings in these stands were from locally sourced seed. No pruning or thinning has occurred. Some in-fill planting was undertaken in the **Stand 7** after early mortality caused by an extended drought. Soils are described as Typic Acid Brown Soils (BAT) (Waiotira clays) (Hewitt, 1998), with a higher than normal sand content. Drainage, apart from minor natural seeps, is good.

Figure 4.3. Stand 8. Planted in 1996 at 1124 stems/ha, seed for this planting was sourced from mature trees on the property. This stand is typical of the young kauri stands on farmland.

Stands 9, 10 & 11, Great Barrier Island – The NZFS planted many stands of kauri on Great Barrier Island (Halkett, 1982). Three planted kauri stands established near Port Fitzroy in 1954 have been included in this study. All plots were established beneath tall, thinning kanuka. **Stand 10** was planted on a river terrace above a minor stream that flows into the Kaiarara Stream. **Stand 9** contains two PSPs, while the other two stands contain one each. Seedlings were 3/0 Waipoua seed source. Prior to planting, the sites were cleared of ground and tree ferns. Six releasing operations were conducted before 1972, while two low pruning operations to a maximum of 2.7 m were undertaken in 1979 and 1984. Soils were described as Typic Orthic Granular Soils (NOT) of medium to low fertility (Hewitt, 1998). Regeneration of kauri has established within all three stands.

Stands 12, 13 & 14, Auckland – This site is comprised of three individual kauri stands established in open parkland amongst a series of exotic and indigenous plantations. Jointly they comprise an estimated 1.0-1.5 hectares of kauri. **Stands 12** and **13** were planted in 1927, and **Stand 14** in 1947. Individual stand maintenance has involved the management of grass growth. No pruning or thinning has occurred. Soils are described as Typic Impeded Allophanic Soils (LIT) of medium to low fertility (Hewitt, 1998).

Stand 15, Auckland – This is a small experimental planted stand established in 1955 from seed of Waipoua origin. The stand is approximately 0.2-0.3 hectares. Maintenance of kauri involved releasing seedlings from grass competition by cultivating between seedlings, and removal of occasional heavy lower branches from 1960-1973. No other silvicultural treatments were applied. Mortality since the 1986 assessment was attributed to *Phytophthora cinnamomi*. Soils are described as Typic Yellow Ultic Soils (UYT) (Karaka and Weymouth central yellow brown loam) of low to medium fertility (Hewitt, 1998).

Stand 16, Bay of Plenty – This is a privately owned planted stand of approximately 1.0 hectares. It was established in 1997 on the site of a retired kiwi fruit orchard (Figure 4.4). The site contains two PSPs that were established when the stand was six years old. Maintenance of the stand since planting has been high, with continuous control of competing weeds and grass. Kauri was watered during extended dry periods in their early growth. Soft, fast-growing terminal leaders damaged by wind were pruned, often with new leaders initiating from the whorl below or from resting buds on the stem. All kauri were low pruned in 2007. Soil profiles are modified, but are described as Typic Orthic Allophanic Soils (LOT) (Hewitt, 1998).

Stand 16 was the best performing stand (height and basal area) of planted kauri measured to date. It has been used as an example of the potential growth and performance of the species.

Figure 4.4. Stand 16 at age 7. At age 12 this high-performing stand was similar in height and diameter to other planted stands at age 30. (*Image No. 490502 - copyright to Scion*).

Stand 17, Waikato – This is a small stand (0.3 hectares) established, in 1960, into open pasture on an exposed hill site near the Maungakawa Reserve, to the east of Cambridge. Kauri was frequently released from competing grass when young, no other silviculture was undertaken. Soils are described as Typic Orthic Allophanic Soils (LOT) (Puketarata silt loam and clay loam derived from Mairoa ash on greywacke) and are of medium fertility (Hewitt, 1998).

Stand 18, East Cape – This is a small stand (0.3 hectares) established in 1946, near Te Puia Springs, as part of a mixed privately owned exotic/indigenous arboretum. Kauri was released from a low cover of manuka on a number of occasions until they were 2-3 m tall. No other silvicultural operation was recorded. Soils are described as Orthic Brown Soils (BO) (Patoka fine sandy loam) of low to medium fertility (Hewitt, 1998).

Stand 19, Taranaki – A 2.0 ha area was planted in 1936 with various indigenous tree species, including three discrete stands of kauri. Lines were cut through bracken fern and tutu (*Coriaria arborea* L.) cover. The ground was cultivated by spade and seedlings planted at 1.8 m × 1.8 m spacing. Seed source is presumed to be Waipoua Forest as other plantings in New Plymouth at the same time came from this source. The site was released by hand in the early years after planting. The stand was lightly thinned in 1968 to remove unthrifty and malformed trees. The average clear bole was 7.5 m in 1996. In 2002 a thinning was undertaken for stand health and public safety reasons by the New Plymouth District Council to remove all multi-leadered kauri. Soils are described as Typic Orthic Allophanic Soils (LOT) (fine soft, non-cohesive New Plymouth yellow brown loams) (Hewitt, 1998). Regeneration of kauri has established within the stand.

Stand 20, Taranaki – A large planted stand (approximately 2.0 hectares) established as a woodlot in 1935 from Waipoua seed source. The stand contains three permanent sample plots. Early undated photographs suggest that seedlings were planted in lanes cut into bracken fern cover with scattered mahoe (*Melicytus ramiflorus* J.R.Forst. & G.Forst.) and other shrubs and small trees. The condition of the seedlings and the appearance of the site suggested that seedlings were hand-released (Herbert, et al., 1996). The average clear bole was 5.4 m in 1996. No other silvicultural treatment of this stand occurred until 2004 when a thinning was undertaken to remove all multi-leadered kauri. Soils are described as Typic Orthic Allophanic Soils (LOT) (fine soft, non-cohesive New Plymouth yellow brown loams) (Hewitt, 1998). Regeneration of kauri has established within the stand.

Stands 21 & 22, Hawkes Bay – This forest contained three kauri stands within a mixed exotic/indigenous forest. Together they are approximately 1.0-1.5 hectares, and form part of Holt's Forest Trust at Waikoau, about 40 km north-west of Napier. The two older stands, established in 1955 and 1963, had permanent sample plots established in 1986. Kauri, of Waipoua Forest origin, was planted onto sites with gentle to steep slopes that had been cleared of bracken and blackberry (*Rubus fruticosis* L.). After planting kauri were hand-released from regrowth on a regular basis (Pardy & Bergin, 1987c). Kauri in the 1963 planting had been pruned on a number of occasions (Figure 4.5). There was no thinning of either stand. Soils are described as Buried-allophanic Orthic Pumice Soils (MOBL) (Gisborne sandy loam derived from Gisborne ash) and are of low to medium natural fertility (Hewitt, 1998). Regeneration of kauri has established within the stands.

Stand 23, Hawkes Bay – A small, privately owned planted stand (0.2-0.3 hectares) that was established in 1956 during the creation of a mixed exotic/indigenous arboretum. Kauri was planted into lines cut in a thin cover of kanuka. The kanuka cover was slowly removed over a twenty year period; no other silvicultural treatments were applied. The site was subjected to periodic droughts over a number of years which affected survival of kauri on this site. Soils are described as Immature Orthic Pumice Soils (MOI) (Gisborne sandy loam derived from Gisborne ash pumice over papa mudstone) of low fertility (Hewitt, 1998).

Figure 4.5. Stand 21. This stand has been maintained at high stand density. Note the clean boles, with lower branches having abscised or been pruned in early pruning operations. Crowns are small due to competition.

Stand 24, Taranaki – A small stand (0.2 hectares) established in an urban reserve in Hawera in 1936. The kauri were planted into an open grass site, and were released on several occasions in the early years after planting. No other silvicultural treatment has been applied. Soils are described as Typic Orthic Allophanic Soils (LOT) (yellow brown loam derived from Egmont ash) of medium fertility (Hewitt, 1998).

Stand 25, Otago – This stand is a small, privately owned planted stand (0.2 hectares), located approximately 12 kms to the west of Dunedin. It was established in 1955, amongst a larger planting of mixed indigenous species. It is the only planted kauri stand from the South Island included in this study (Figure 4.1). Kauri were hand-released from competing ground vegetation when young, no other silviculture has occurred. These trees produced viable seed within twenty years of planting. Soils are described as Typic Fluvial Recent Soils (RFT) (Warepa soils derived from Schist loess over schist, greywacke and igneous rocks) of low natural fertility (Hewitt, 1998).

Table 4.2. Soil Codes and descriptions (from Hewitt, 1998).

Soil Code	Soil Sub-group description
BAM	Mottled Acid Brown Soils
BOM	Mottled Orthic Brown Soils
BOT	Typic Orthic Brown Soils
LIT	Typic Impeded Allophanic Soils
LOT	Typic Orthic Allophanic Soils
MOT	Typic Orthic Pumice Soils
NXT	Typic Oxidic Granular Soils
RFT	Typic Fluvial Recent Soils
RFW	Weathered Fluvial Recent Soils
ROW	Weathered Orthic Recent Soils
UPT	Typic Perch-gley Ultic Soils
UYT	Typic Yellow Ultic Soils

Table 4.3. Number of plots within planted kauri stands by region, and their age and periodicity of measurement at the last assessment.

Region	No. of plots	Minimum Age (years)	Maximum Age (years)	Minimum period of measurement (years)	Maximum period of measurement (years)
Northland	10	14	67	2	23
Great Barrier Island	4	30	44	15	29
Auckland	4	54	81	10	50
Waikato	1	49	49	23	23
Bay of Plenty	2	6	12	6	6
East Cape	1	63	63	23	23
Taranaki	5	73	83	33	35
Hawkes Bay	3	46	53	21	24
Otago	1	55	55	24	24
All stands	**31**	**6**	**62**	**2**	**50**

Table 4.4. Stand and site variables for all planted kauri. Sites are ranked by latitude (north to south).

Stand	Region	Initial stand density (stems/ha)	Elevation (m)	Annual Rainfall (mm)	Annual sunshine (hrs)	Daily mean temp (^{0}C)	Latitude	Soil type
1	Northland	1089	100	1334	2070	15.7	35.16 ^{o}S	RFW
2	Northland	1000	120	1934	1925	13.7	35.65 ^{o}S	BOM
3	Northland	1250	120	1934	1925	13.7	35.65 ^{o}S	BOM
4	Northland	832	20	1600	1925	15.4	35.71 ^{o}S	LOT
5	Northland	1320	200	1350	1900	15.1	35.71 ^{o}S	NXT
6	Northland	1194	200	1350	1900	15.1	35.71 ^{o}S	NXT
7	Northland	447	60	1250	1900	15.1	36.03 ^{o}S	BAT
8	Northland	843	60	1250	1900	15.1	36.03 ^{o}S	BAT
9	Great Barrier Island	625	20	1750	2100	15.2	36.18 ^{o}S	NOT
10	Great Barrier Island	675	20	1750	2100	15.2	36.18 ^{o}S	NOT
11	Great Barrier Island	625	30	1750	2100	15.2	36.18 ^{o}S	MOBL
12	Auckland	395	80	1220	2100	14	36.89 ^{o}S	LIT
13	Auckland	400	80	1220	2100	14	36.89 ^{o}S	LIT
14	Auckland	320	80	1220	2100	14	36.89 ^{o}S	LIT
15	Auckland	519	20	1220	2100	14	37.07 ^{o}S	UYT
16	Bay of Plenty	625	20	1198	2260	14.4	37.66 ^{o}S	LOT
17	Waikato	902	340	1635	1980	13	37.86 ^{o}S	LOT
18	East Cape	2000	440	2000	2100	13.8	38.06 ^{o}S	BO
19	Taranaki	2240	60	1540	2114	13.5	39.06 ^{o}S	LOT
20	Taranaki	1680	60	1540	2114	13.5	39.08 ^{o}S	LOT
21	Hawkes Bay	2000	340	1756	2100	11.9	39.24 ^{o}S	MOBL
22	Hawkes Bay	2000	340	1756	2100	11.9	39.24 ^{o}S	MOBL
23	Hawkes Bay	2000	320	1750	1900	11.9	39.28 ^{o}S	MOI
24	Taranaki	765	80	1062	2087	13.6	39.58 ^{o}S	LOT
25	Otago	1250	60	770	1631	10.5	45.83 ^{o}S	RFT

4.3 SECOND-GROWTH STANDS

Seven second-growth stands were used in this study. Second-growth kauri stands were defined as stands that naturally arose on sites previously occupied by kauri. These sites were cleared during early European logging, or earlier burning by Māori. Much of this cleared land included steep slopes and poorer quality soils and was abandoned from agricultural use. Kauri eventually re-invaded these sites from nearby forest where a kauri seed source still existed. Typically these sites would have established a mixed cover dominated by manuka and kanuka prior to kauri germination and establishment. At the initiation of the individual trials a remnant of this cover was often still present (Figure 4.6). The majority of kauri within these stands were predominantly in the ricker or monopodial form typical of younger kauri (Figure 4.6). Some “breakout” into a semi-mature form in a minor component of kauri in individual stands was also occurring. All stands had growth measurements taken from the time that the individual treatments were applied.

The natural stands used in this study covered almost the entire current latitudinal range of the species (Table 4.5, Figure 4.1) and were chosen for their previous history of measurement. The stands were predominantly towards the eastern side of the North Island. Six of the seven stands were originally established as thinning trials (Table 4.5). One stand was a growth plot (Whenuakite). In 1979 the soil in the Mangatangi stand was identified as being nitrogen (N) deficient. On this site treatments established were unthinned control, thinning, and combined thinning/non-thinning fertiliser treatments. The effect of the application of fertiliser treatments (varying rates of N as ammonium sulphate) were short-lived, therefore only the unthinned control and thinned/unfertilised stands were used in this study. Trials located at Herekino Forest, Russell Forest, Great Barrier Island, Whenuakite, and Kaimai Forest Park were on land administered by the Department of Conservation, while the Mangatangi stand was administered by the Auckland Regional Council. At each site kauri was the dominant canopy species prior to and after thinning. Individual site parameters are included in Table 4.6.

Figure 4.6. Mangatangi stand with kauri in ricker form emergent over the remnants of a kanuka and hardwood canopy. Other canopy species on this site were tanekaha, hard beech and rewarewa (*Knightia excelsa* R.Br.).

Table 4.5. Location, treatment, and plot size of second-growth stands (sites are ranked by latitude).

Site	**Region**	**Treatment**	**Plot Area (ha)**
Herekino	Northland	Unthinned Thinned	0.09 0.09
Papakauri	Northland	Unthinned Thinned	0.41 0.41
Kaiarara	Great Barrier Island	Unthinned Thinned	0.10 0.15
Whangaparapara	Great Barrier Island	Unthinned Thinned - light Thinned - heavy	0.18 0.28 0.29
Whenuakite	Coromandel	Unthinned - growth	0.07
Mangatangi	Auckland/Waikato	Unthinned Thinned Thinned/fertilised Unthinned/fertilised	0.02 0.02 0.02 0.02
Waitengaue	Bay of Plenty	Unthinned Thinned	0.117 0.081

Herekino thinning trial – Herekino Forest

The Herekino trial is located above the Waitomo Stream catchment in Herekino Forest, approximately 13 kms southwest of Kaitaia, at 400 m above sea level (a.s.l.). The trial, established in 1936, was one of the earliest of the kauri thinning trials. The trial is comprised of two equal sized (0.09 ha) blocks. The stand was dominated by kauri prior to and after thinning. Diameter, basal area increment and survival are the only parameters to have been measured for this site. Height of kauri was not measured. No estimate of kauri age had been made. Height and age estimates have been made for modeling growth and performance (see Methods Chapter for details). The trial was assessed for a period of 38 years, from 1936-1974.

Papakauri thinning trial – Russell Forest

The Papakauri trial is located in the Papakauri Stream catchment, Russell Forest, approximately 18 kms southeast of Russell. The trial, established in 1963, was a 3.9 hectare block of rolling hill country at 40-160 m a.s.l. The trial consisted of two treatments; an unthinned control and a thinning treatment. Prior to thinning, the stand was dominated by kauri. Other canopy species were tanekaha, rimu (*Dacrydium cupressinum* Lamb.), totara and rewarewa. After thinning, a 0.405-hectare rectangular measurement strip was located within each of the treatments. Kauri in this stand were estimated, from cut stumps, to be on average 138-years-old (Halkett, 1982). The trial was assessed for a period of 46 years, from 1963-2009.

Kaiarara thinning trial – Great Barrier Island

The Kaiarara trial is located in the Kaiarara Stream catchment on Great Barrier Island, approximately 3 kms southeast of Port Fitzroy. The trial, established in 1963, was located on a sheltered broad low-lying ridge at 100-200 m a.s.l., and consisted of paired control and thinning treatments. Prior to thinning, kauri was the dominant canopy species. Competing canopy species recorded in this site included rimu, totara, kanuka, toru (*Toronia toru* (A.Cunn.) L.A.S.Johnson & B.G.Briggs), toro (*Myrsine salacina* Heward ex Hook.f.), and rewarewa. Thinning removed all competing vegetation, leaving an almost pure kauri stand. Kauri were estimated, from increment cores, to be on average 137-years-old (Steward & Kimberley, 2002). The trial was assessed for a period of 35 years, from 1963 to 1998.

Whangaparapara thinning trial – Great Barrier Island

The Whangaparapara trial was established in 1958, and is located to the east of Kaitoke No. 2 Creek in the Kaitoke Creek catchment, approximately 8 kms southeast of Port Fitzroy. The understorey contained tanekaha, rimu and maire (*Nestegis spp.*). A remnant of an over-mature kanuka nurse crop survived in many places through the stand at the time the trial was established. The site was large enough for the establishment of two thinning intensities and one unthinned treatment. All plots were rectangular in shape. The site is 50-100 m a.s.l. Age of the stand was not assessed, however initial early European logging of this site occurred at a similar time to the Kaiarara stand therefore ages of regenerated kauri were presumed to be similar on both Great Barrier Island sites.

Two thinning treatments were applied in this trial; a light thinning and heavy thinning. In the light thinning the old kanuka nurse crop was removed. To prevent the creation of large amounts of thinning slash and to reduce damage to the residual crop, thinning was undertaken by ringbarking the selected stems. Dense groups of pole-size kauri were thinned leaving the better form, larger kauri at more even spacing. In the heavy thinning treatment the kanuka nurse crop was also removed and further kauri were thinned to give the better kauri in the upper canopy level more room for development than in the lighter thinning treatment. The trial was measured for 13 years, from 1958-1971.

Whenuakite growth plot – Coromandel Peninsula

The Whenuakite growth plot is located within a four hectare second-growth stand dominated by kauri and tanekaha. The stand is in the Manuka Stream catchment, in the Tairua hill country (50-150 m a.s.l.), approximately 6 kms northwest of Tairua. The soils are of volcanic origin of low to medium nutrient status. An extensive forest structure and composition monitoring trial was established in 1971 by the NZFS, and reassessed in 1987 (Burns & Smale, 1990). Currently a single 0.072 ha circular growth plot, established in 1997, is being monitored. The kauri was estimated, from increment cores, to be on average 120-years-old (Steward & Kimberley, 2002). The growth plot has been measured over a 13 year period, from 1997-2010.

Mangatangi thinning trial – Hunua Ranges

The Mangatangi trial is located on an east facing slope, in the Mangatangi Stream Catchment, Hunua Ranges, approximately 25 kms east of Papakura. It was established in 1979 to assess the effects of thinning and fertiliser treatments on a second-growth kauri stand (Barton, 1996). Sixteen square 0.01 hectare subplots were established with thinning and thinning/fertiliser treatments randomly allocated. Prior to thinning the site was dominated by kauri, but also contained tanekaha, rimu, rewarewa, towai (*Weinmannia silvicola* Sol. ex A.Cunn.) and hard beech. Fertiliser treatments were applied to thinned and unthinned plots (Barton & Madgwick, 1987). Before thinning, the stand had a mean stocking of 2790 stems/ha greater than 5.0 cm in diameter (range 1800-4800) (Figure 4.7). Thinning of selected plots reduced stocking to 700 stems/ha (Figure 4.8). The kauri was estimated, from increment cores, to be on average 136-years-old (Steward & Kimberley, 2002). The trial was assessed from 1979 to 2010, 31 years. As the current study is focused principally on the growth of kauri and the effect of thinning on second-growth stands, only the unfertilised thinned and unthinned treatments were included from this site.

Figure 4.7. Mangatangi unthinned control plot. Unthinned plots were up to 3300 stems/ha for all species >5.0 cm diameter.

Figure 4.8. Mangatangi thinned plot. Thinning removed the numerous small diameter kauri and other competing species seen in Figure 4.7 above. The small diameter kauri poles that can be seen are in-fill growth that occurred since 1979.

Waitengaue thinning trial – Kaimai Forest Park

The Waitengaue trial, established in 1957, is located on a sheltered moderately steep ridge above the Waitengaue Stream in the Kaimai Forest Park, at 240-300 m a.s.l., approximately 9 kms NW of Katikati. The area around the trial site was originally logged in 1908 (evidence of earlier burning was also reported), although no trees were felled from the immediate trial site. The trial consists of an unthinned control (Figure 4.9), and a thinned treatment. The site was dominated by kauri, but also contained an important component of hard beech, and tanekaha, rimu, and miro (*Prumnopitys ferruginea* (D.Don) de Laub.). Hard beech is known to establish with kauri in the forests of the Waikato (Collins & Burns, 2001), therefore a further aim of the thinning was to maintain and develop a hard beech resource with the kauri. All trees marked for thinning were felled, except for large old hard beech that were ring-barked. The kauri was estimated, from increment cores, to be on average 218 years old (Steward & Kimberley, 2002). The trial was assessed for a period of 51 years, from 1957-2008.

Figure 4.9. Waitengaue unthinned stand. Kauri comprised almost 90% of the canopy on this site, with tanekaha and hard beech (left of figure) being important components of the forest structure. The kauri in this stand averaged 218 years of age.

Table 4.6. Stand and site variables for second-growth kauri stands. Sites are ranked by latitude (north to south).

Stand	Region	Elevation (m)	Annual Rainfall (mm)	Annual Sunshine (hrs)	Daily Mean temp. (^{o}C)	Latitude	Soil Type
Herekino	Northland	350-400	1444	2000	14.6	35.22 ^{o}S	BOT
Papakauri	Northland	40-160	1375	2015	15.1	35.36 ^{o}S	BOT
Kaiarara	Great Barrier Island	100-200	1640	2097	14.8	36.10 ^{o}S	BOT
Whangaparapara	Great Barrier Island	50-100	1637	2105	15.0	36.13 ^{o}S	NO
Whenuakite	Coromandel	100	1941	1984	14.1	36.95 ^{o}S	BOT
Mangatangi	Auckland/Waikato	100-200	1816	1922	13.4	37.12 ^{o}S	UYT
Waitengaue	Bay of Plenty	240-300	2097	1871	13.4	37.50 ^{o}S	BOT

CHAPTER 5

METHODS

5.1 INTRODUCTION

All kauri stands (planted and natural) used in this thesis had a history of measurement prior to the commencement of this study. Much of the early data and information on plot history, where it existed, was held in unpublished permanent records or project reports held by Scion (New Zealand Forest Institute Limited), or was sourced from the owners. These were the planted and natural stands that could be located at the time and for which useful data could be obtained from historical records or were able to be reconstructed for further measurement.

5.2 METHODS

5.2.1 Plot establishment and measurement

Data was obtained using permanent sample plots (PSPs) (Ellis & Hayes, 1991). The size of PSPs used for individual planted stands was determined by the size of the stand and number of stems/ha. Within larger planted stands, more than one PSP was installed e.g. **Stand 3**, **Stand 9**, **Stand 20**. In smaller stands (e.g. **Stand 18**, **Stand 19**) it was difficult to install a standard size sample plot (0.04 ha) (Ellis & Hayes, 1997). However, in these situations, the kauri typically had adjoining forest comprising species of equal stature and similar growth rate. This enabled the use of all stems within a stand, including those that would otherwise be defined as edge-trees (Cancino, 2005).

Not all planted stands initially had data based on PSPs. In 1986, Pardy et al. (1992) used growth plots in planted stands to obtain initial or further data on the height and diameter growth of kauri in planted stands. During the 1986 assessments, all measured trees were tagged. Latterly, PSPs were overlaid to encompass previous growth plots. In second-growth stands pre-existing trials were either converted to PSP status, or had a PSP established (e.g. Whenuakite).

The relationship between stand density and quadratic diameter, commonly known as the self-thinning rule (Reineke, 1933) or Yoda's law (Yoda, et al., 1963), was developed from data from both planted and natural (mature and second-growth) stands where kauri was the dominant species and where full site occupancy was assumed. Temporary plots were established in natural forests of Northland, Auckland, Waikato and Bay of Plenty regions. At each site, stem counts for all species (stand density), and their diameters were obtained. Additional data was obtained from Ahmed &

Ogden (1987) from a study of population dynamics of 25 mature kauri forests throughout the species natural range. For each site the quadratic mean diameter of kauri and stems/ha were calculated. Quadratic mean diameters were plotted against stand density on logarithmic (log) and normal scales.

All plots, except those on Great Barrier Island and the Herekino trial, were re-measured for this study. The Great Barrier Island plots were not remeasured due to costs, while the Herekino thinning trial was not measured due to safety reasons.

Within each PSP, all stems were numbered, and the following information/data were gathered:

- Diameter (cm) at breast height (DBH) of all trees at 1.4 m above ground, on the highest side.
- Total tree height (m) of a selection of trees, with preference to those previously measured for height. Extra heights were measured to cover the range of sizes, where necessary. Early heights were measured using height poles, later with Suunto clinometer and tape, while the latest heights were measured with a digital hypsometer Vertex with transponder.
- Planting pattern
- Current stand density (stems/ha)
- Initial stand density (stems/ha)
- Current stand age (years)
- Record of survival and mortality
- Stand elevation (metres above sea level)
- GPS coordinates

5.2.2 Data Entry and Checking

Data were entered into individual Excel spreadsheets, by site. Individual stems were followed over a time series for height and diameter. Many of the early measurements of the oldest stands (planted and natural) were in imperial units. These were converted to metric units in Excel using the conversion factors in Table 5.1

Data were plotted to identify errors in measurement, transcription, or conversion from imperial to metric units. Data that appeared to be anomalous were checked against their original sources and corrected, where necessary. Excel spreadsheets were produced that combined summarised plot data for all planted and natural stands in a form compatible with SAS (Statistical Analysis Software – SAS Institute Inc., Cary, NC, USA) analysis.

Table 5.1. Conversion factors from imperial to metric units for height, DBH and area.

Height – feet into metres	H x 0.3048
DBH – inches into centimetres	D x 2.54
Area – acres into hectares	1 acre = 0.4046856 hectares

5.3 ANALYSIS

5.3.1 Constraints

The data for this study were obtained from PSPs in 25 planted stands located on a range of sites throughout New Zealand, and seven second-growth natural stands. The planted stands used for this study were the most developed stands for this species that could be located. Other, very young plantings (1-5 years of age) were located during the time of this study but were considered to be too young to yield useful data for the study, given the often extended and variable nature of establishment of kauri reported earlier. Further trials within second-growth forest that contained a thinning component are known to exist, particularly in the Waipoua Forest area, however either their data and or location were not able to be determined.

5.3.2 Planted Stands

The majority of planted stands used in this study represent stands that were established without the aid of a nurse crop or over-storey species as described by Bergin & Gea (2007). Where a vegetative cover existed at establishment, the developing stands were expected to have received only minimal, if any, benefit from the existence of the cover on the individual sites.

The planted kauri stands used in this study were not necessarily planted or managed for the purpose of growing timber, nor were they established for the purpose of developing models of growth and yield. The assessment of the stands did not follow a regular pattern of measurement at set intervals. Some stands were measured almost annually for long periods of time, while other stands were measured irregularly with large temporal gaps between each measurement. The number of planted stands included in this study is small when compared with datasets for other commercial forestry species.

Only two planted stands have been thinned (**Stands 19** & **20**). Thinning occurred in 2002 (**Stand 19**) and 2004 (**Stand 20**), when stand density was still well in excess of 1000 stems/ha. Stand development at the time was significantly affected by their high stand density. The thinning prescription did not define a uniform stand density to improve the growth rate of kauri or the development of timber. Prior to thinning, the incidence of multi-leadering was 0-70% and intense competition had caused kauri crowns to collapse due to shading. Thinning was only to remove all double- or multi-leadered stems and, when completed, resulted in an extremely variable stand density. After thinning, kauri was left with much less competition, but with only a small residual crown. Where no substantive thinning occurred, kauri growth has continued to stagnate. The current post-thinning data was comprised of two measurements for **Stand 19** and one for the larger **Stand 20**. The data was not sufficient in size, quality or time since thinning to develop a thinning function for planted kauri.

5.3.3 Second-growth stands

Second-growth stands were chosen on the basis of them having complete (as far as possible) stand history and measurement records, and being physically easily located. They each had a history of comparing thinned and control treatments (excluding Whenuakite). While most of the second-growth stands were thinned, it was not the purpose of this study to develop a thinning function for second-growth stands. A thinning function may be developed in a future study.

To enable comparison between stands, stand types and treatments, all plot measurements were converted to a per hectare basis, and mean top height (MTH), mean top diameter, quadratic diameter, basal area/ha, volume/ha, and survival/mortality were calculated.

5.3.4 Age

All planted stands were of known age. Ages of second-growth stands were obtained from increment cores by Steward & Kimberley (2002) for the Whenuakite, Kaiarara, Mangatangi and Waitengaue stands, and from Halkett (1982) for the Papakauri stand. The Whangaparapara stand had a similar logging and site occupancy history to that of the Kaiarara stand. For this study it was therefore assumed to be similar in age. Stand age was not determined for Herekino by increment core or assessment of cut stumps. No comparable stands were assessed in close proximity. An age for this stand was derived by fitting a regression curve to the age and diameter data for all other natural stands combined.

5.3.5 Height/Diameter/Basal area

Mean top height and mean top diameter were calculated as the average height and diameter respectively of the 100 largest-diameter stems/ha. Average tree diameter was defined as quadratic mean diameter (Equation 5.1), as the quadratic mean diameter is better correlated to stand volume than the arithmetic mean (Curtis & Marshall, 2000). Basal area was calculated as the sum/hectare of cross-sectional stem area at breast height (1.4 m).

$$\textit{Quadratic mean DBH} = \sqrt{\frac{\sum_{i=1}^{n} dbh_i^2}{n}} \qquad \text{(Equation 5.1)}$$

Height and diameter curves were graphed in Excel (MS Excel 2007) for each stand at each measurement period. A non-linear regression curve was fitted for height and diameter for each measurement period. The regression equation for each site and each measurement was used to estimate total tree height of stems that were not measured. Estimated heights were entered onto the database.

Diameter distribution was assessed using the Anderson-Darling test of normality in Minitab 15 (Minitab Statistical Software, 2000). Diameter distributions were tested on individual stands with diameters from their last assessment.

5.3.6 Volume

Total standing volume per hectare was calculated as the sum of individual tree volumes predicted by the pole-kauri volume table (Ellis, 1979) (Equation 5.2). Volume mean annual increment (MAI) was calculated for each measurement within each sample plot.

$$\text{Whole-tree volume for pole-kauri} = 2.070654\,\mathrm{LN}(D)+0.838619\,\mathrm{LN}(H)-3.138731 \qquad \text{(Equation 5.2)}$$

where D = diameter at breast height,
H = total tree height,
LN = Natural Log

CHAPTER 6

SUMMARY OF THE DEVELOPMENT OF KAURI IN PLANTED STANDS

6.1 INTRODUCTION

Kauri has been planted, to various extents, almost since European discovery of the species (Steward & Beveridge, 2010). Reasons for planting have been varied, but often included (or did not preclude) the long-term option of providing a resource of specialty timber. Kauri was usually planted as small (<2.0 ha), even-aged single-species stands across a range of site types (Pardy, et al., 1992). Many were established outside of the described current natural range of the species (Sando, 1936a). All plantings identified with a forestry option were initiated without any knowledge of rotation length or eventual potential outcome. Factors that influence decisions to invest in kauri plantations are information on rotation lengths and predictions of recoverable volumes (Herbert, et al., 1996). Little has been known about the performance of kauri grown in planted stands.

Halkett (1982) summarised the amount of kauri planted by the New Zealand Forest Service from 1974-1983 (estimated 780 ha) but made no comment on their early performance. In the 1980s, a comprehensive survey of native tree plantings was undertaken. Growth information for height and diameter was obtained for a number of kauri plantings (Pardy, et al., 1992). The survey provided a glimpse at the potential performance of kauri on a range of sites. However, the study failed to obtain information on basal area and volume development. Herbert et al. (1996) measured kauri on two Taranaki sites (aged 60) and developed a growth and productivity model for kauri. These stands were at high stand density (in excess of 1300 stems/ha) and extrapolated results to age 120 appeared to be high, particularly for basal area. The predictions were not tested against other kauri plantings and were therefore not necessarily reflective of the species overall performance.

In 2002, anecdotal reports were received about a young planted kauri stand in the Bay of Plenty where extraordinary growth in height and diameter were being observed, but not measured. Permanent sample plots were installed into the stand in 2003 to record performance. Measurements of the PSPs from 2004-2009 confirmed the unusual growth reported earlier, and that the growth continued to be well above that recorded in any other planted stand.

These previous studies left a tantalising image of a native conifer performing over and above any data previously recorded and well in excess of the erroneous and anecdotal information that plagues the establishment for management of this species. This chapter contains the data from the measurements of 25 individual planted kauri stands. This is the largest dataset for planted kauri yet compiled. The data has been broadly analysed in this chapter with the objective of identifying trends in height and diameter growth, and basal area and volume development. The development of stand-level models of growth and productivity of kauri in planted stands occurs in a later chapter (Chapter 8).

6.2 METHODS

The per-hectare summary data consisted of 121 plot measurements from 31 PSPs within 25 planted kauri stands in New Zealand. Detailed descriptions of the methods for data capture, testing and analysis for kauri grown in planted stands are contained in Chapter 5. All PSPs were measured at least twice, although at irregular periods. At each assessment, total height, diameter and survival were measured, with development of basal area and volume calculated from those measurements. This study has focussed on the development of kauri at the stand-level, therefore the variables of height, basal area and volume have been emphasised.

Unmeasured heights were estimated by fitting non-linear regression curves to the height and diameter data for each stand, and for each measurement period. Power curves were found to give the best fit. Individual equations were used to estimate heights for the individual measurement periods. Diameters were measured for all stems at each assessment. Diameter distribution at the last assessment was plotted for each stand. Diameter was normally (Anderson-Darling test of normality) or near-normally distributed in 75% of planted kauri stands. Volume was calculated as whole-tree volume. Volumes were calculated using the pole-kauri equation(Equation 5.2) (Ellis, 1979).

To highlight the potential for the species represented by a high-performing stand located in the Bay of Plenty (**Stand 16**), the performance and development data for this stand has been presented separately in this chapter and compared with all other stands.

6.3 RESULTS

6.3.1 Description of Permanent Sample Plots and Sites

At the first assessment stands ranged from 4-71 years, and from 12-83 years at the last assessment. Ten stands were in the 50-59 age class and reflected a major plantation programme by the NZFS in the 1950s. Individual stands in this study were observed for periods of 2-50 years.

At planting, stands ranged from 320-2240 stems/ha (mean 1096) (Table 6.1). Site elevation averaged 117 m above sea level, but was as high as 440 m for **Stand 18**, and as low as 20 m for five stands. Stands planted outside the species natural range averaged 217 m elevation. Annual rainfall averaged 1495 mm. Highest rainfall occurred at the site with the highest elevation (**Stand 18**). Average annual sunshine hours was 2031 hours. The most southern stand (**Stand 25** - 45.83 °S), recorded the lowest sunshine hours (1631 hours), it also had the lowest daily mean temperature (10.5 °C) and the lowest annual rainfall (770 mm).

Table 6.1. Initial stand density and site characteristics of all planted kauri stands.

	Initial stand density (stems/ha)	Elevation (m)	Annual Rainfall (mm)	Annual sunshine hrs	Daily mean temp (°C)	Latitude (°S)
Mean	1096	117	1495	2031	14.0	37.44
Min.	320	20	770	1631	10.5	35.16
Max.	2240	440	2000	2260	15.7	45.83
s.e.	101.8	21.1	54.6	23.2	0.2	-
s.d.	566.8	117.4	304.1	129.1	1.2	-

At their last assessment stands averaged 55.4 years of age and were at a stand density of 853.2 stems/ha (Table 6.2). Mean diameter for all stands was 31.7 cm and mean top height was 19.7 m. Basal area of all stands averaged 65.0 m^2/ha. Whole-tree volume averaged 577.1 m^3/ha. Volume mean annual increment for all stands was 9.9 m^3/ha/yr, but was as high as 17.6 m^3/ha/yr. Results for each stand are contained in Appendix 1.

Table 6.2. Mean performance of kauri in planted stands at their last assessment.

	Age (years)	Stand density (stems/ha)	Quad. mean DBH (cm)	Mean Top DBH (cm)	Mean top height (m)	Basal area (m^2/ha)	Volume (m^3/ha)	Volume MAI (m^3/ha)
Mean	55.4	853.2	31.7	39.3	19.7	65.0	577.1	9.9
s.d.	18.6	425.7	11.3	12.7	5.7	31.5	314.6	4.8
s.e.	3.2	79.1	2.1	2.4	1.1	5.9	58.4	0.9
Min.	12	218	7.6	12.6	6.1	2.7	9.2	0.52
Max.	83	1845	51.9	61.8	29.1	104.6	1175.9	17.6

6.3.2 Growth of kauri

Height

Actual heights were compared to estimated heights and residuals were plotted (Figure 6.1). For estimated heights, 91% were within 1.5 m of the mean, and 80% were within 1.0 m of the mean.

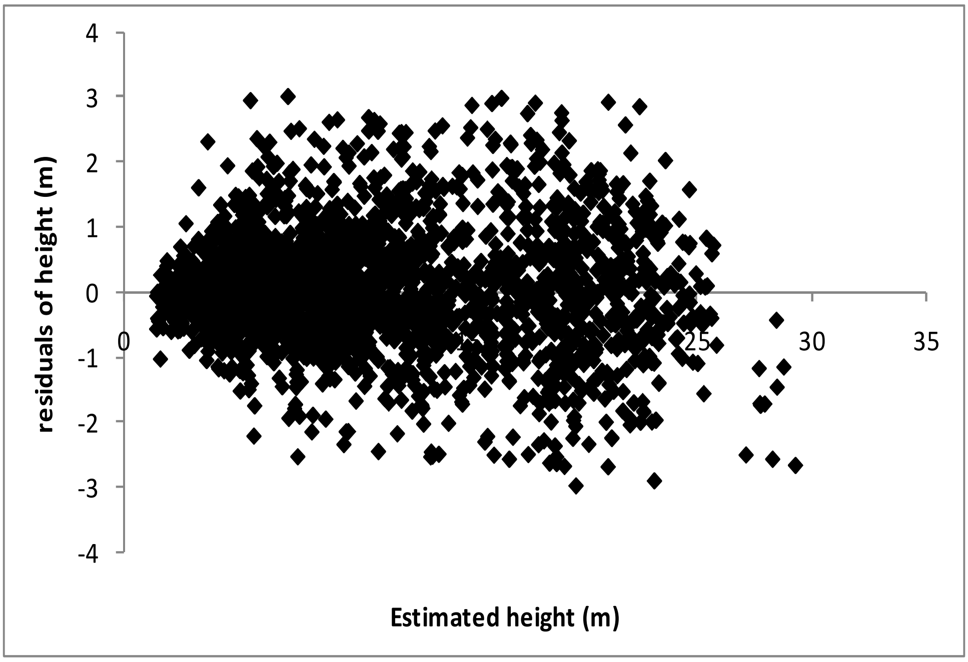


Figure 6.1. Unmeasured heights were estimated from nonlinear regression curves fitted to height/DBH data. Estimated heights were compared to measured heights with 80% of the residuals being within 1.0 m of the mean (RMSE = 0.9, mean = 0.044).

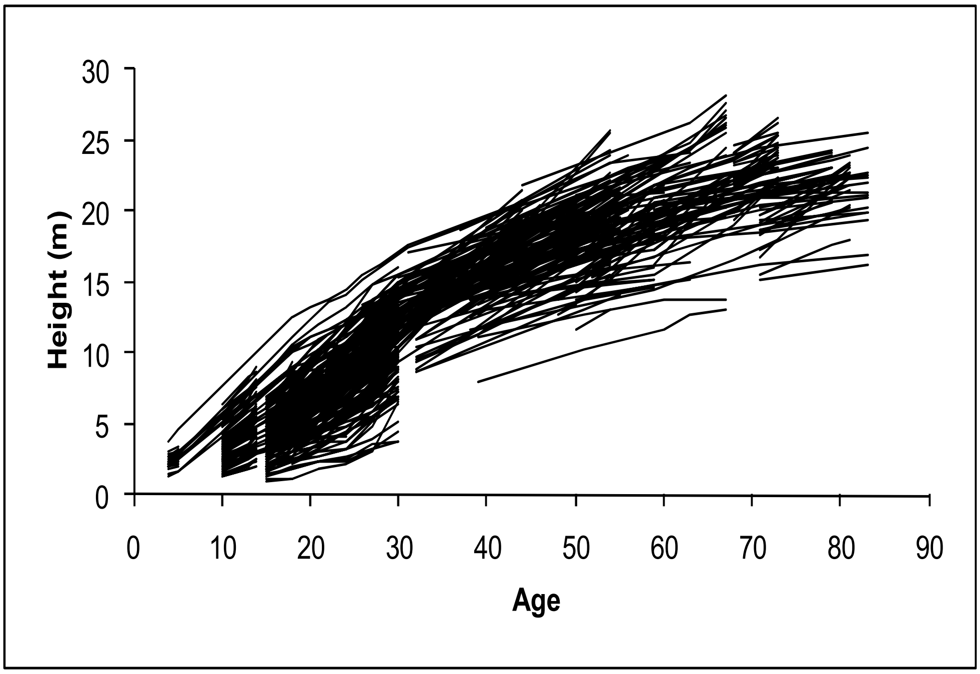


Figure 6.2. Height development of individual kauri in all planted stands. Height growth for stands averaged 0.39 m/yr, but was as high as 0.56 m/yr.

Height increment averaged 0.39 m/yr over all sites. Mean top height averaged 10.2 m by age 30, 14.0 m by age 50, and 17.5 m by age 60 (Figure 6.2). Stands from 12-49 years averaged 0.5 m/yr for height increment, with those >50 years averaging 0.36 m/yr. The greatest height MAI (0.56 m/yr) was in **Stand 8** (age 14, 1008 stems/ha). The lowest height MAI (0.27 m/yr) was in **Stand 24** (age 83, 630 stems/ha). By age 70, height increment was consistently less than 0.3 m/yr. Mean annual height increment was similar in stands that were within and outside the species natural range. Height growth was not affected by stand density.

Diameter

The mean diameter increment was 0.62 cm/yr for all stands (Figure 6.3). Three stands had diameter MAI >0.8 cm/yr (**Stands 17, 15, 14** - 902, 519, 320 initial stems/ha respectively). For all stands <600 stems/ha at their last measurement, diameter MAI exceeded 0.7 cm/yr. Stands >1000 stems/ha had a diameter MAI of 0.53 cm/yr.

Stands where diameters were not normally distributed had larger average diameters (39.1 v. 31.2 cm), and were older than stands with normal distribution (64.5 years v. 50.5 years). Stand density was also higher (886 v. 804 stems/ha), while the height/DBH relationship was weaker.

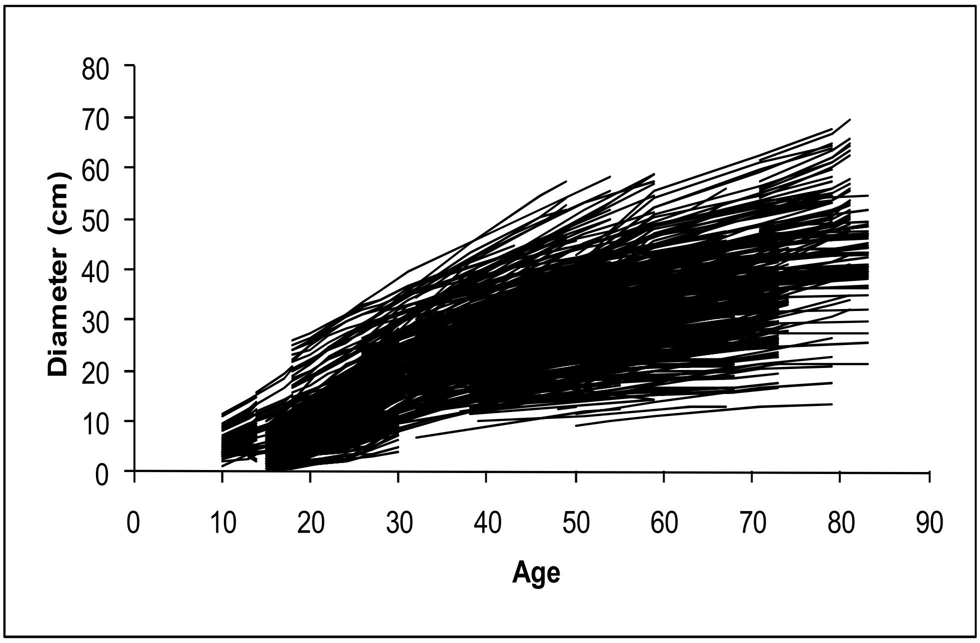


Figure 6.3. Diameter development of individual kauri in all planted stands. Diameter growth showed some relationship to stand density with DBH increment affected by high stand density.

Diameter/Stand Density Relationship

Data from 49 stands (planted and natural), where full site occupancy was assumed, were combined and a regression equation was fitted (Equation 6.1). The data was graphed on normal and logarithmic (log) scales (Figure 6.4). The relationship of mean quadratic diameter against stand density in both planted and natural stands was similar (r^2 0.8883).

$$\text{Quadratic mean diameter} = 660.69 \text{x} SD^{-0.456} \qquad \text{(Equation 6.1)}$$

Where SD = current stand density

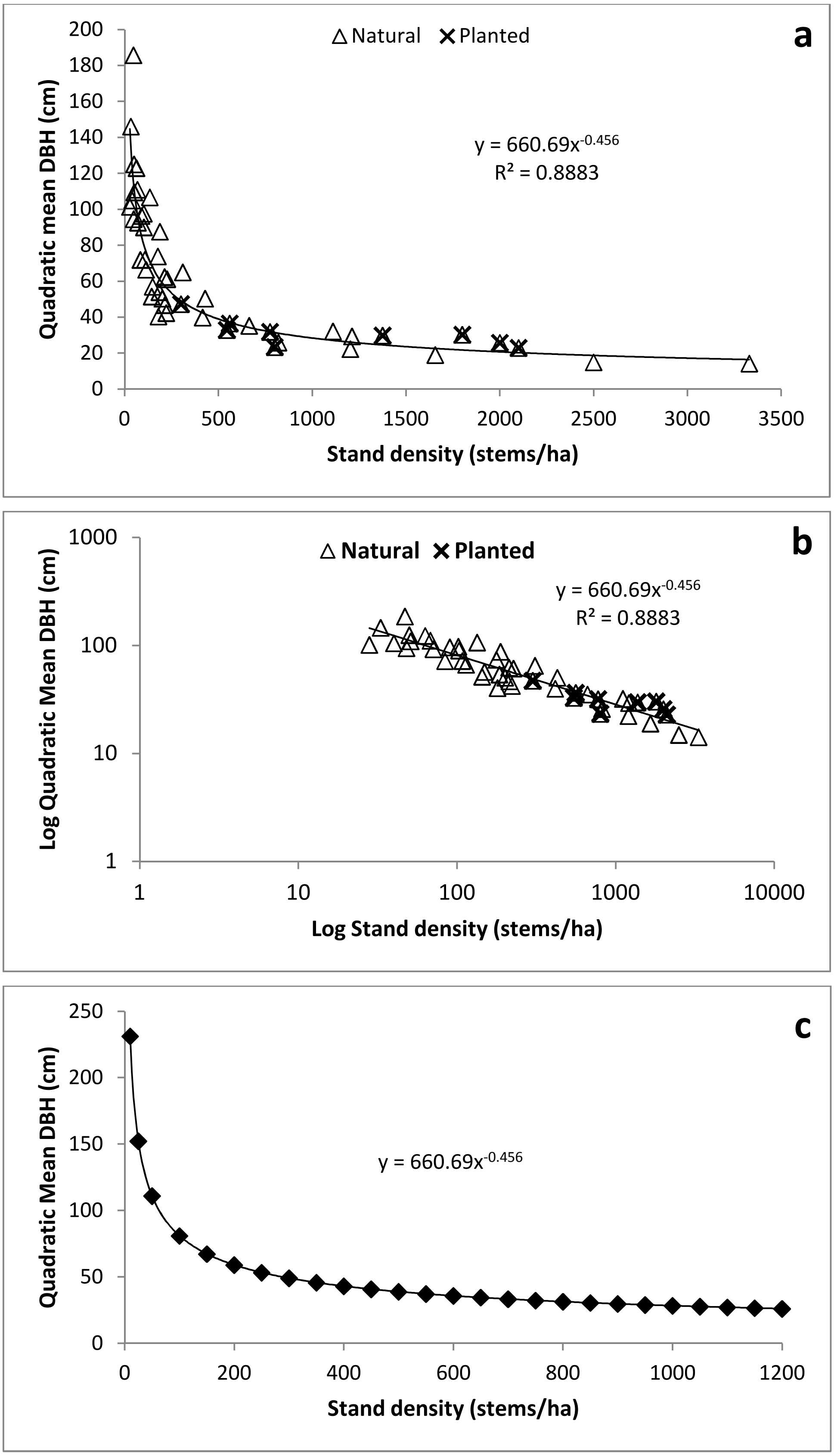


Figure 6.4. Relationship of quadratic mean diameter with stand density for 49 planted and natural stands assumed to be at or near full site occupancy on normal (a) and log scales (b), with predicted quadratic mean diameter plotted for stand density between 10-1200 stems/ha (c).

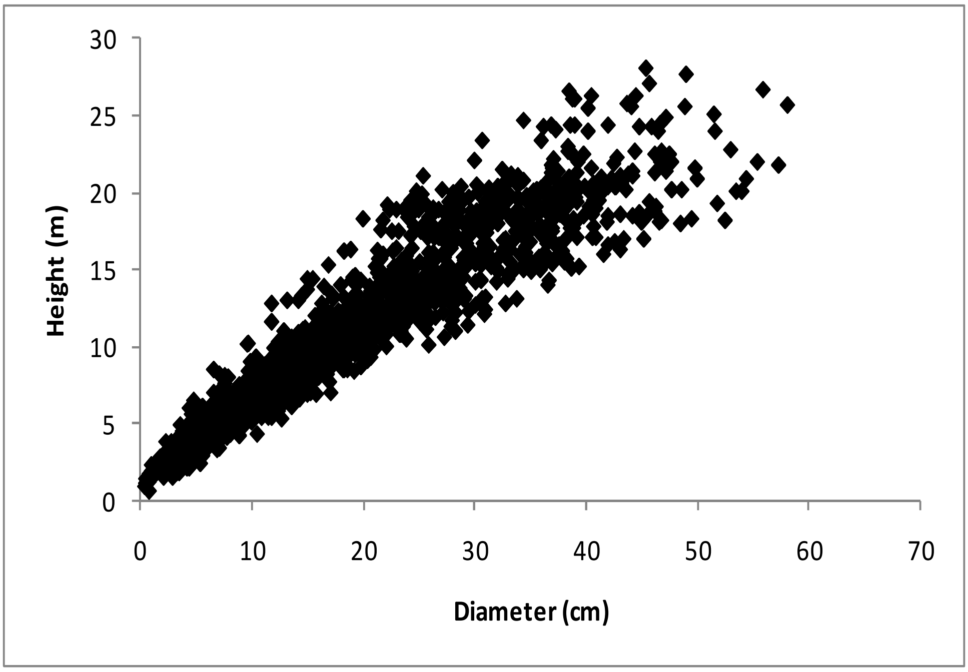


Figure 6.5. Height and diameter relationship of kauri in planted stands. The relationship was strong in young stands but is not supported when individual trees age and where kauri begin to move into a mature form.

Height/Diameter Relationship

Height and diameter were strongly related (Figure 6.5). The height/DBH relationship was strongest in stands <55 years of age e.g. **Stand 11** (age 30), **Stand 7** (age 18). A weak height/DBH relationship existed for older stands e.g. **Stand 12** (age 79), and older stands that were only measured over short time intervals e.g. **Stand 24** (age 83, height MAI 0.27 m/yr).

Basal Area

The maximum basal area was 103 m^2/ha in **Stand 21** (age 51, stand density 1800 stems/ha) (Figure 6.6). Basal area MAI across all stands was 1.16 m^2/ha, but was as high as 2.03 m^2/ha/yr (**Stand 21**). Basal area reached its maximum by age 50. Basal area MAI peaked between ages 45-70 years.

Basal area mean annual increment was higher in regions outside the species natural range. However, the stands outside the species natural range averaged 1228 stems/ha at their last measurement, and 645 stems/ha for those within the species natural range. The higher basal area increment for the stands outside the species natural range was therefore related to stocking rather than a latitudinal influence.

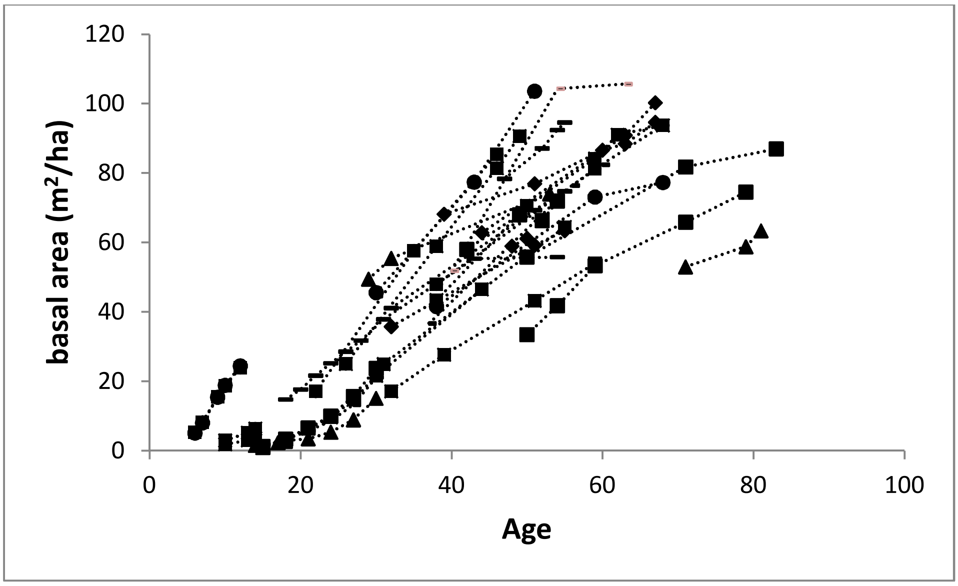


Figure 6.6. Basal area development in all kauri planted stands. Basal area was slow to develop for the first 20 years, but peaked at 2.03 m^2/ha/yr.

Volume

Whole-tree volume averaged 596.4 m^3/ha for all planted kauri stands. The highest volume and volume MAI was in the 67 year-old **Stand 4** (1184 m^3/ha, 17.67 m^3/ha/yr) (Figure 6.7). The lowest volume was in the 18 year old **Stand 7** (10.0 m^3/ha, 0.55 m^3/ha/yr). Volume MAI averaged 10.3 m^3/ha/yr for all stands. Volume exceeded 800 m^3/ha (MAI 12.9 m^3/ha/yr) in stands that averaged 62 years and 1169 stems/ha. By age 30, kauri in planted stands had not exceeded 4.5 m^3/ha/yr MAI, and by age 50 MAI averaged 7.3 m^3/ha/yr.

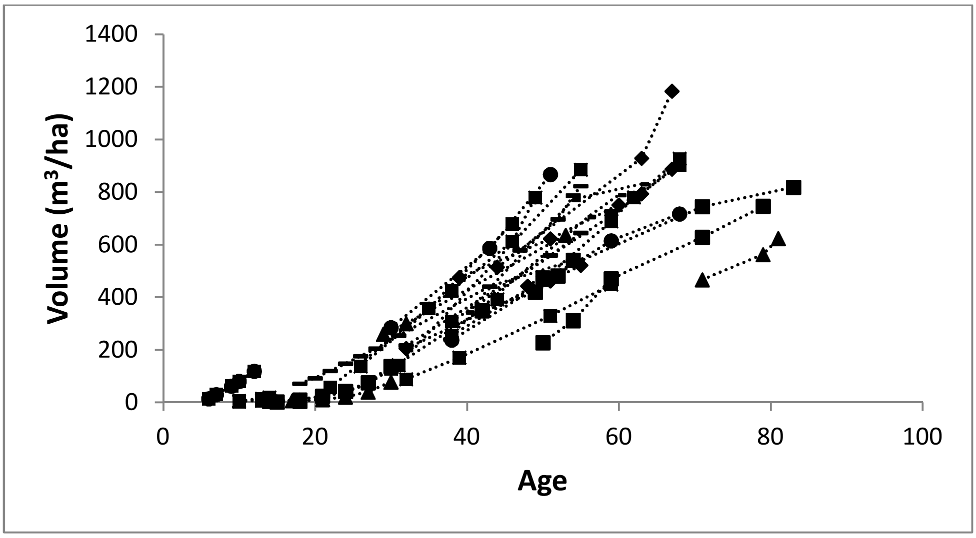


Figure 6.7. Volume increment by age for all sites and measurements (based on whole-tree volumes). Volume was slow to develop in the majority of stands for the first 20-25 years. Maximum volume increment was 17.67 m^3/ha/yr.

Mortality

Mortality averaged 22.3% (range 0.0-52.5) in all stands. Stands with a higher initial stand density had higher overall mortality. Stands >1000 stems/ha initial stand density had a mean mortality of 25.7%, while those <1000 stems/ha had a mean mortality of 18.2%. From planting to age 30, an average of 15.7% mortality occurred, although this included mortality of 51.2% in the 18 year-old **Stand 7**. When **Stand 7** was excluded, average mortality to age 30 was 8.6%. By age 50, mortality in all stands was 16.1%, increasing to 22.2% by age 70. Where mortality was attributable to an identifiable cause (drought – **Stands 7 and 23**; disease – **Stand 15**), mortality averaged 44.1%.

Stand 16 (Comparison with all other planted stands)

At the last assessment for **Stand 16** (age 12), mean top height was 11.0 m and mean diameter was 22.3 cm (Table 6.3, Figure 6.8, Figure 6.9). Height MAI was 0.92 m/yr since planting, but was as high as 1.1 m/yr. Diameter MAI was 1.85 cm/yr since planting, but was as high as 2.6 cm/yr. Basal area at age 12 was 24.2 m^2/ha (MAI 2.02 m^2/ha). Volume at age 12 was 118 m^3/ha (9.8 m^3/yr).
When compared to all other stands, height increment in **Stand 16** was 2.4 times faster, and almost 3 times better for diameter increment (Table 6.3). At age 12 years its growth and productivity was similar or better than kauri in planted stands that were up to 30 years of age. Kauri up to 30 years of age had volume production of 0.12 m^3/stem, while in Stand 16 individual stems were producing 0.19 m^3/stem at age 12.

Table 6.3. Comparison of height, diameter, basal area and volume performance between Stand 16 and all other planted kauri stands in age bands.

Stand	**Age (years)**	**Ht (m)**		**DBH (cm)**		**Basal Area (m^2/ha)**		**Volume (m^3/ha)**		**Current Stand Density**
		Mean	MAI	Mean	MAI	Mean	MAI	Mean	MAI	
Stand 16	12	11.0	0.92	22.3	1.85	24.18	2.02	118	9.87	621
Stands 14-30 years	23	10.4	0.45	16.1	0.69	12.1	0.47	65	2.35	554
Stands 30-60 years	52	20.4	0.39	34.4	0.66	72.6	1.40	638	12.29	903
All Stands	54	20	0.39	33.1	0.63	65.5	1.16	596.4	10.3	804

Stand 16 had the lowest elevation of all planted sites (20 m a.s.l.) (Table 6.4). Annual sunshine hours for this stand were higher, by 6.9% over the next best sites (**Stands 19 and 20**) and 12.3%

better than the average sunshine hours for all planted stands. **Stand 16** had the third lowest rainfall of all planted sites. However, the kauri received irregular irrigation during dry summer months. Most importantly, **Stand 16** occupied a retired kiwi fruit orchard and benefitted from modified soil horizons and high soil fertility, although the level of fertility was residual to its previous horticultural use.

Table 6.4. Comparison of site variables between Stand 16 and all other planted stands.

Stand	Initial Stand density (stems/ha)	Elevation (m)	Annual Rainfall (mm)	Annual Sunshine (hrs)	Daily Mean temp. (0^C)	Natural Soil fertility
Stand 16	625	20	1198	2260	14.4	3.0
All	1099	135	1498	2012	13.9	1.6

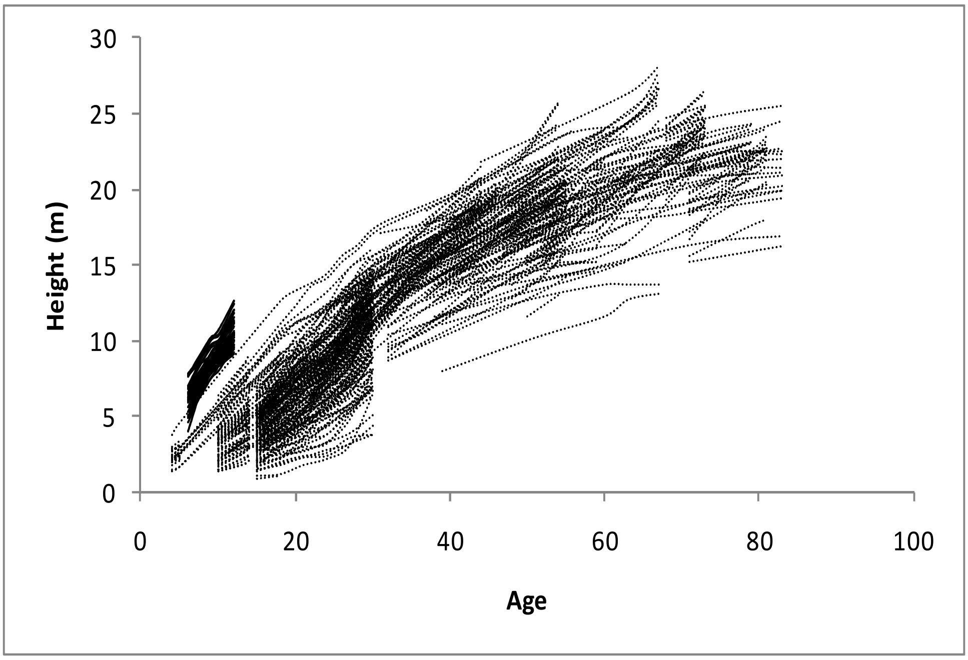


Figure 6.8. Stand 16 height development in comparison to all other planted kauri. Solid lines represent Stand 16; dotted lines represent all other planted kauri stands.

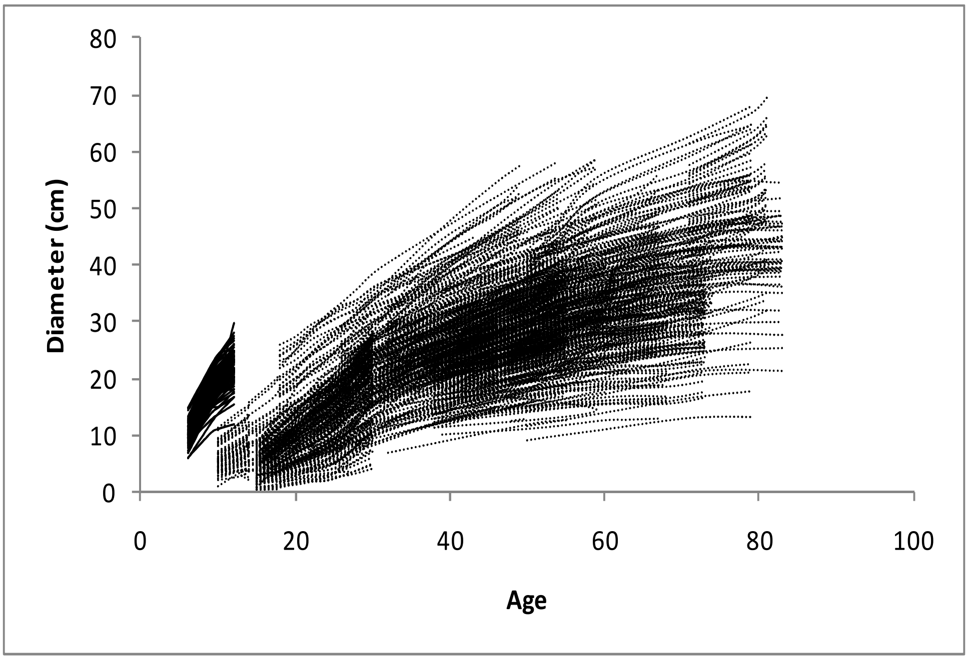


Figure 6.9. Stand 16 diameter development in comparison to all other kauri. Solid lines represent Stand 16; dotted lines represent all other planted kauri stands.

6.4 CONCLUSIONS

Strong general trends were seen in the data for planted kauri stands, particularly for height growth, the relationship of height and diameter, the ability to estimate height from diameter, and the relationship of diameter to stand density. These trends are relevant to the species while in the monopodial or ricker form.

Height growth of kauri in planted stands showed little variance across a range of sites, and particularly over a range of stand densities. Kauri at 320 stems/ha in urban reserves in Auckland grew at a similar rate to those at 2000 stems/ha near the East Cape, and to those at 875 stems/ha on the Taieri Plains to the south of Dunedin. The relationship of height (m) and diameter at breast height (cm) is strong while kauri is still in the ricker form. Estimating total tree height from height/DBH curves for individual stands gave an acceptable level of accuracy where the majority of estimated heights were within 1.0 m of the mean of the residuals. The height/DBH relationship began to show signs of breaking down in older stands (70+ years), or in with low density stands (<400 stems/ha) where kauri began to develop open-crown form more typical of mature kauri.

Diameter mean annual increment in excess of 1.0 cm/yr for more than measurement period had not previously been recorded for kauri. Diameter MAI in **Stand 16** had not fallen below 1.7 cm/yr for the six years that it was assessed, and had been as high as 2.6 cm/yr for periodic mean annual increment. Height MAI in this stand was also higher for a sustained period than had been previously recorded, and was not below 0.9 m/yr since measurement began.

The relationship of mean stand diameter and stand density had not previously been investigated for planted kauri. The relationship was strong for both planted and natural stands of kauri in a combined data set. This relationship indicated the point at which mean stand diameter and basal area increment slows, and where self-thinning would occur unless thinning was undertaken. Using a simple visual assessment of observed full site occupancy resulted in little deviation of stands assumed to be at or near the self-thinning line. Six of the current planted stands had reached the self-thinning line and had a current annual increment of 0.38 cm/yr against a mean of 0.61 cm/yr MAI for all stands.

Survival in the planted kauri stands was generally high, irrespective of the lack of after planting maintenance or silviculture applied to the stands. This result is in opposition to the usual assumption of the difficulty of establishment of kauri and presumptions of high mortality.

In general the results found in this initial analysis of the data have shown a greater level of productivity than has previously been recorded for the species, for all of the variables of growth and productivity measured.

CHAPTER 7

SUMMARY OF THE DEVELOPMENT OF SECOND-GROWTH KAURI STANDS

7.1 INTRODUCTION

Much of the difficult country initially cleared for agriculture was abandoned and quickly reverted to a native vegetation cover. Substantial areas became second-growth kauri forest where a seed-source remained in close proximity (Steward & Beveridge, 2010). The area of well-established second-growth kauri in New Zealand has been estimated to be 60 000-100 000 hectares (Erne Adams, 1973; Lloyd, 1978; Halkett, 1982). Stand density in these second-growth stands frequently exceeded 1000 stems/ha for all species greater than 5-10 cm diameter, and sometimes approached 5000 stems/ha (Steward & Kimberley, 2002). The development of those stands was expected to be protracted and uncertain, without intervention.

In the 1930s the first of a series of kauri thinning trials was established in Herekino Forest (Sando, 1936a, 1936b). Later, the New Zealand Forest Service (NZFS) silviculturally treated a further (estimated) 5000 hectares of second-growth forest in Russell Forest and on Great Barrier Island. The objective was to shorten succession time by releasing young kauri from a competing over storey (Whitmore, 1977). Further thinning trials were initiated in Russell Forest, Great Barrier Island, the Hunua Ranges and Kaimai Forest Park between the late 1950s and late 1970s. These trials aimed to reduce within-stand competition and to improve the performance and quality of retained kauri stems. At Russell and Hunua, thinned kauri and other merchantable species were harvested, while on Great Barrier Island all stems were felled to waste (Halkett, 1982; Barton & Madgwick, 1987). At Hunua, thinning was combined with fertiliser applications in second-growth kauri forest (Barton & Madgwick, 1987).

Thinning of second-growth stands was predicted to increase diameter growth of kauri by about three times that of untreated stands (Barton, 1996). Diameter growth was also expected to be variable, based on site and competition factors, but was estimated to be in the order of 0.25-0.65 cm/yr. Height growth was assumed to be in the order of 0.25-0.50 m/yr (Barton, 1999). Halkett (1982) summarised the productivity of the second-growth resource. Data was limited, and productivity was assumed to vary widely. In well-stocked but untended stands, productivity was estimated to be 5-9 m^3/ha/yr. Thinning and/or fertilising was assumed to increase productivity to an estimated 6-10 m^3/ha/yr.

Where second-growth kauri forest is still predominantly in the ricker form it is the nearest natural forest to relatively young planted stands of kauri. It provides a baseline of growth and productivity against which the performance of planted kauri can be compared. Seven of the trials established in second-growth stands were selected as being representative of the species over its latitudinal range. These were some of the oldest trials in second-growth kauri forest. Six of the seven stands included a thinning treatment.

This chapter contains the data from the measurements of seven individual second-growth stands of kauri. It is the first instance that these trials have been combined, and comprise the largest dataset for second-growth stands yet compiled. The chapter describes the dataset and looks for broad trends in height and diameter growth, and basal area and volume development, and the effect of thinning. The development of stand-level models of growth and productivity of kauri in second-growth stands occurs in a later chapter (Chapter 8).

7.2 METHODS

The per-hectare summary data consisted of 51 plot measurements from 13 PSPs within seven second-growth stands. Detailed site descriptions are contained in Chapter 4, while descriptions of the methods for data capture, testing and analysis for kauri in second-growth stands are contained in Chapter 5. All PSPs were measured at least three times, although at irregular periods. At each assessment, data on total height, diameter and survival were measured. The development of basal area and volume were calculated from those measurements. In six of the seven second-growth stands, all trees greater than 5.0 cm DBH were measured and identified by species. At Whangaparapara, only kauri was identified by species, but all species were measured. This study has focussed on the development of kauri at the stand level, therefore the variables of height, basal area and volume have been emphasised.

Age of individual kauri and mean stand age in second-growth stands were initially estimated from 5.0 mm increment cores taken at 1.4 m above ground from the Mangatangi, Whenuakite, Waitengaue and Kaiarara study sites. Increment cores were taken at breast height from a selection of stems that represented the diameter range of each stand. Ages for stems not cored were calculated by fitting non-linear regression curves to diameter and estimated age data. Power curves were found to give the best fit to the data. Missing ages were calculated (calculated age). Ages for kauri in second-growth stands in this study were age-at-breast-height. No allowance was made for the time taken for individual kauri to reach 1.4 m in height. The height/age curve for kauri in control stands suggests that to reach 1.4 m in height could take 25 years.

Individual kauri heights not measured during PSP measurements were estimated by fitting non-linear regression curves to the height and diameter data for each stand, and for each measurement period. A Power curve gave the best fit to height/diameter data. Estimated heights were calculated for the individual measurement periods. Volume was calculated as whole-tree volume. Volumes were calculated using the pole-kauri equation (Equation 5.2) (Ellis, 1979).

Table 7.1. Stand composition of second-growth stands (unthinned control stands only) by site, at the first and last assessments. Sites arranged north to south.

Stand*	First assessment Species composition			Last assessment Species composition		
	% kauri	**N kauri/ha**	**Total stems/ha**	**% kauri**	**N kauri/ha**	**Total stems/ha**
Unthinned						
Herekino	100.0	903	903	100.0	854	854
Papakauri	60.8	225	370	61.6	225	365
Kaiarara	41.5	830	2000	62.8	810	1290
Whangaparapara	33.0	205	622	100.0	194	194
Whenuakite	53.0	378	713	55.2	378	685
Mangatangi	78.6	2200	2800	77.8	2450	3150
Waitengaue	89.6	1692	1889	97.2	1180	1214
All	**65.1**	**919**	**1328**	**79.2**	**870**	**1107**
Thinned						
Herekino	100.0	371	371	100.0	371	371
Papakauri	95.9	116	121	95.8	114	119
Kaiarara	97.0	224	231	97.0	224	231
Whangaparapara light thin	85.3	587	688	100.0	587	587
Whangaparapara heavy thin	73.6	345	469	100.0	345	345
Mangatangi	100.0	700	700	82.9	1700	2050
Waitengaue	53.5	370	691	76.1	667	877
All	**86.5**	**387**	**467**	**93.1**	**573**	**654**

*The results for thinned stands excludes the Whenuakite stand where no thinning treatment was applied, but includes two thinning intensities at Whangaparapara.

7.3 STAND COMPOSITION

Kauri averaged 65.1% of the tree species >5.0 cm DBH prior to thinning (range 33.0-100.0%) in all stands (Table 7.1). Other species recorded were competing canopy species (e.g. tanekaha), or were remnants of the original nurse crop (e.g. kanuka), or were in-fill growth of sub-canopy species normally associated with a kauri dominated forest structure.

Thinning to reduce competition, and to create a more uniform spatial separation between individual kauri stems, resulted in kauri increasing as a percentage of the species composition in all stands except the Mangatangi stand (Table 7.1). The number of kauri/ha remained comparatively constant from the first to last assessment in all stands except Mangatangi and Waitengaue where considerable in-fill growth of kauri was recorded during their measurement periods.

7.4 RESULTS

7.4.1 Description of plots and stands

At the first assessment stands ranged from 83-146 years, and from 114-196 years at the last assessment. Individual stands were observed for periods of 13-50 years. When trials were established, stands ranged from 205-2200 stems/ha (mean 919 stems/ha) (Table 7.2). Site elevation averaged 174.3 m above sea level, and was as high as 375 m for the Herekino and Waitengaue stands. Annual rainfall averaged 1707 mm. Average annual sunshine hours was 1999 hours. Daily mean temperature averaged 14.3 ^{o}C.

Table 7.2. Initial stand density and site characteristics of all second-growth stands before thinning treatments were applied.

	Initial stand density (stems/ha)	Elevation (m)	Annual Rainfall (mm)	Annual Sunshine (hrs)	Daily Mean temp. (^{o}C)	Latitude (^{o}S)
Mean	919	174.3	1707	1999	14.3	35.22
Min	205	75	1375	1871	13.4	36.34
Max	2200	375	2097	2105	15.1	37.50
s.e.	289.9	28.9	104.4	38.1	0.3	-

Calculated ages derived from DBH/age curves were compared to estimated ages. Residuals of age were plotted (Figure 7.1), with 62.7% being ±10 years of the mean, and 84.9% being ±20 years of the mean.

Thinning of second-growth stands resulted in a decrease in mean stand age for four of the six thinned stands. Average reduction in age was 21 years, but was as much as 28 years. Conversely the Herekino and Kaiarara thinned stands both recorded a minimal increase in age (mean 3 years). Thinning of second-growth stands selected older kauri, irrespective of their diameter or potential merchantability.

Figure 7.1. Residuals of age derived from calculations of age estimated from breast height increment cores (RMSE = 13.7975, mean = -1.4128). Approximately 65% of calculated ages were within 10 years of the mean.

Height of kauri averaged 20.6 m. Height MAI averaged 0.19 m/yr. Average diameter was 27.6 cm. Diameter MAI averaged 0.25 cm/yr (range 0.13-0.38 cm/yr). Highest DBH MAI was seen in stands with lower stand density (205-378 kauri/ha), and conversely the lowest DBH MAI was in stands with high stand density (1692-2200 kauri/ha). Basal area was as high as 77.2 m^2/ha in the Herekino stand where kauri was the only species recorded. Basal area MAI was 0.4 m^2/ha/yr for all stands. Volume MAI averaged 3.1 m^3/ha/yr for all unthinned stands. Results for each stand and treatment are contained in Appendix II.

Table 7.3. Stand age, stand density, height and diameter for kauri in all unthinned second-growth stands at their first assessment (sites ranked north to south).

Stand	**Age**	**Stand density (stems/ha)**	**Height (m)**	**Height MAI (m)**	**DBH (cm)**	**DBH MAI (cm)**
Herekino	123	903	19.3	0.16	33.0	0.27
Papakauri	130	225	19	0.15	33.1	0.25
Kaiarara	85	830	15.5	0.18	20.1	0.24
Whangaparapara	105	205	20.9	0.20	31.2	0.30
Whenuakite	115	378	30.4	0.26	44.0	0.38
Mangatangi	83	2200	17.3	0.21	12.7	0.15
Waitengaue	146	1692	21.8	0.15	19.3	0.13
Mean	**112**	**919**	**20.6**	**0.19**	**27.6**	**0.25**
s.e.	**8.8**	**289.9**	**1.8**	**0.02**	**4.1**	**0.03**
s.d.	**23.2**	**767.1**	**4.8**	**0.04**	**10.7**	**0.09**

7.4.2 Growth of kauri

Height

Estimated heights were plotted against actual heights. Residuals were plotted (Figure 7.2) with 68.4% being within 1.0 m of the mean and 92.3% being within 2.0 m of the mean. Estimated heights were strongly related to actual heights for both unthinned and thinned stands.

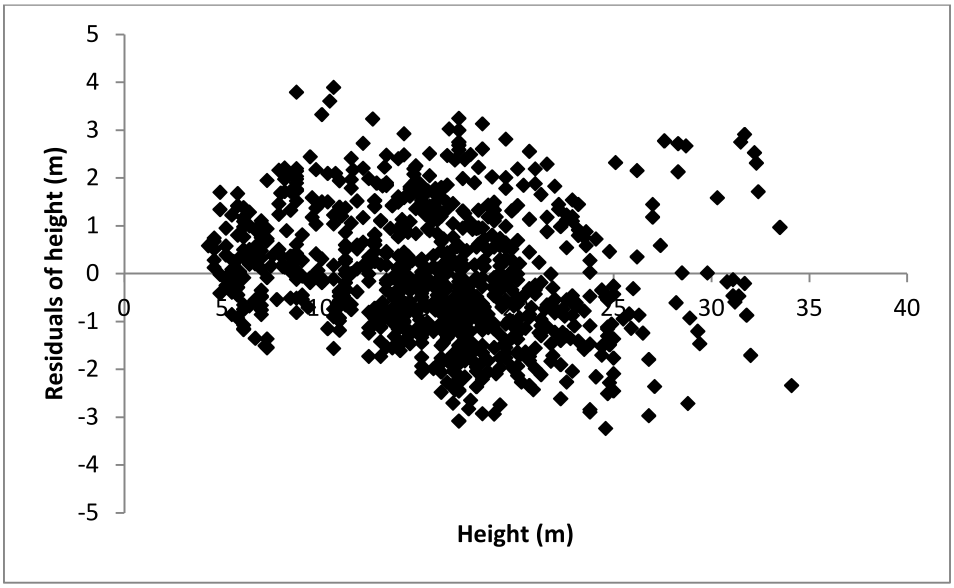


Figure 7.2. Residuals of height plotted against measured height. Estimated heights were biased towards underestimating height the taller the tree (RMSE = 1.21, mean = 0.07).

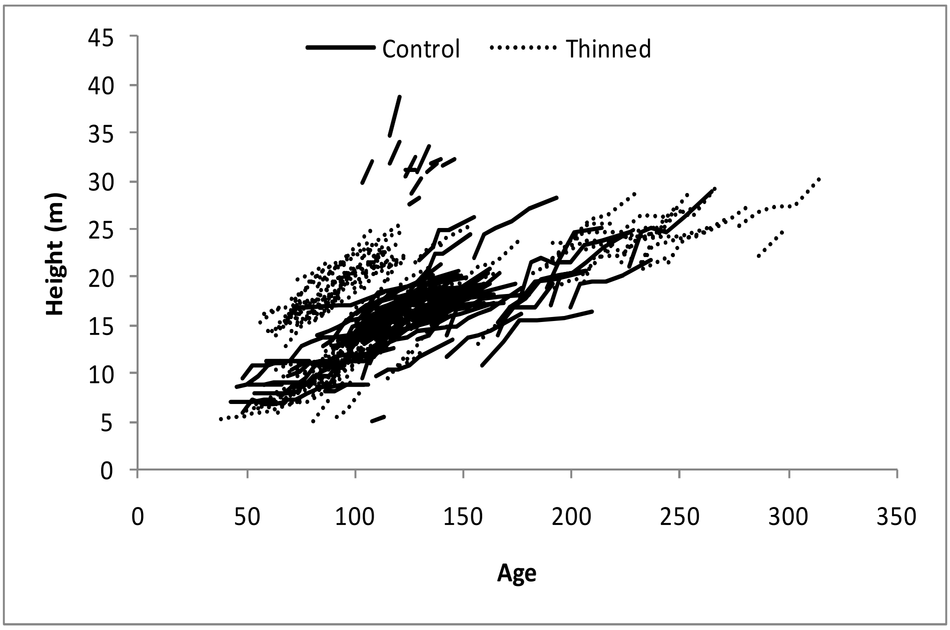


Figure 7.3. Height development of kauri in unthinned control and thinned second-growth stands. The Whenuakite stand contained the tallest kauri, approaching 40 m for the tallest tree at the last measurement. Whenuakite did not receive a thinning treatment, therefore thinned stand heights appear artificially lower than unthinned.

Thinning had a small influence on height growth. Unthinned stands performed better than thinned stands for mean height and mean annual increment (Figure 7.3, Table 7.4). Stand density did not affect height growth within individual treatments. Height at the last assessment ranged from 19.3-34.3 m in unthinned stands (MAI 0.13-0.27 m) and from 16.8-28.1 m in thinned stands (MAI 0.14-0.20 m). For all stands and treatments combined, a mean height of 20 m was not achieved until 200 years of age. Periodic height increment (first to last assessment) showed a similar trend for control kauri to have faster height growth than thinned (Table 7.5).

Table 7.4. Height and diameter growth of kauri in second-growth unthinned and thinned stands at their last assessment.

Treatment	Mean age (years)	Mean height (m)	Height MAI (m)	Mean DBH (cm)	DBH MAI (cm)
Unthinned	**144**	**25.5**	**0.18**	**33.4**	**0.24**
Thinned	**129**	**23.1**	**0.19**	**34.7**	**0.27**

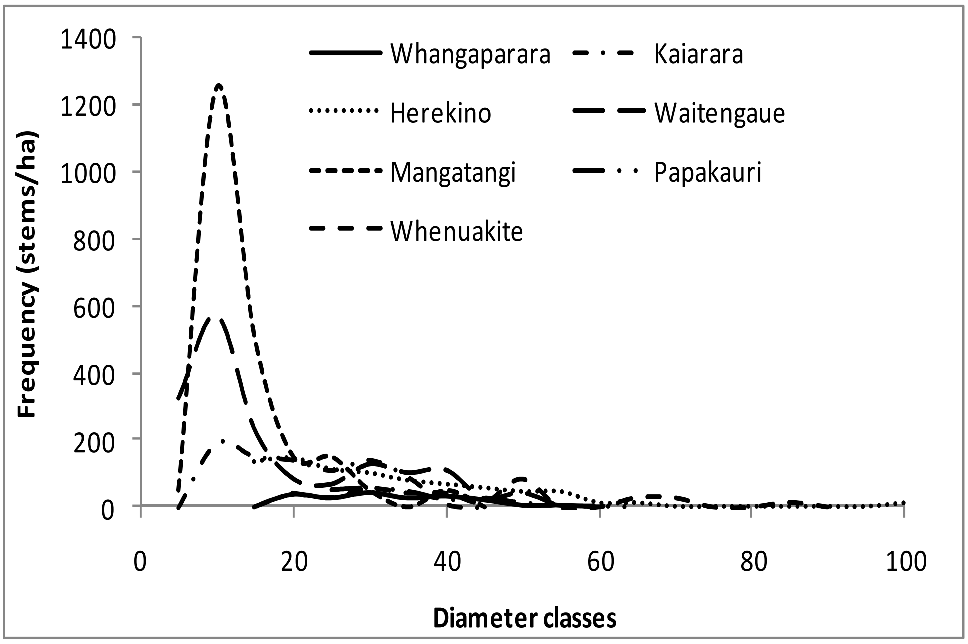


Figure 7.4. Diameter distribution of kauri in unthinned second-growth stands. Diameter distribution displayed the reverse "J" distribution typical of natural stands where large numbers of small diameter stems are found.

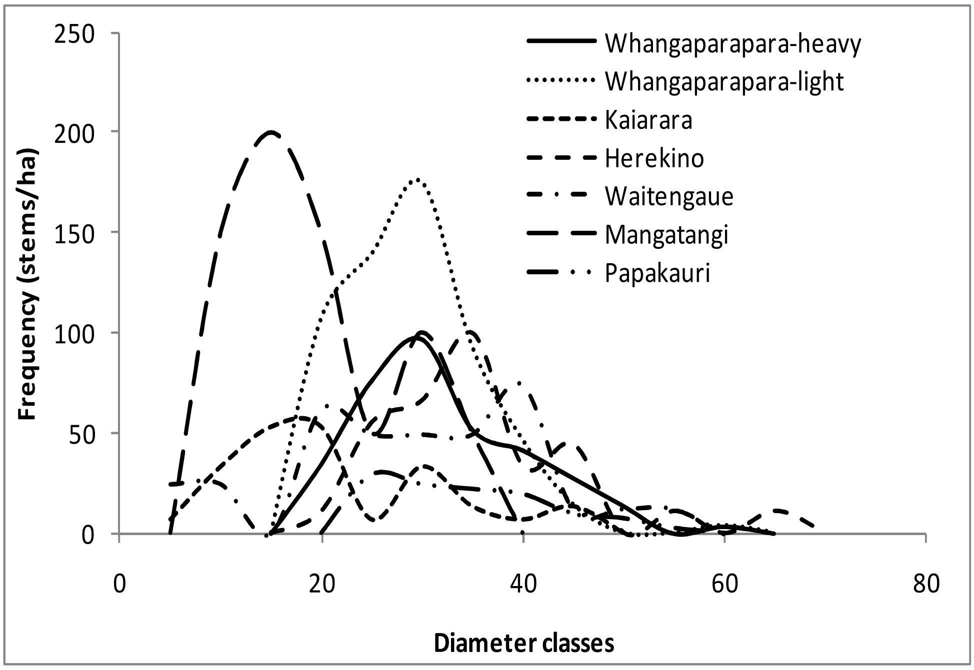


Figure 7.5. Diameter distribution of kauri after thinning. Thinning produced a diameter structure that approached more normal distribution.

Table 7.5. Periodic annual increment (first to last measurement) for kauri in unthinned and thinned second-growth stands.

Treatment	**Height PAI (m/yr)**	**Diameter PAI (cm/yr)**	**Basal Area PAI (m^2/ha/yr)**	**Volume PAI (m^3/ha/yr)**
Unthinned	0.16	0.21	0.63	9.28
Thinned	0.15	0.25	0.57	6.51

Diameter

Diameter distribution of kauri in unthinned stands displayed the reverse “J” distribution typical of natural stands (Figure 7.4). Thinning that removed the numerous small diameter sub-canopy kauri resulted in diameters approaching a more normal distribution for most stands (Figure 7.5).

Mean diameter of kauri in unthinned and thinned stands were similar at 33.4 and 34.7 cm at their last assessment (Table 7.4, Figure 7.6). Thinning resulted in a small increase in DBH MAI (0.03 cm/yr), and 0.04 cm/yr for PAI (first to last assessment). The largest mean diameter (46.7 cm) was found in the Whenuakite unthinned stand, which also had the highest DBH MAI at 0.37 cm/yr (Table 7.3). The heavy thinning treatment at Whangaparapara resulted in a better DBH MAI than the lighter thinning treatment, although both thinning treatments performed better than the unthinned stand. In both unthinned and thinned stands, diameter growth reduced with higher stand density. Height and diameter were strongly related for both unthinned and thinned kauri stands.

Figure 7.6. Diameter development of individual kauri within unthinned control and thinned second-growth stands.

Assessments of individual stands allowed for the inclusion of in-fill kauri growth in subsequent measurements as kauri stems arrived at or exceeded 5.0 cm DBH. Considerable numbers of kauri in-fill growth were recorded in the Mangatangi and Waitengaue stands. In-fill growth occurred more often in the thinned stands than the unthinned. In-fill kauri growth in the Mangatangi and Waitengaue stands suppressed the mean diameter, and diameter MAI reported for the thinning treatment in these stands (Table 7.6). The effect on unthinned stands was at most minimal. This effect was not removed when stand performance was analysed, or in later modeling.

Basal Area

Kauri comprised 76.0% of the basal area (range 38.3-100.0%) in unthinned stands at their first assessment, and 89.7% in thinned stands (Table 7.7). Maximum basal area (77.2 m^2/ha) was recorded in the Herekino unthinned stand (903 kauri/ha), while the lowest (15.7 m^2/ha) was recorded in the Whangaparapara unthinned stand (205 kauri/ha) (Figure 7.7). At their last assessment kauri had increased to 88.8% of basal area in all unthinned stands and 97.1% in thinned stands. Basal area in unthinned stands increased by 16.3 m^2/ha from the first to last assessment and by 17.2 m^2/ha in thinned stands. Basal area PAI was strongly related to stand density (stems/ha) for unthinned and thinned stands (Table 7.5).

Table 7.6. Comparison of the effect on diameter and diameter mean annual increment by kauri in-fill growth in the Mangatangi and Waitengaue stands. In-fill growth affected diameter growth in thinned stands more than unthinned stands.

Stand	Treatment	Mean age (years)	All kauri		Original kauri only	
			Mean DBH (cm)	DBH MAI (cm)	Mean DBH (cm)	DBH MAI (cm)
Mangatangi	Unthinned	114	16.2	0.14	16.9	0.15
	Thinned	90	18.3	0.20	26.0	0.23
Waitengaue	Unthinned	196	29.6	0.15	29.6	0.15
	Thinned	184	34.5	0.19	45.1	0.29

Figure 7.7. Basal area development of kauri in seven second-growth stands. Kauri represented >88% of basal area in thinned stands. Highest basal area was 99.9 m^2/ha in the Herekino unthinned stand. More variance in basal area was seen between individual stands in unthinned stands than in thinned stands. Basal area increment in thinned stands was marginally higher than in unthinned stands.

Table 7.7. Basal area of all second-growth stands at their first and last assessments (range in brackets).

Stand		**Basal area (m^2/ha)**		
		all species	**kauri**	**% kauri basal area**
Unthinned	first assessment	**48.9** (26.8-77.2)	**39.2** (15.7-77.2)	**76.0** (38.3-100.0)
	last assessment	**61.7** (18.1-99.9)	**55.5** (18.1-99.9)	**88.8** (74.4-100.0)
Thinned	first assessment	**25.8** (8.3-38.6)	**22.3** (8.1-34.9)	**89.7** (67.4-100.0)
	last assessment	**40.9** (19.3-69.1)	**39.5** (18.6-62.5)	**97.1** (90.5-100.0)

Table 7.8. Comparison of whole-tree volume of kauri within seven second-growth stands that received a thinning treatment.

Stand	**Treatment**	**Vol (m^3/ha)**	**Vol MAI (m^3/ha/yr)**
Herekino	Unthinned	1111.5	6.90
	Thinned	619.6	3.73
Papakauri	Unthinned	319.8	1.82
	Thinned	232.4	1.57
Kaiarara	Unthinned	335.8	2.80
	Thinned	135.8	1.12
Whangaparapara	Unthinned	173.9	1.47
	Thinned-light	393.1	4.01
	Thinned-heavy	323.5	3.30
Whenuakite	Unthinned	861.2	6.83
	Thinned	-	-
Mangatangi	Unthinned	401.2	3.52
	Thinned	318.3	3.50
Waitengaue	Unthinned	866.4	4.42
	Thinned	675.4	3.67
All	**Unthinned**	**581.4**	**3.97**
	Thinned	**385.4**	**2.99**

Volume

Whole-tree volume averaged 581.4 m^3/ha in unthinned stands and 385.4 m^3/ha in thinned stands at their last assessment (Table 7.8, Figure 7.8). Volume was as high as 1111.5 m^3/ha in the Herekino unthinned stand and as low as 173.9 m^3/ha in the Whangaparapara unthinned stand. Thinned stands had a lower volume MAI than unthinned stands. The highest volume MAI was 6.9 m^3/ha/yr in the

Herekino unthinned stand. The lowest volume MAI was 1.12 m^3/ha/yr in the Kaiarara thinned stand. Thinning resulted in a higher volume MAI on only one site (Whangaparapara) when compared to the unthinned stand. Kauri volume increment was more related to stand density (stems/ha) and basal area than age for both unthinned and thinned stands. Volume PAI (first to last assessment) followed the same trend with unthinned stands (9.28 m^3/ha/yr) having a higher PAI than thinned stands (6.51 m^3/ha/yr) (Table 7.5).

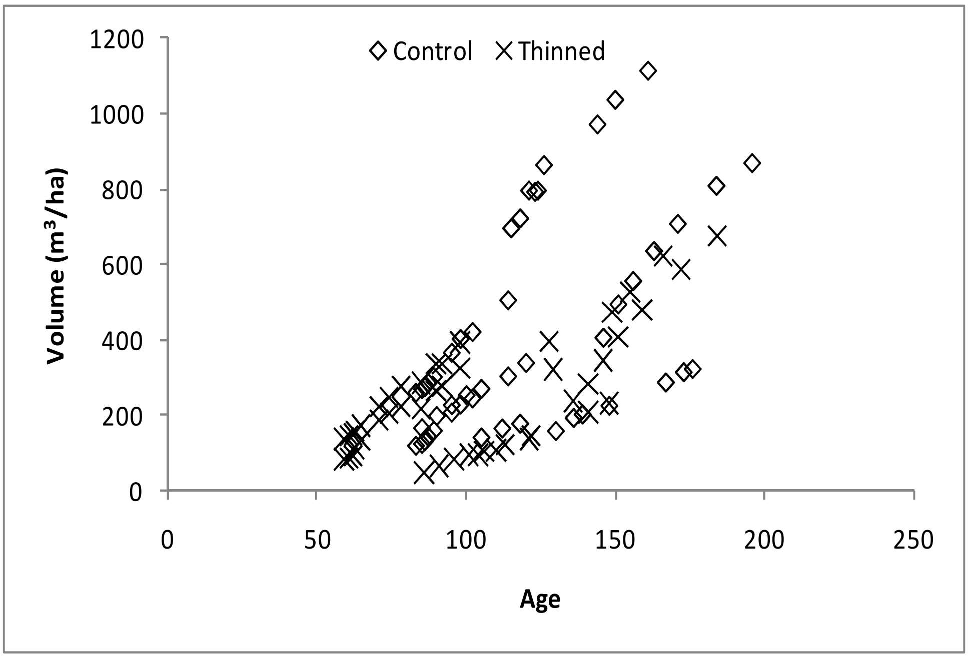


Figure 7.8. Volume development of kauri in second-growth stands. Mean volume increment in thinned stands was 2.99 m^3/ha/yr compared to 3.97 m^3/ha/yr for unthinned control stands. Volume increment in unthinned stands showed greater variance than in the thinned stands. Maximum volume was 1111.5 m^3/ha in the Herekino unthinned stand. The highest volume in thinned stands was 675 m^3/ha in the Waitengaue stand.

7.5 CONCLUSIONS

Thinning to reduce within-stand competition in second-growth kauri stands was presumed would result in better growth and productivity than in stands where no silvicultural intervention occurred. However, thinning did not result in the diameter growth, basal area increment, or volume production as was expected. Height growth was not affected by thinning, and performed similarly for MAI and PAI to unthinned stands. Diameter growth of kauri in thinned stands was consistently higher than in control stands, but not substantively enough to replace the basal area or volume that was removed during thinning in the up to 50 years since thinning treatments were applied. The greater basal area and volume productivity in unthinned stands was entirely attributable to higher stand density (stems/ha) than in the thinned stands.

Unthinned second-growth kauri stands displayed a substantive amount of variance in all measured parameters from stand density to growth and productivity. Many of these are presumed to be site related. Thinning of second-growth stands resulted in performance and productivity becoming more similar between individual stands that received a thinning treatment. Thinning removed much of the variance found between natural stands.

The effect on the age structure of second-growth kauri stands after thinning treatments were applied was unexpected and had not been observed in prior studies of these stands. Tree diameter has normally been reported to be a poor indicator of tree age. However, in this study, the use of DBH/age data from kauri in the ricker form (with ages derived from increment cores) provided estimated ages for unmeasured stems that were within acceptable limits (±10-20 years) for kauri in excess of 300 years.

CHAPTER 8

MODELLING GROWTH AND YIELD OF KAURI

8.1 INTRODUCTION

The growth and potential productivity of kauri has been a point of much conjecture. Most of the information in current circulation has been anecdotal. This chapter uses the data described in Chapter 6 (planted kauri) and Chapter 7 (natural second-growth kauri) to develop robust stand-level growth and productivity models of height, basal area and volume. None of the models that had been developed earlier made use of all available data, nor made the important direct comparisons between the performance and productivity of kauri in planted stands with that of the natural second-growth resource. Second-growth stands were assumed to be a viable and productive source of kauri timber, and apparently only lacked management to improve their performance. The stand-level models developed in this chapter will be useful in developing the thinking around the potential of kauri as a commercial forestry species.

8.2 BACKGROUND

Early estimates of productivity of kauri were made from data from natural stands by Lloyd (1978), while initial predictions and prescriptions were made for its management by a number of authors (Hutchins, 1919; Barton, 1975; Barton & Horgan, 1980; Barton, 2000). There seemed an inherent assumption that the results from natural stands would be applicable to kauri grown in planted stands. A preliminary stand productivity and economic model for planted kauri was eventually developed, based on two 60-year old planted stands in New Plymouth (Herbert, et al., 1996). The models for mean top height and basal area, both based on the von Bertalanffy-Richards growth function, estimated basal area of 96.0 m^2/ha at age 60 (1375 stems/ha) from measured data, and extrapolated to 131.5 m^2/ha at 120 years (estimated 957 stems/ha) (Table 8.1). Estimated whole-stem volumes of 804 m^3/ha at age 60, and 1431 m^3/ha at age 120 were also given (Figure 8.1). There was an assumption that at age 120 and 957 stems/ha DBH MAI would still be 0.35 cm/yr, down from a peak of 0.63 cm/yr at age 20. This assumption was not supported by subsequent measurements of stands prior to thinning operations in 2002 and 2004. Diameter MAI had almost stopped by 2002. Diameter CAI had reduced to 0.26 cm/yr in the Brookland stand, and was 0.10 cm/yr in the Fred Cowling stand, with stand density at both sites still well in excess of 1000 stems/ha (Steward, 2002; 2004 – unpublished Contract Reports for New Plymouth District Council). With only two stands included in their growth model, both at high stand density and on similar Taranaki sites, this model could not be considered suitable for general use across New Zealand.

Table 8.1. Estimated stand and tree growth predictions from kauri planted on two sites at New Plymouth (from Herbert et al., 1996). Relationship to age 60 was modelled data, and to age 120 was by extrapolation.

Age	Stand density (trees/ha)	Mean DBH (cm)	Mean top height (m)	Basal area (m^2/ha)	Total stand volume (m^3/ha)
20	1375	12.5	7.9	16.9	79
40	1375	23.8	15.4	61.0	418
60	1375	29.8	21.1	96.0	804
80	1293	33.8	25.2	116.2	1103
120	957	41.8	30.2	131.5	1431

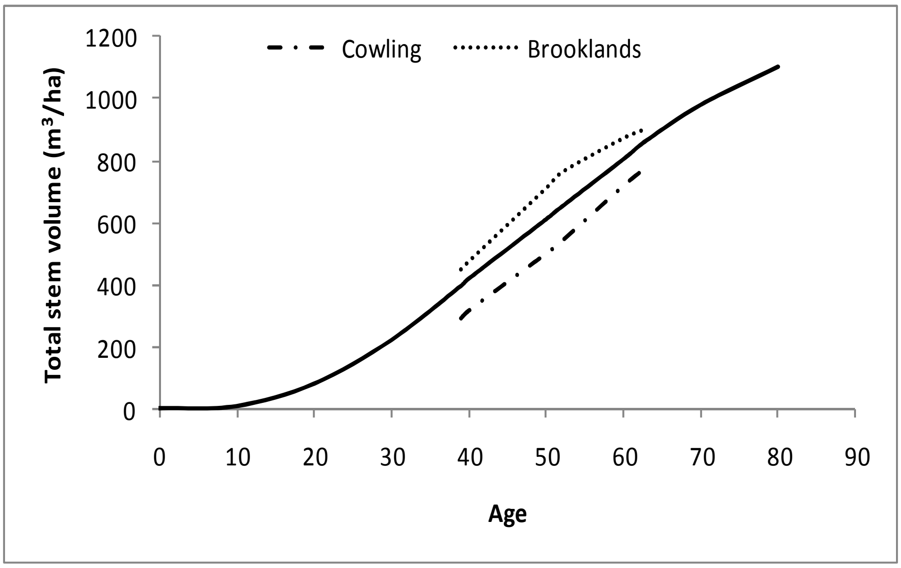


Figure 8.1. Kauri volume model developed by Herbert et al. (1996) from two planted stands at Taranaki. Mean stand density (age 60) was 1375 stems/ha when the model was developed.

A stand basal area model (based on a von Bertalanffy-Richards generalised growth function) was developed from data from thirteen planted kauri stands (Chikumbo & Steward, 2007). Despite the limitations in the data (particularly the irregularity of measurement) the dynamical modelling approach developed a state space model that was asymptotically stable. The model was valid for stand density within the range of 300-1400 stems/ha. Predicted basal area values were similar to those of Herbert et al. (1996) until age 60. From age 60 the extrapolated values of Herbert et al. were considerably larger (22% at age 80) than those of Chikumbo & Steward (2007) at the same age (Figure 8.2).

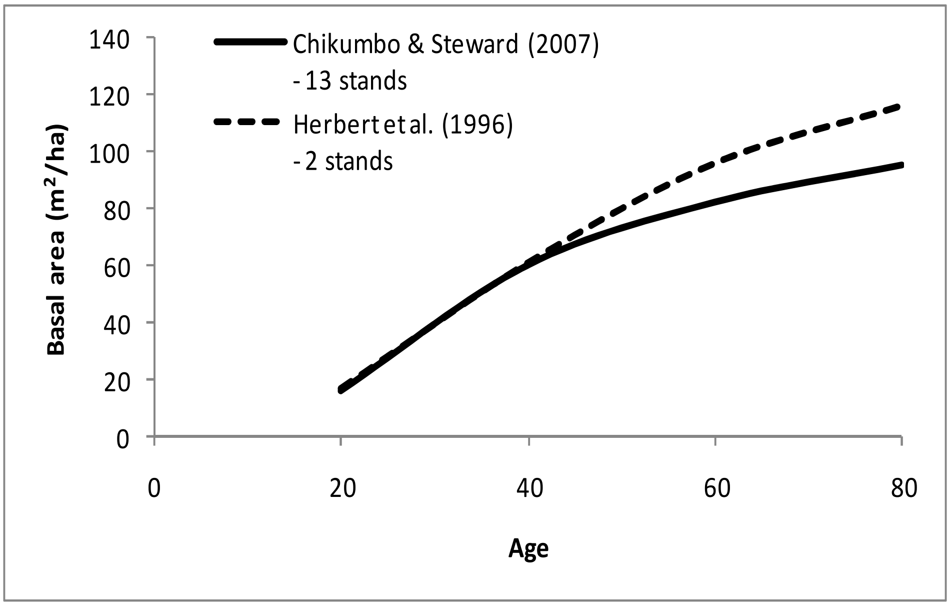


Figure 8.2. Comparison of basal area estimates in planted kauri stands between the Herbert et al. (1996) and Chikumbo & Steward (2007) models.

8.3 MODELLING

Three basic forms of sigmoidal growth function were tested for modelling height and basal area for all stand types (planted, second-growth unthinned, second-growth thinned). These were the von Bertalanffy-Richards (von Bertalanffy, 1949; Richards, F. J., 1959; Pienaar & Turnbull, 1973), the Schumacher (Schumacher, 1939) and the Weibull (Weibull, 1939; Yang, et al., 1978) models (Table 8.2). Various forms of each model were tested along with several different methods of estimating their parameters. The different model forms tested for modelling height are listed in Table 8.4. When used for height models, all these models have an intercept of 0.5 m on the assumption that seedlings were likely to be this height when planted. For consistency, the same intercept was used for second-growth stands. For basal area, the same model forms were tested except that an intercept of zero was used (it is accepted that some basal area exists, however at 1000 stems/ha it amounted to <0.1 m^2/ha). All models incorporate three parameters that are referred to as the asymptote (*a*), slope (*b*) and shape (*c*) parameters. Data for modelling were contained in Excel (2007) spreadsheets. Methods for data collection are contained in Chapter 5.

For the von Bertalanffy-Richards model, the following forms were tested. First a simple yield form of the function (Model 1) was fitted using the SAS Version 9.1 NLIN procedure. This form is not particularly useful except as a generic model for predicting average performance, however. In practice, these models will generally be used as difference equations, for projecting growth forward in time from a known measured value. Essentially, the difference equation involves algebraically eliminating one of the three parameters and replacing it with the measured value which acts as a starting point for projecting growth forward. Effectively, the eliminated parameter is treated as a 'local' parameter which can take a value necessary to maintain compatibility with the measured starting point. Both anamorphic and polymorphic forms were tested. The polymorphic form with local slope gives curves that converge at one upper asymptote (Clutter, et al., 1983). The anamorphic difference form gives curves with a common slope parameter and different asymptotes for the range of input values.

Table 8.2. Three sigmoidal growth functions in yield form on which mean top height and basal area models were developed.

Equation	
von Bertalanffy-Richards	$y = a(1 - e^{-bT})^{c}$
Schumacher	$y = ae^{(-bT^{c})}$
Weibull	$y = a\left(1 - e^{-bT^{c}}\right)$

Two general methods of fitting the different forms of each model were tested. Firstly, the SAS NLMIXED procedure was used (Littell, et al., 1996). In this approach, one of the parameters is specified to a local parameter which varies with each site. This parameter is assumed to be randomly distributed from a normal distribution. Various forms in which either the slope (Model 2) or intercept (Model 3) were assumed local were tested, along with more complex versions in which both slope and intercept varied as functions of a local parameter (Models 4 and 5). When using NLMIXED, the dependent variable was height (or basal area), and the independent variable was age.

Secondly, the difference form of each equation was created and fitted using the NLIN procedure. The two forms of difference equation in which the slope (Model 6) or the intercept (Model 7) parameter was eliminated were tested. In this method of fitting the model, the function was fitted using adjacent pairs of measurements. For planted stand data the mean number of measurement intervals was 3.3 (range 1-10), and for second-growth stands was 4.7 (range 2-8). Models were initially developed using planted stand data. The dependent variable was the second measurement (of height or basal area) and the independent variable was the first measurement of each pair.

The model forms tested for the Schumacher model were similar to the seven forms tested for the von Bertalanffy-Richards model. The only exception here was that for height, the asymptote was bounded to 45 m when fitting the model. Early forms of the Schumacher growth function predicted height growth linearly and extreme estimates for the asymptote (*a* parameter) were achieved (e.g. 151.8 m). For kauri in planted stands a maximum mean top height of 29 m was recorded and 38 m in second-growth stands. To determine an appropriate value to bound the height equation a sample of sixty kauri with mature and semi-mature form were measured for total height in five forests of Northland, New Zealand. Maximum height of the sample was 52.2 m, and 25% of the sample taller than 35.0 m. Therefore a height of 45.0 m was an acceptable compromise between the extreme maximum (60 m) and the heights found in comparatively young planted and second-growth stands. For the Weibull model, only the simple yield and the nonlinear mixed models (NLMIXED) with local slope parameter were tested (Models 15 and 16) as it was quickly apparent that this sigmoidal model was inferior to either the von Bertalanffy-Richards or Schumacher models.

Models were initially fitted to planted, second-growth unthinned and thinned data separately, and finally in a dataset that combined all three types. Final fitted models were selected that had the smallest root mean square error (RMSE) and least biased residuals. The normality of residual distributions was a third criterion for model selection.

8.4 PLANTED KAURI

8.4.1 Height

Schumacher models with a local slope parameter generally performed better than von-Bertalanffy-Richards models with local slope parameter. Von-Bertalanffy-Richards models tended to over-predict early height growth. The Schumacher models produced sigmoidal curves that better reflected the data. While these initial Schumacher models performed well, the asymptote (*a* parameter) estimates exceeded known maximum kauri height, often more than two-fold. Therefore, two further Schumacher models were fitted using the SAS NLMIXED procedure, and the difference form of the model form with a bounded asymptote (*a*) parameter (Models 10 & 13). These two models performed similarly. The anamorphic Model 13 (Table 8.4) fitted using the difference form was chosen as the best (Equation 8.1).

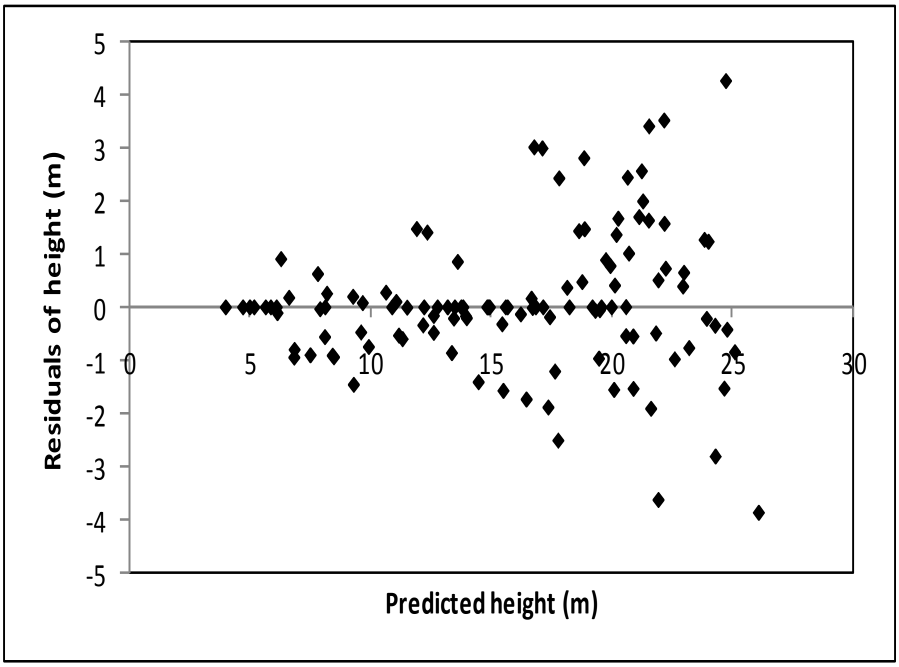
$$\mathbf{MTH = 0.5+\mathit{a}\times exp(((T/50)^{\mathit{c}})\times ln((SI-0.5)/\mathit{a}))} \qquad \text{(Equation 8.1)}$$

where;

MTH = mean top height
T = age
0.5 = starting height of seedlings
a = bounded asymptote parameter estimate (44.5)
c = shape parameter estimate (-0.7903)
ln = Natural Log
SI = Site Index (mean top height at age 50)

Parameter estimates (and their standard errors) for the anamorphic Schumacher MTH model for planted kauri stands were (note parameter *a* was bounded)

Parameter	Parameter estimate	s.e.
a	44.5	-
c	-0.7903	0.025



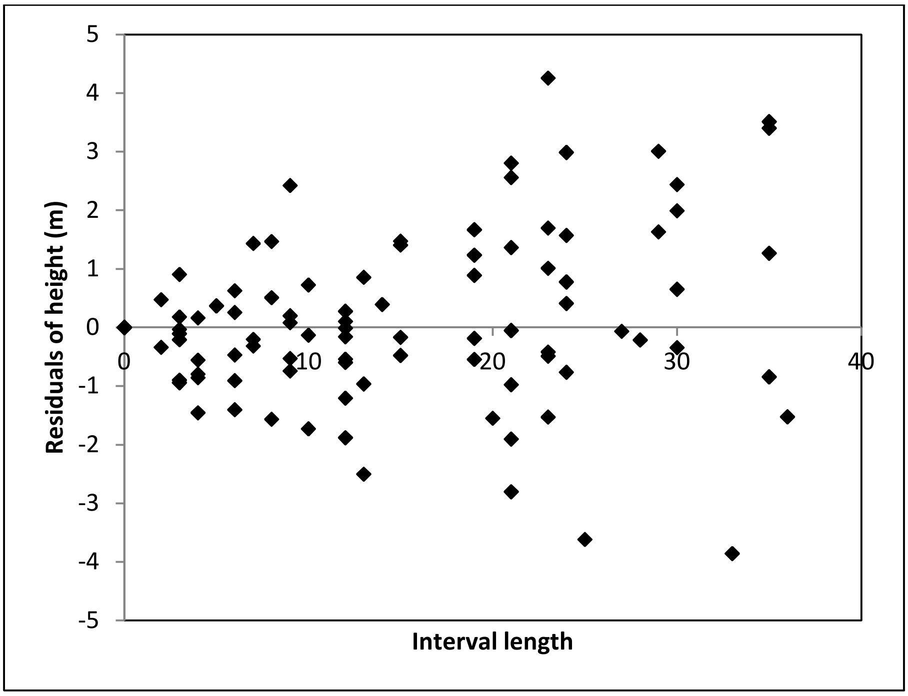


Figure 8.3. Schumacher mean top height model. Residuals of mean top height plotted against predicted mean top height, and Interval length (RMSE = 1.301, bias = 0.09).

Predicted heights were calculated for each stand at each measurement period. Predicted heights were subtracted from actual heights to give residuals of MTH. Except for the simple yield form, this was achieved by converting the model into a difference form, and projecting growth forward from the previous measurement. The residuals of observed-predicted height were plotted by age and by interval length (Figure 8.3). Model 13 for MTH had little bias (0.09) and the lowest root mean square error (RMSE) (1.301). To project growth forward in time the form of the model (Equation 8.1) is: **$\mathrm{MTH} = 0.5 + a \times \exp((T/T_i)^c \times ((\mathrm{MTH}_i - 0.5)/a)$** (where; T = age of prediction, T_i = age of initial measurement, MTH = mean top height, MTH_i = initial mean top height).

Site index refers to the timber potential for a site for a particular species, usually at a fixed age somewhere near the expected rotation length for the species. A number of methods are possible to calculate site index. In forestry, the usual method to develop site index is from stand height records, as good site quality is also often reflected in good height growth (Clutter, et al., 1983). For kauri in planted stands and second-growth stands (unthinned and thinned plots) site index was defined as Mean Top Height at age 50, and was calculated from the height models. Site index (height at age 50) was calculated for each planted kauri stand (Table 8.3). Maximum site index (28.4 m) was found in the 12 year old **Stand 16**, while the lowest was 15.8 m in two stands. Mean site index was 20.4 m.

Table 8.3. Site index (height at age 50) for each planted kauri stand. Sites arranged north to south.

Stand	height (m)	Stand	height (m)	Stand	height (m)
1	15.8	**10**	21.5	**19**	19.5
2	20.6	**11**	20.4	**20**	19.6
3	20.4	**12**	17.5	**21**	20.5
4	25.9	**13**	16.9	**22**	21.2
5	19.2	**14**	17.2	**23**	20.0
6	19.3	**15**	22.3	**24**	15.8
7	20.1	**16**	28.4	**25**	22.7
8	22.5	**17**	19.7	**Mean**	**20.4**
9	19.6	**18**	22.1		

Table 8.4. Equations tested during modelling of kauri height. Models identified as performing better in planted kauri stands were subsequently fitted to second-growth unthinned and thinned data independently. For basal area, the same equations were tested in planted and second-growth stands, except for the removal of the 0.5 m intercept included as the estimated starting height of seedlings. All equations are presented in SAS form. For models fitted using the nonlinear mixed modelling procedure, *d* is a local parameter which varies between stands.

Model No.	**Type**	**Equation**
von Bertalanffy-Richards		
1	Nonlinear Simple yield model	$y = 0.5 + a \times (1 - \exp(-b \times age))^{c}$
2	Nonlinear mixed model with local slope parameter	$y = 0.5 + a \times ((1 - \exp((b + d) \times age)))^{c}$
3	Nonlinear mixed model with local asymptote parameter	$y = 0.5 + (a + d) \times ((1 - \exp(b \times age)))^{c}$
4	Nonlinear mixed model with local slope parameter and asymptote a linear function of slope	$y = 0.5 + a \times (1 + a_1 \times d) \times ((1 - \exp((b + d) \times age)))^{c}$
5	Nonlinear mixed model with local site index and slope a linear function of site index	$y = 0.5 + (a + d) \times ((1 - \exp(b \times (1 + b_1 \times d) \times age)) / (1 - \exp(b \times (1 + b_1 \times d) \times 50)))^{c}$
6	Difference form with local slope parameter	$y = 0.5 + a \times (1 - (1 - ((mth_1 - 0.5/a)^{(1/c)})^{(age/age_1)})^{c}$
7	Difference form with local asymptote parameter	$y = 0.5 + (mth_1 - 0.5) \times ((1 - \exp(-b \times age)) / (1 - \exp(-b \times age_1)))^{c}$

Table 8.4 cont.

Model No.	Type	Equation
Schumacher		
8	Nonlinear Simple yield model	$y = 0.5 + a \times \exp(-b \times age^{c})$
9	Nonlinear mixed model with local slope parameter and asymptote unbounded	$y = 0.5 + a \times \exp(-(b + d) \times age^{c})$
10	Nonlinear mixed model with local slope parameter and asymptote bounded < 45 m	$y = 0.5 + a \times \exp(-(b + d) \times age^{c})$
11	Nonlinear mixed model with local asymptote parameter	$y = 0.5 + (a + d) \times \exp(-b \times age^{c})$
12	Difference form with local slope parameter with asymptote unbounded	$y = 0.5 + a \times \exp(((age/age_{1})^{c}) \times \log((mth_{1} - 0.5)/a))$
13	Difference form with local slope parameter and asymptote bounded at < 45 m	$y = 0.5 + a \times \exp(((age/age_{1})^{c}) \times \log((mth_{1} - 0.5)/a))$
14	Difference form with local asymptote parameter	$y = 0.5 + (mth_{1} - 0.5) \times \exp(b \times age_{1}^{c-b} \times age^{c})$
Weibull		
15	Nonlinear Simple yield model	$y = 0.5 + a \times (1 - \exp(-b \times age^{c}))$
16	Nonlinear mixed model with local slope parameter	$y = 0.5 + a \times ((1 - \exp((b + d) \times age^{c})))$

Growth trajectories for MTH were plotted and showed little variation despite stands ranging in age from 12-83 years and from 320-2000 stems/ha (Figure 8.4). Growth in early years after planting was slow until age 10 when height MAI was under 0.3 m/yr. Until age 40, height MAI increased to over 0.4 m/yr, and then declined. For better performing stands height MAI was as high as 0.52 m/yr until age 20, and above 0.40 m/yr until age 60, before declining.

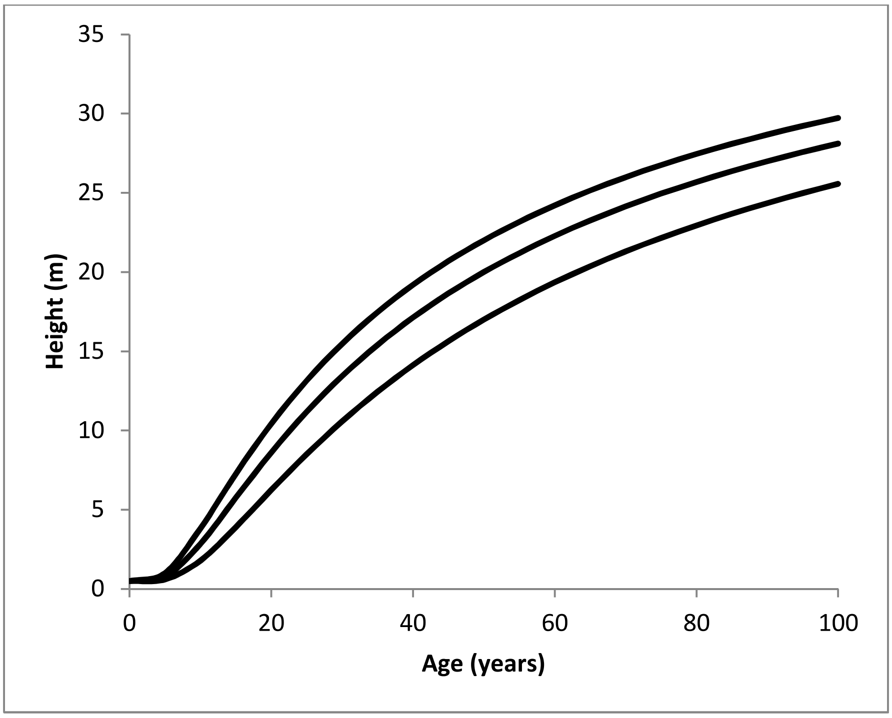


Figure 8.4. Anamorphic height/age curves for planted kauri from measurements of 25 stands. Curves represent the 90th, mid and 10th percentile site index values for planted kauri. The curves are based on actual measurements to age 83.

8.4.2 Basal Area

Equations used to model height growth were tested against basal area data. Equations were modified by removing the 0.5 m starting height value. All equations were unbounded. As with height modelling, equations with a local slope parameter performed best. The polymorphic von Bertalanffy-Richards equation (Equation 8.2) in difference form with local slope parameter was chosen as the best fit (Model 6, Table 8.4). The form of this model for projecting a measurement of basal area G1 at age T1 forward to age T is:

$$\mathbf{G} = a\times(1-(1-((\mathrm{G}_i/a)^{1/c})^{\mathrm{T/T}_i}))^c \qquad \text{(Equation 8.2)}$$

where;

G = predicted basal area

G_i = basal area at initial measurement

T = age of prediction

T_i = age of initial measurement

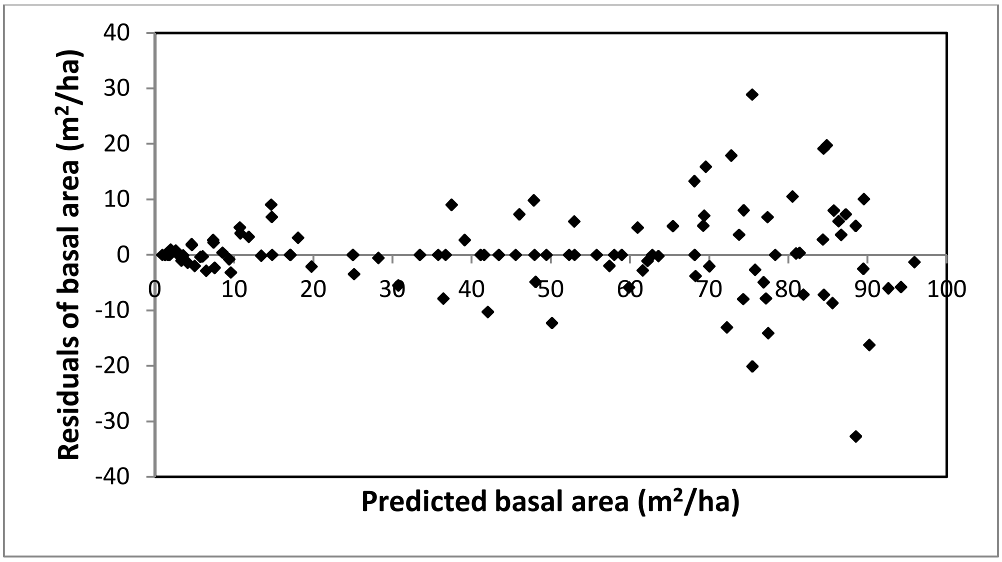
a = asymptote parameter estimate (101.4)

c = shape parameter estimate (5.6971)

Parameter estimates (and their standard errors) for the polymorphic von Bertalanffy-Richards basal area model for planted kauri stands were

Parameter	Parameter estimate	s.e.
a	101.4	6.729
c	5.6971	0.642

Modelling the effect of stand density (stems/ha) on diameter growth and basal area development is part of an on-going study and will be reported on in the future. Predicted basal areas were calculated for each stand at each measurement period and subtracted from the actual basal area. The residuals of predicted basal area were plotted by predicted basal area and interval length (Figure 8.5). Model 6 (Table 8.4) had the lowest bias (0.44) and RMSE (7.58).



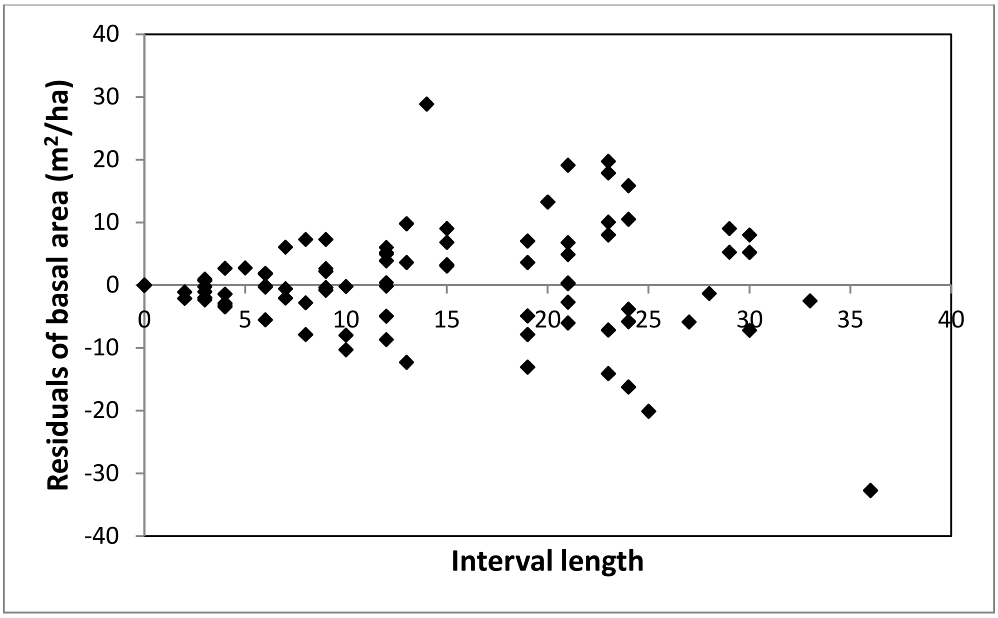


Figure 8.5. Von Bertalanffy-Richards basal area model. Residuals of basal area plotted against predicted basal area and interval length (RMSE = 7.58, bias = 0.44).

Basal area trajectories were plotted and are shown in Figure 8.6. Basal area development was slow in the 10-15 years after planting at 0.26-0.48 m^2/ha/yr. By age 60 basal area was 78.1 m^2/ha, and did not approach its maximum until age 70 in best performing planted stands.

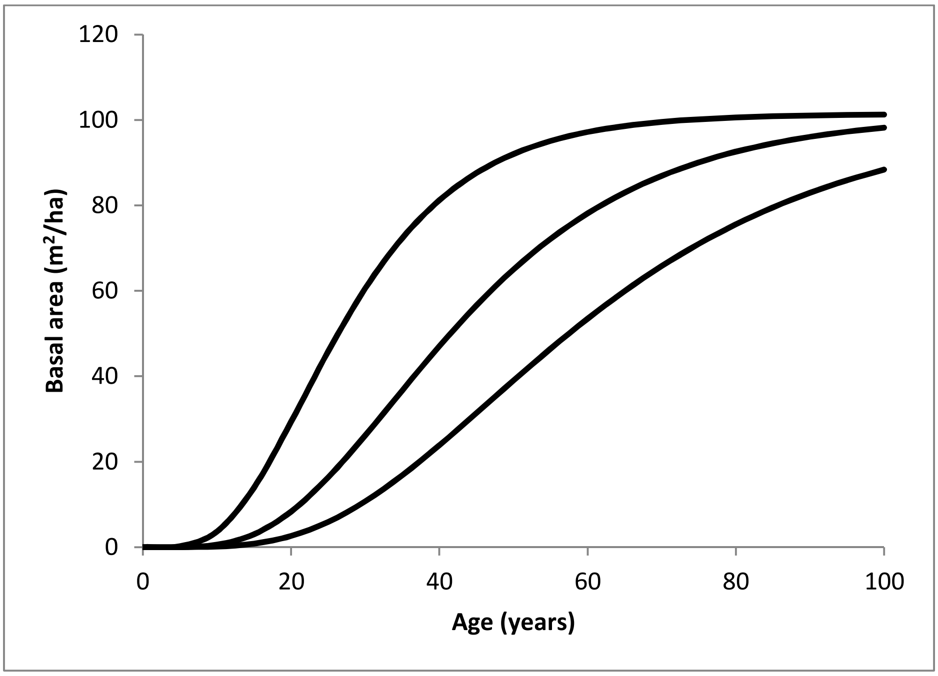


Figure 8.6. Polymorphic basal area/age curves for planted kauri from measurements of 25 stands. Curves represent the 90th, mid and 10th percentile values for planted kauri. The curves are based on actual measurements to age 83.

8.4.3 Volume

Volumes of individual stems were estimated using the pole volume function of Ellis (1979). These were summed for each stand measurement to provide per hectare estimates of volume. A stand-level volume function was then fitted to this data using the SAS NLIN procedure. The form given by Equation 8.3 was used. Predicted basal area and mean top height values were then used in conjunction with the stand-level volume function to provide predicted volumes.

$$\mathbf{Vol} = \boldsymbol{b} \times \mathbf{G}^{a} \times \mathbf{MTH}^{c} \qquad \text{(Equation 8.3)}$$

where;
Vol = volume
G = basal area
MTH = mean top height
a = asymptote parameter estimate (0.956)
b = slope parameter (0.703)
c = shape parameter estimate (0.883)

Parameter estimates (and their standard errors) for the volume model for planted kauri stands ($r^2$0.990) were

Parameter	Parameter estimate	s.e.
a	0.956	0.0892
b	0.703	0.0297
c	0.883	0.0482

Volume was slow to develop with little volume in most stands before age 20 (Figure 8.7, Table 8.5). By age 60 volume was estimated to be in excess of 700 m^3/ha for mid performing stands, with MAI at 11.7 m^3/ha/yr. Periodic annual increment peaked at age 60 at 18.0 m^3/ha/yr.

Table 8.5. Estimates of stand growth for planted kauri stands at given ages. Values to age 80 are modelled on actual performance.

Age	**Height (m)**	**Basal Area (m^2/ha)**	**Volume (m^3/ha)**	**Volume MAI (m^3/ha/yr)**	**Volume PAI (m^3/ha/yr)**
10	2.8	0.6	1.1	0.1	0.1
20	8.6	8.3	35.8	1.8	3.5
40	17.1	47.1	343.2	8.6	15.4
60	22.3	78.1	702.6	11.7	18.0
80	25.7	92.6	936.8	11.7	11.7

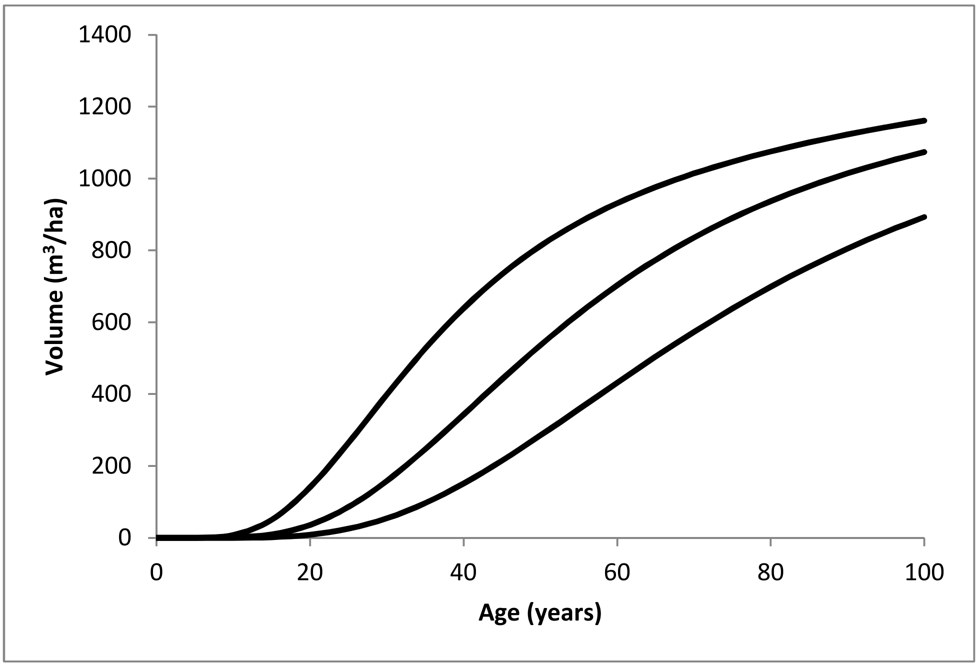


Figure 8.7. Volume/age curves for planted kauri from measurements of 25 stands (RMSE = 14.91, bias = 0.91). Curves represent the 90th, mid, and 10th percentile values for planted kauri stands. Volumes are based on actual measurements to age 83.

RMSE and bias for the volume model for kauri in planted stands were

RMSE	bias
14.91	0.91

All stands showed good agreement between the volumes predicted by the volume model and the actual data points at each measurement (Figure 8.8). **Stand 4** (age 67) and **Stand 16** (age 12) indicated a greater potential for planted kauri (Figure 8.9). **Stand 4** (765 stems/ha at age 67) had volume MAI exceeding 20 m^3/ha/yr from age 20, and is predicted to still be at 15 m^3/ha/yr at age 80. Periodic annual increment was as high as 28.8 m^3/ha/yr at age 40, when volume exceeded 820 m^3/ha. **Stand 16** (with 621 stems/ha at age 12) exhibited higher performance with volume MAI predicted to be in excess of 14 m^3/ha/yr at age 15, increasing to over 21 m^3/ha yr at age 20.

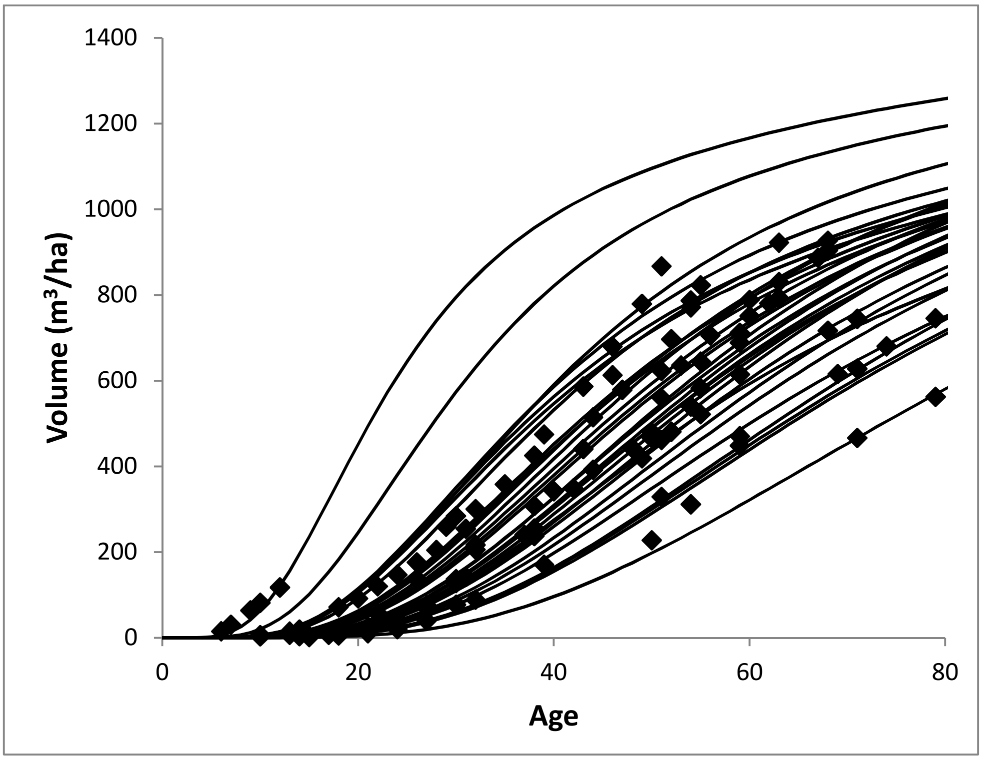


Figure 8.8. Family of volume/age curves for each planted kauri stand overlaid over individual data points. There is good agreement between curves for each planted stand and the actual data.

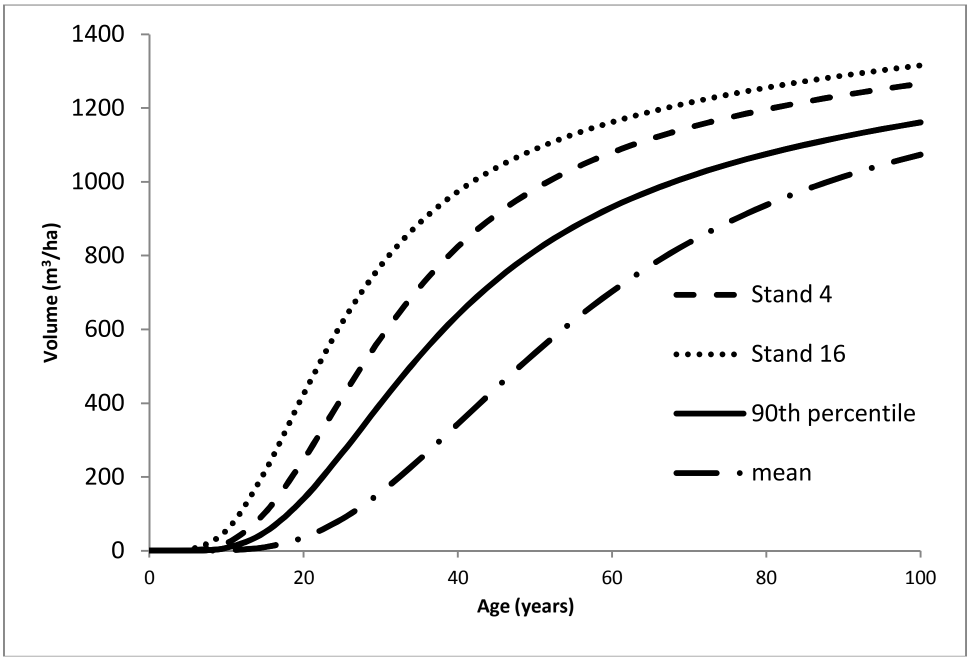


Figure 8.9. Comparison of predicted whole-tree stand volume of Stand 4 (age 73) and Stand 16 (age 12) with all planted kauri stands (mean and 90th percentile).

8.4.4 Mortality

Mortality was not observed at regular intervals during any of the stands histories (Figure 8.10). The exact point at which mortality occurred was not recorded as there were long intervals between observations for some stands. Mortality (%/yr) was calculated for three periods with the equations

1. planting to the first assessment $= \mathbf{(1-(N_1/N_0)^{(1/T1)})\times 100}$
2. first assessment to last assessment $= \mathbf{(1-(N_2/N_1)^{(1/T3)})\times 100}$
3. entire rotation (to date) $= \mathbf{(1-(N_2/N_0)^{(1/T2)})\times 100}$

where; N_0 = initial stand density T_1 = age at first assessment
N_1 = stand density at first assessment T_2 = age at last assessment
N_2 = stand density at last assessment T_3 = time between first and last assessment

Mortality in all planted kauri stands expressed as a percentage of the crop/yr.

	mean	**range**	**s.e.**
Planting to first assessment	0.64	0.0-3.91	0.15
First to last assessment	0.30	0.0-2.59	0.11
Entire rotation	0.56	0.0-3.91	0.14

The highest rate of mortality generally occurred in the years prior to the first assessment for most stands. Before the first assessment the average mortality was 0.64%/yr for all stands. Mortality was high in one stand (drought) and averaged 3.9%/yr from planting to the first assessment. Over the entire rotation (planting to the last assessment) mortality in all stands averaged 0.56%/yr. Stands where drought affected survival had higher mortality (2.7%/yr). When these were removed (two stands) mortality reduced to 0.4%/yr. During the period of observation for all planted stands (first to last assessment) mortality averaged 0.3%/yr, and reduced further when two drought prone sites were excluded.

In this study, a mortality equation has not been developed. A mortality equation will be developed as new stands are observed over regular intervals and are added to the database.

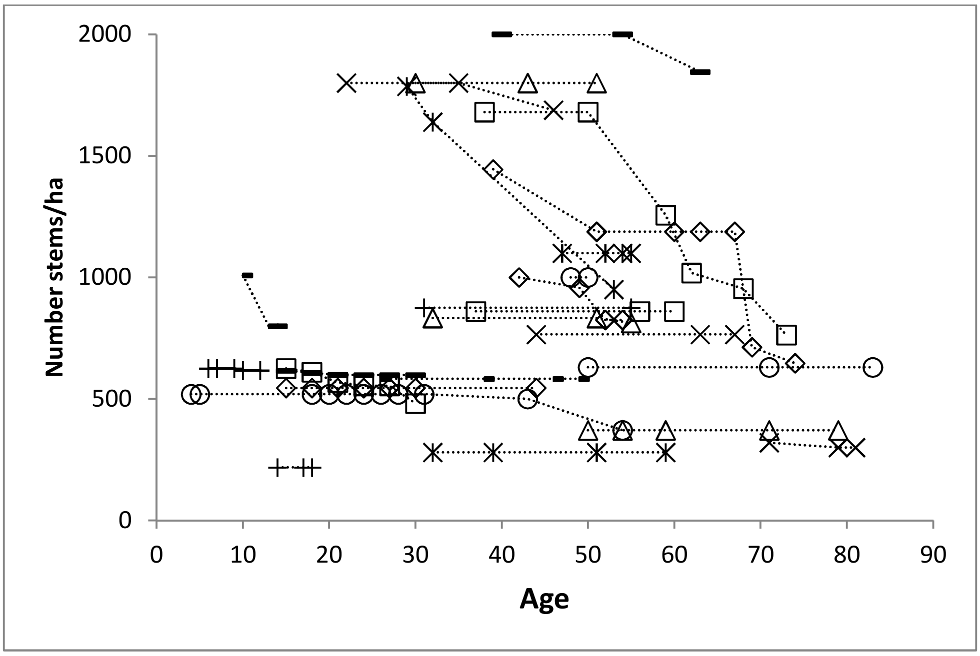


Figure 8.10. Survival (N stems/ha) within individual planted stands at each measurement. Mortality was not observed at regular intervals and therefore was not modelled.

8.5 SECOND-GROWTH KAURI

Models developed for kauri in planted stands for mean top height, basal area and volume were re-fitted to second-growth stands separately with recalculated parameter estimates. The equations found to fit planted kauri stands were also found to give the best fit for second-growth kauri.

8.5.1 Height

Height growth in unthinned and thinned stands was fitted separately using Equation 8.1 with parameter estimates modelled for each stand type. Site index (at age 50) was calculated for each stand, and stand type separately (Table 8.6). Site index for height (at age 50) varied considerably within treatments, with more variance in the unthinned stands. The highest site index was in the Whenuakite unthinned stand (17.1 m), with the lowest (3.9 m) in the Herekino unthinned stand. Mean site index was similar at 8.4 m (unthinned) and 8.9 m (thinned).

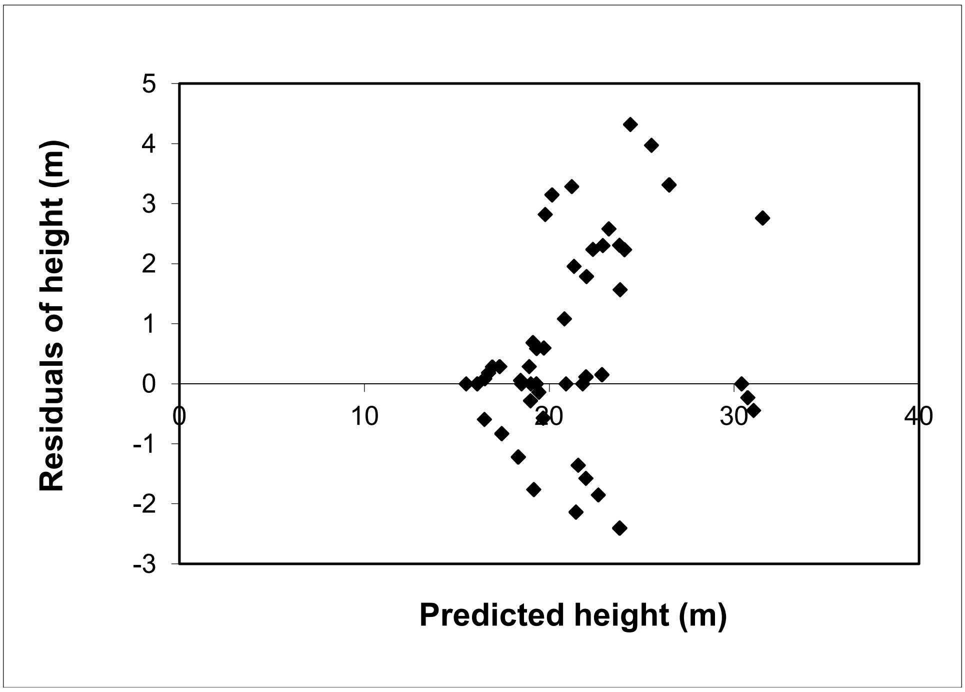
Parameter estimates (and their stand errors) for unthinned and thinned stands used in modelling height growth in second-growth kauri stands were (note parameter *a* was bounded)

Parameter	**Parameter estimate**			
	Unthinned	s.e.	**Thinned**	s.e.
a	44.5	-	44.5	-
c	-1.0488	0.0928	-0.9867	0.0514

Table 8.6. Site index (at age 50) for second-growth unthinned and thinned kauri stands. No thinning treatment in the Whenuakite stand.

Stand	**Site Index (height m)**	
	Unthinned	**Thinned**
Herekino	3.9	5.7
Papakauri	6.3	11.5
Kaiarara	5.6	4.5
Whangaparapara	8.8	12.6
Whenuakite	17.1	-
Mangatangi	9.1	10.9
Waitengaue	8.2	8.3
Mean	**8.4**	**8.9**
Range	**3.9-17.1**	**4.5-12.6**

The unthinned stands height model contained more bias (RMSE = 1.74) than the thinned stands (RMSE = 0.915) (Figures 8.11, 8.12). For both stand types, the models more often under-predicted height compared to actual heights. Bias in the models came from underestimation of height at older ages within two stands (Mangatangi and Waitengaue) that had higher than average stand density.



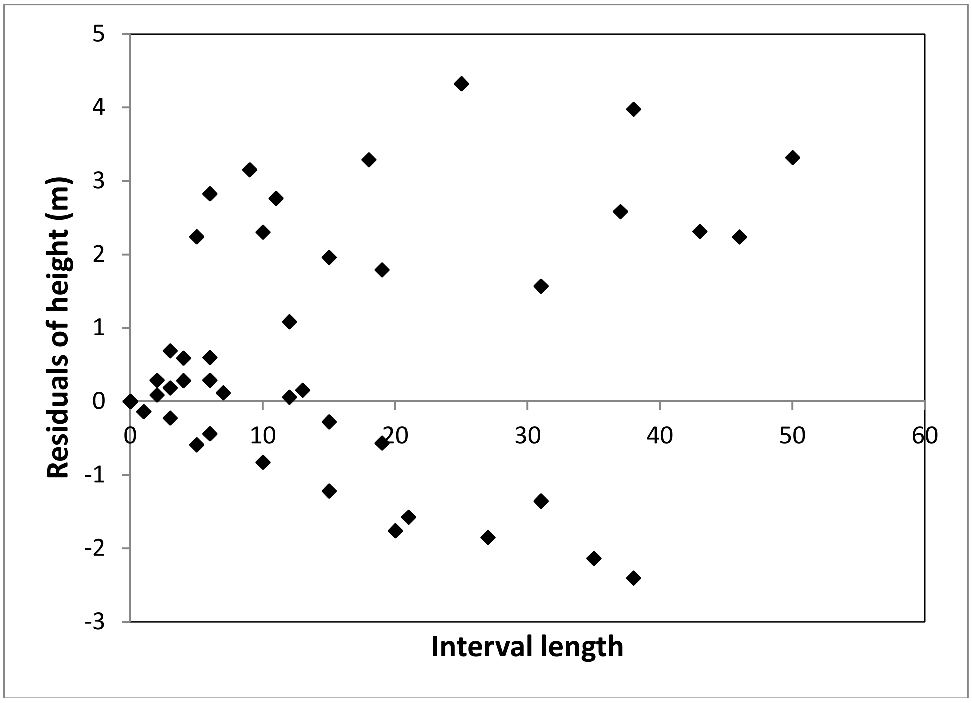
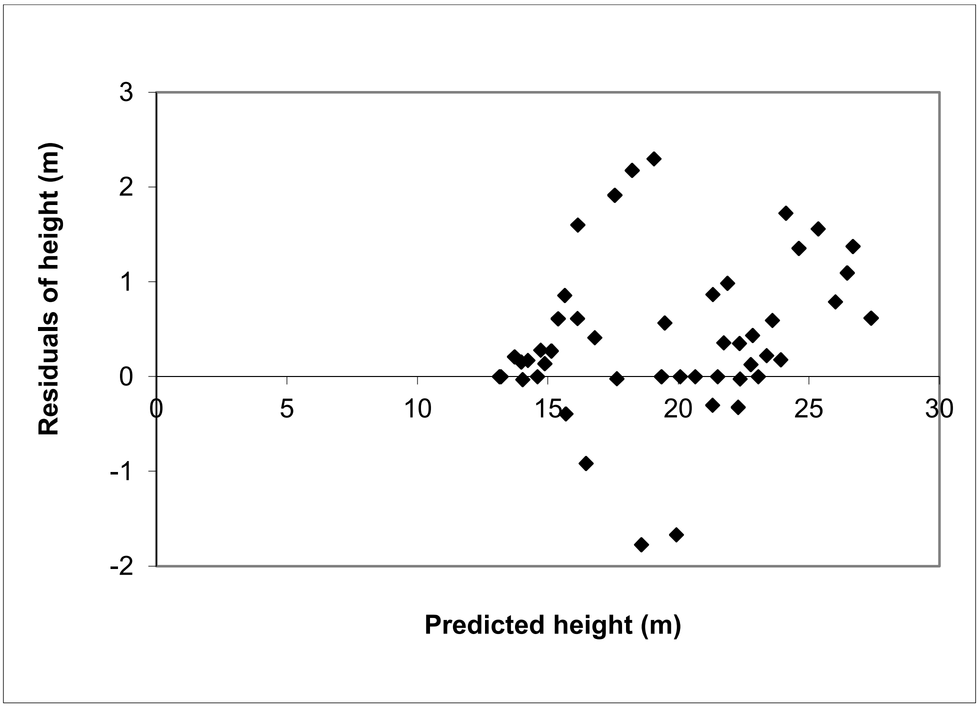


Figure 8.11. Schumacher mean top height model for unthinned (control) stands. Residuals of mean top height plotted against interval length (RMSE = 1.74, bias = 0.61).



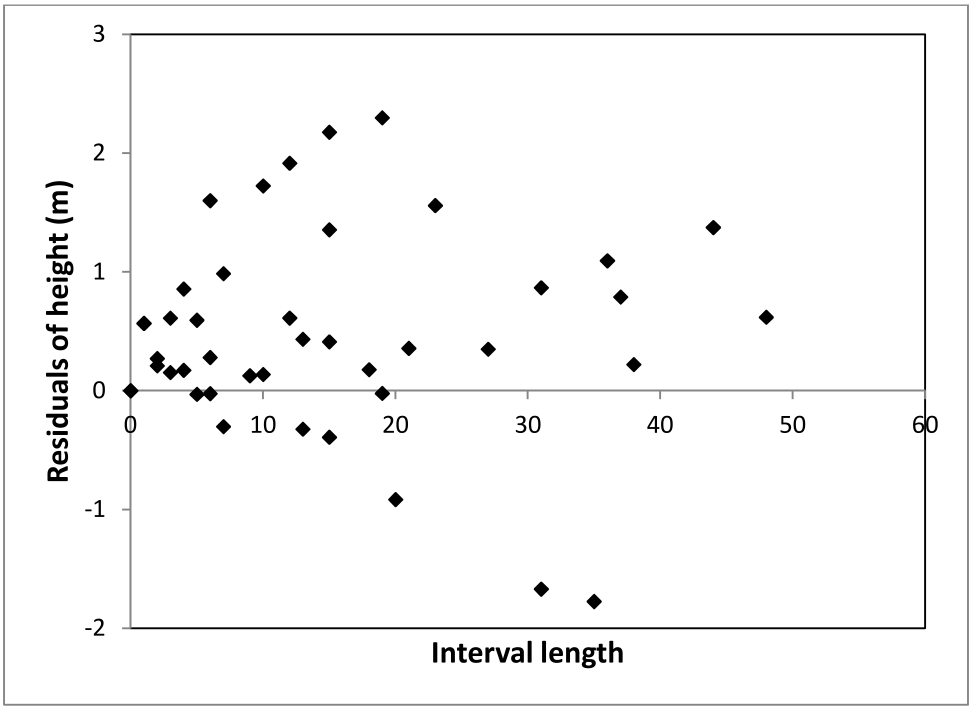


Figure 8.12. Schumacher mean top height model for thinned stands. Residuals of mean top height plotted against predicted height and interval length (RMSE = 0.915, bias = 0.4).

Mean top height trajectories were plotted. Height growth began slowly in both stand types and had not reached 10 m by age 50 (Tables 8.7, 8.8; Figures 8.17, 8.18). Height MAI peaked at age 100 for unthinned (0.19 m/yr) and thinned stands (0.2 m/yr). At age 150, heights were identical for both stand types (25.9 m) and at age 200 varied by only 0.2 m.

Table 8.7. Estimates of stand growth and productivity for kauri in unthinned second-growth stands at given ages. Values to age 200 are modelled on actual performance.

Age	Height (m)	Basal Area (m^2/ha/yr)	Volume (m^3/ha)	Volume MAI (m^3/ha/yr)	Volume PAI (m^3/ha/yr)
25	1.6	2.7	2.6	0.1	0.1
50	8.0	11.0	43.7	0.9	1.6
75	14.4	23.0	150.7	2.0	4.3
100	19.3	36.8	307.2	3.1	6.3
150	25.9	64.5	681.0	4.5	7.5
200	29.9	88.4	1043.8	5.2	7.3

Table 8.8. Estimates of stand growth and productivity for kauri in thinned second-growth stands at given ages. Values to age 180 are modelled on actual performance.

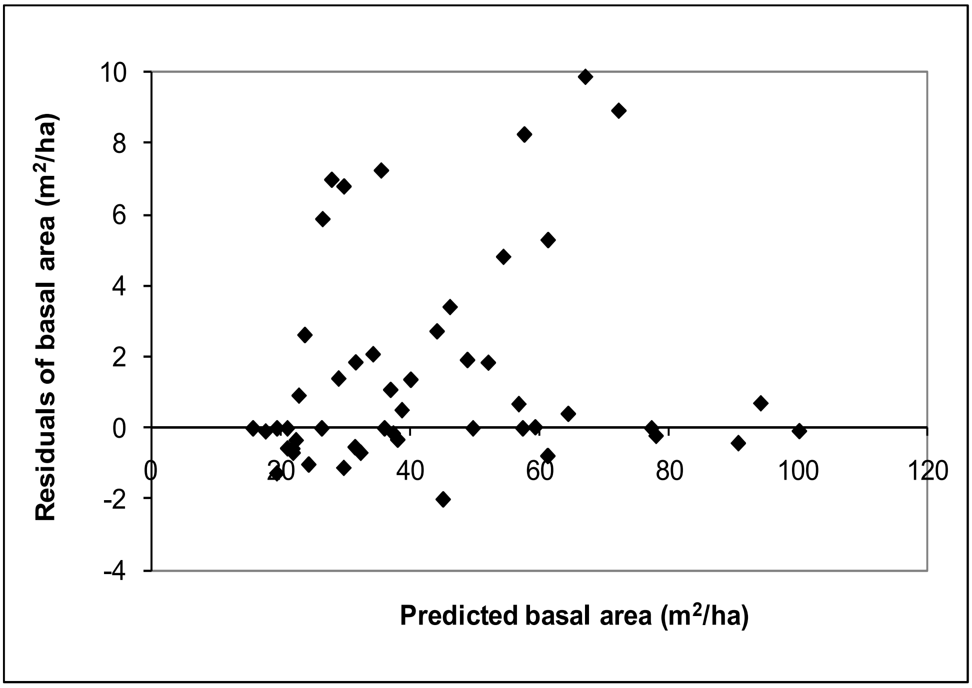
Age	Height (m)	Basal Area (m^2/ha/yr)	Volume (m^3/ha)	Volume MAI (m^3/ha/yr)	Volume PAI (m^3/ha/yr)
25	2.2	1.7	2.3	0.1	0.1
50	9.0	7.0	31.4	0.6	1.2
75	15.2	15.4	106.0	1.4	3.0
100	19.8	26.2	222.9	2.2	4.7
150	25.9	52.6	549.8	3.7	6.5

8.5.2 Basal Area

Basal area was modelled using Equation 8.2 with parameter estimates recalculated for each stand type. The model for thinned stands indicated a high (*a*) parameter estimate (319.1), while the model for unthinned stands gave a lower and more realistic estimate (152.4). Both the unthinned and the thinned stand basal area models displayed some bias when residuals were plotted, with the thinned stands (RMSE = 5.8, bias 1.93) more biased than the unthinned stands (RMSE = 3.29, bias 1.53) (Figures 8.13, 8.14). The fitted method used adjacent pairs of measurements while the plotted method used longer intervals. The actual difference of predicted values at individual points using longer intervals was minor. The same methods for fitting and plotting were used for the planted kauri data. The bias in the models resulted from underestimation of G in the Waitengaue stand, for both thinned and unthinned stands. Excluding the Waitengaue stand reduces the bias from 1.93 to 0.61 (thinned) and 1.53 to 0.86 (unthinned).

Parameter estimates (and their standard errors) for unthinned (control) and thinned stands used in modelling basal area growth in second-growth kauri stands were

Parameter	**Parameter estimate**			
	Unthinned	s.e.	**Thinned**	s.e.
a	152.4	23.752	319.1	720.1
c	2.3382	0.4662	2.1968	1.1266



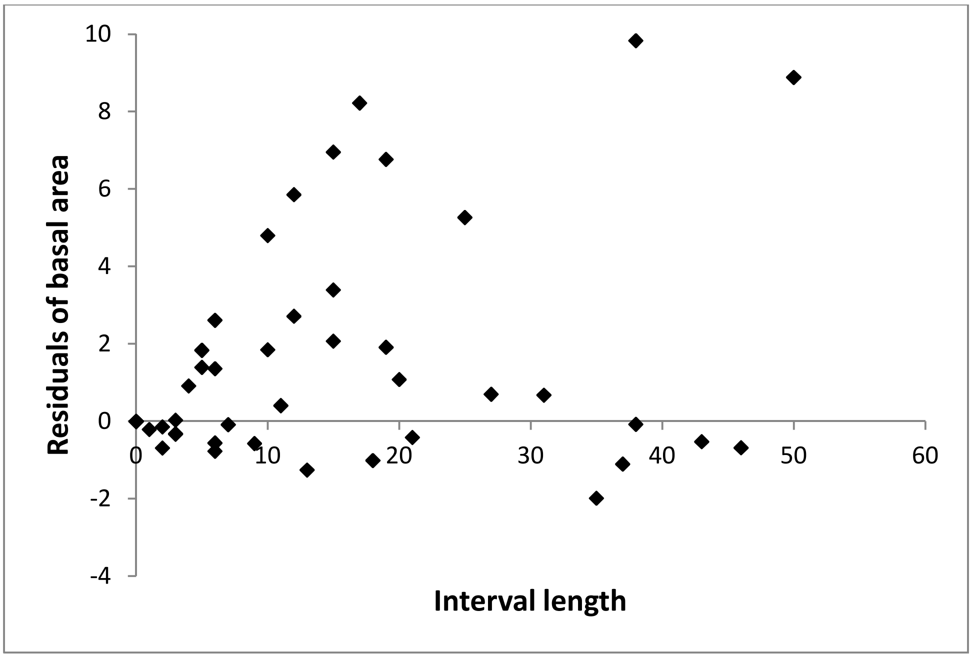
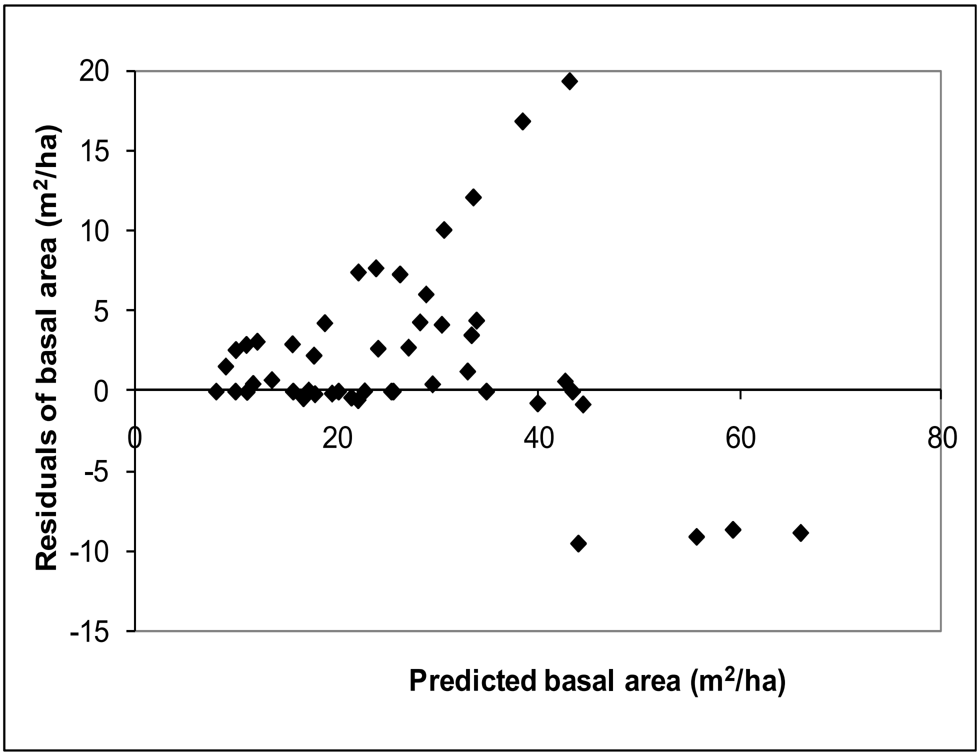


Figure 8.13. Von Bertalanffy-Richards basal area model for unthinned (control) stands. Residuals of basal area plotted against predicted basal area and interval length (RMSE = 3.29, bias = 1.53).



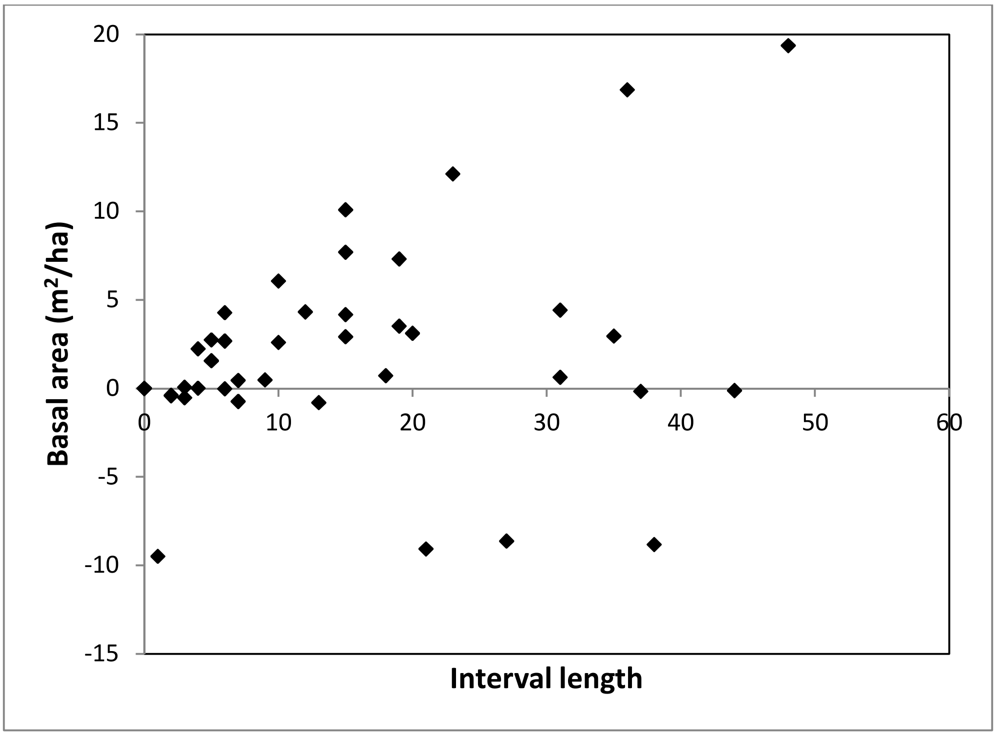


Figure 8.14. Von Bertalanffy-Richards basal area model for thinned stands. Residuals of basal area plotted against predicted basal area (RMSE = 5.8, bias = 1.93).

When the model was plotted against actual data points there was good agreement for most stands (Figures 8.15, 8.16).

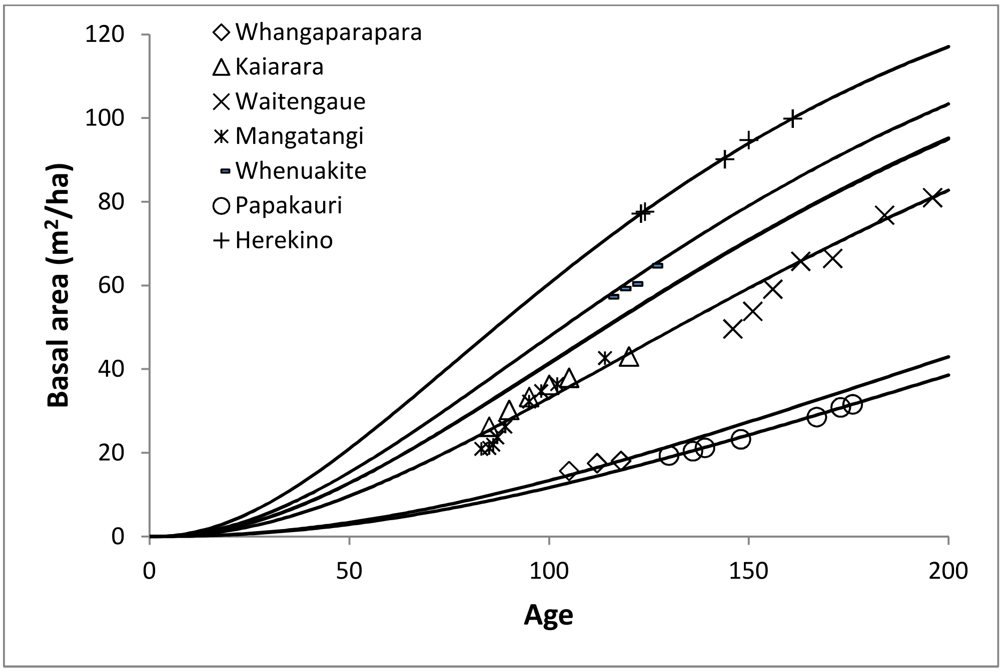


Figure 8.15. Family of basal area/age curves for unthinned second-growth stands with actual data points overlaid. The Waitengaue and Mangatangi stands had unusual early basal area development compared to other stands. The model fits well for all other stands.

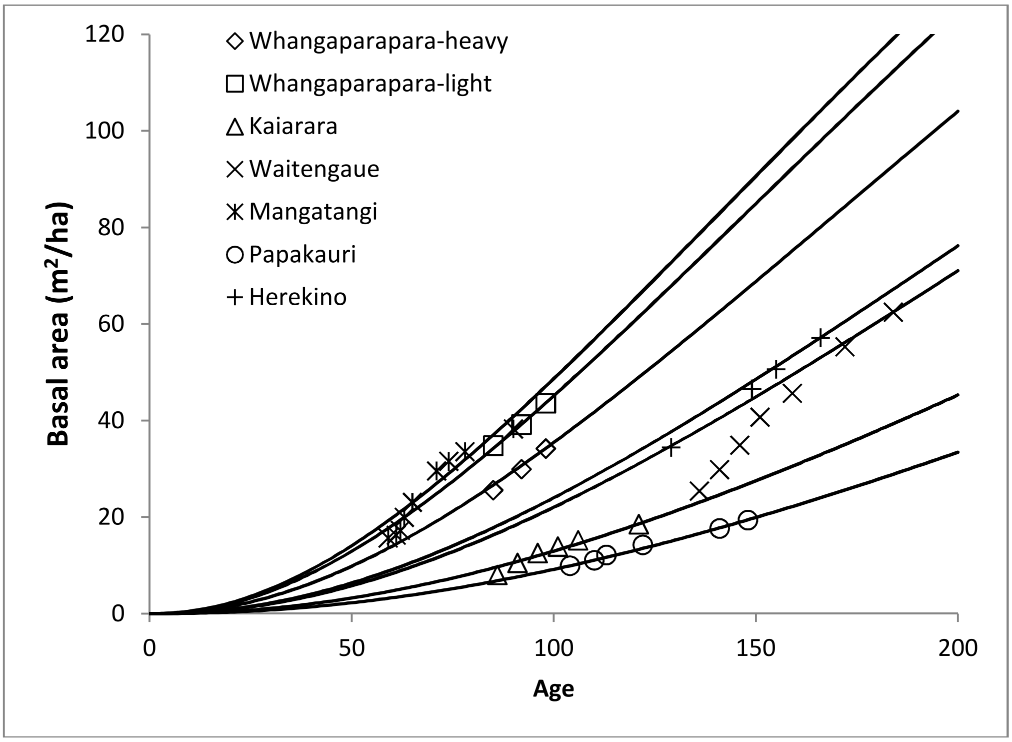
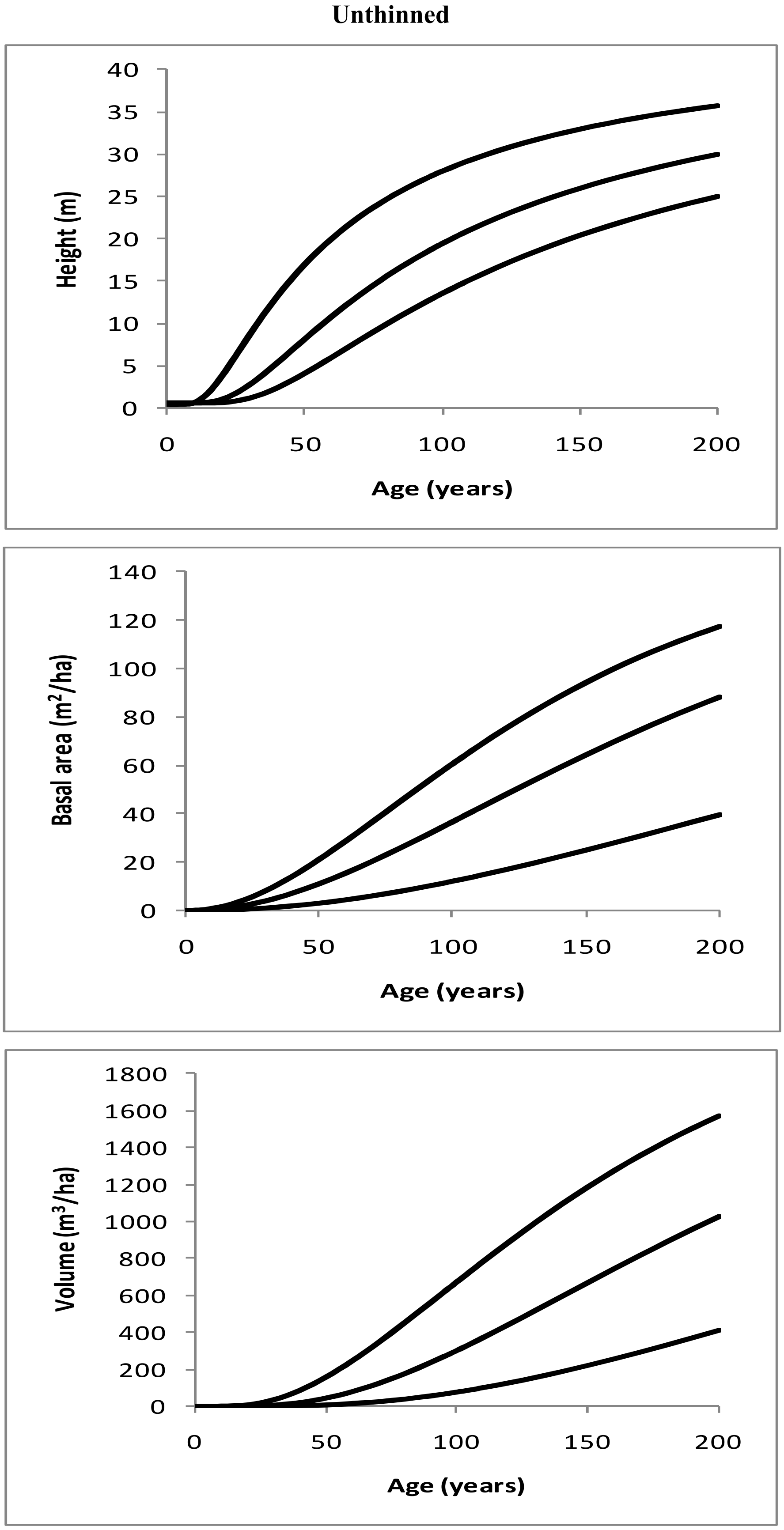


Figure 8.16. Family of basal area/age curves for thinned second-growth stands with actual data points overlaid. The Waitengaue stand had unusual early basal area development compared to other stands. The model fits well for all other stands.



Unthinned

Figure 8.17. Height, basal area and volume models for unthinned (control) second-growth kauri stands. For second-growth stands where only seven stands have been modelled, prediction lines are upper, mid and lower predictions.

Thinned

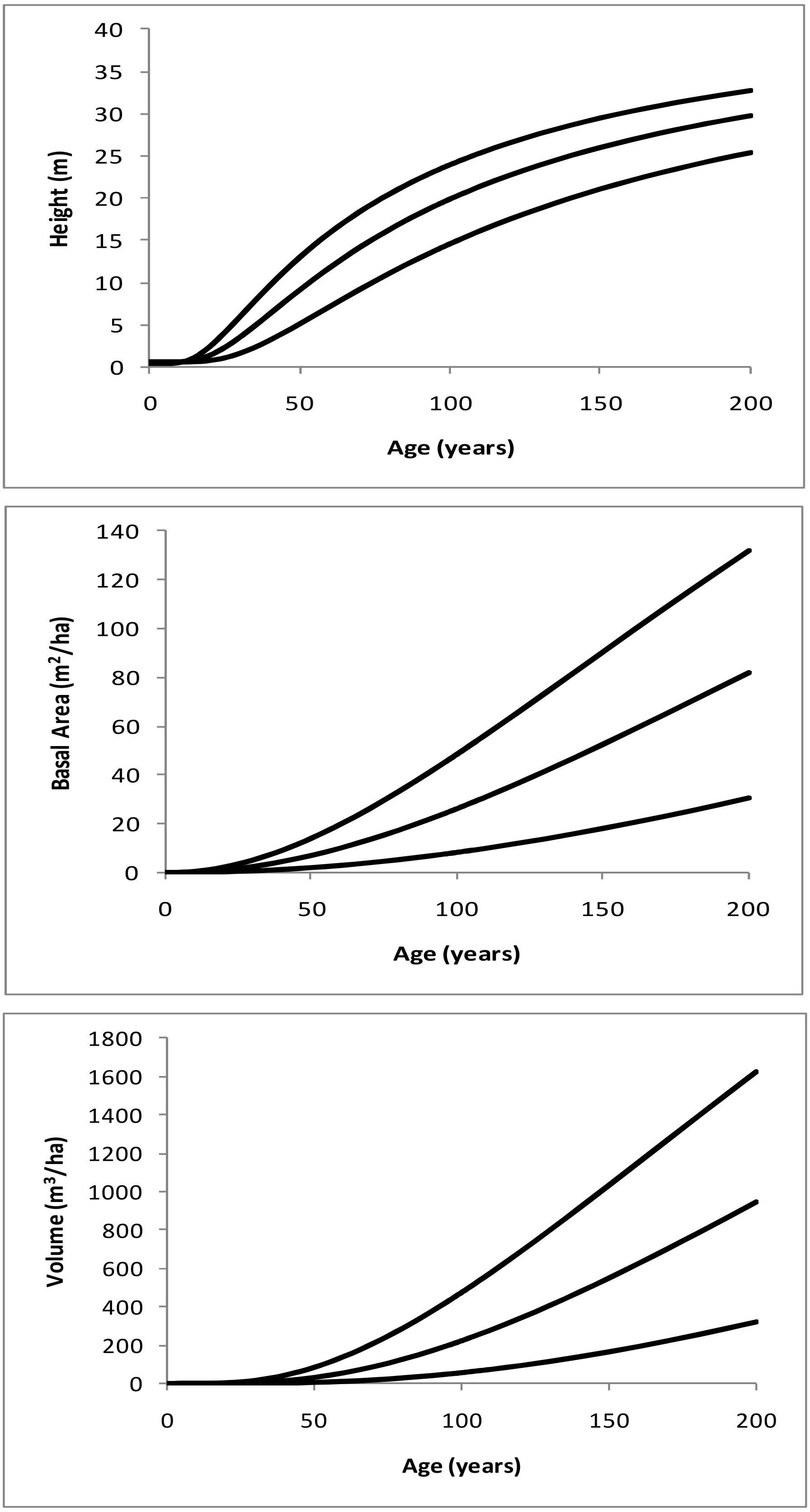


Figure 8.18. Height, basal area and volume models for thinned second-growth kauri stands. For second-growth stands where only seven stands have been modelled, prediction lines are upper, mid and lower predictions.

Basal area trajectories were plotted (Figures 8.17, 8.18). Basal area development began slowly in second-growth stands (Tables 8.7, 8.8). The unthinned stands reached 23 m^2/ha by age 75 (0.31 m^2/ha/yr), while thinned stands took 100 years to reach over 20 m^2/ha (0.2 m^2/ha/yr). Basal area removed in thinning was not predicted to be replaced until age 200 when G estimates became similar (88.4 m^2/ha v. 81.9 m^2/ha).

8.5.3 Volume

Volume was modelled using the same model used for kauri in planted stands (Equation 8.3), with the same (*a*), (*b*), and (*c*) parameter estimates. Volume developed slowly in both stand types with volume MAI only exceeding 5.0 m^3/ha/yr in the unthinned stands at age 200 (Tables 8.7, 8.8). Volume periodic annual increment at age 50 was <2.0 m^3/ha/yr for both stand types and reached its maximum (8.0 m^3/ha/yr) in the thinned stands at age 200.

Parameter estimates (and their standard errors) for the volume model for unthinned ($r^2$0.9926) and thinned ($r^2$0.9938) second-growth stands were

Parameter	Parameter estimate	Unthinned s.e.	Thinned s.e.
a	0.956	0.1557	0.1278
b	0.703	0.4160	0.0467
c	0.883	0.0727	0.0971

Volume trajectories were plotted (Figures 8.17, 8.18). The median projection lines reflect the data for both stand types while the upper projections to age 200 reflect the high (*a*) parameter estimates and the large variance in the data sets. When a family of curves for volume are plotted with actual data points included, the models fit the available data well (Figures 8.19 and 8.20). RMSE and bias for the volume models for second-growth stands were

Stand type	RMSE	bias
unthinned	32.6	-1.645
thinned	16.44	0.36

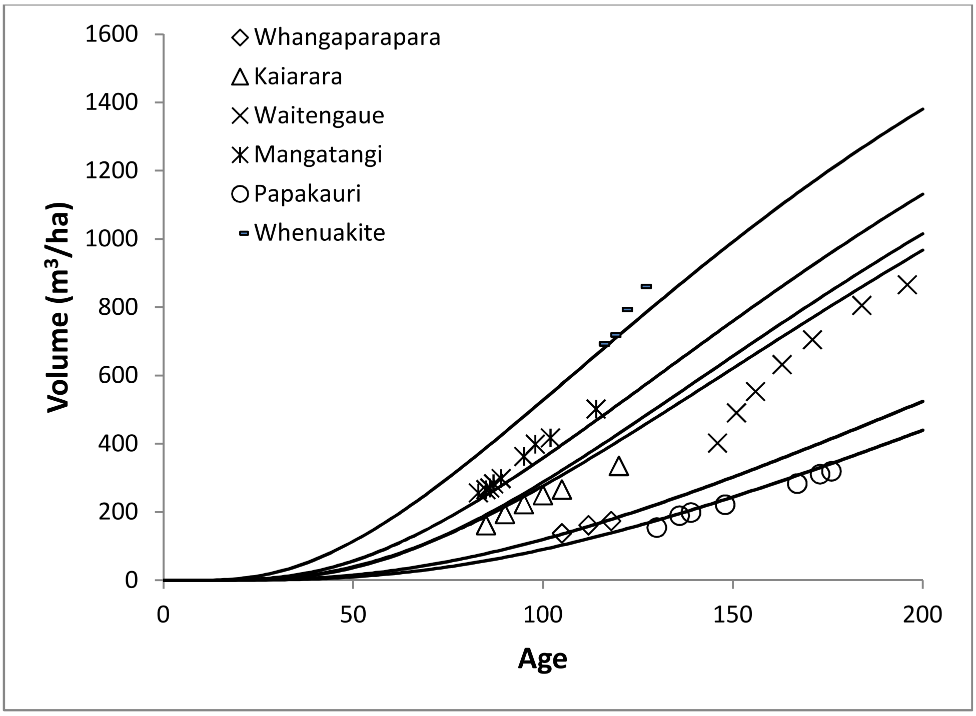


Figure 8.19. Family of volume/age curves plotted for unthinned second-growth stands with actual data points overlaid. The Waitengaue stand had different early volume development when compared to other stands. The model fits well for all other stands.

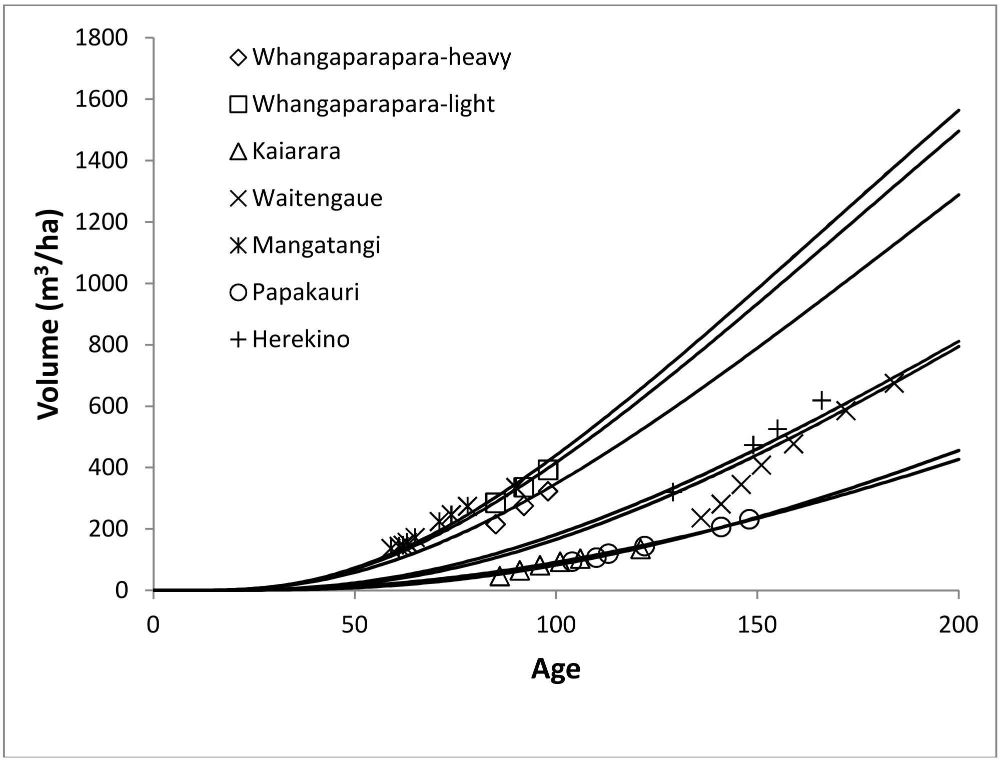


Figure 8.20. Family of volume/age curves plotted for thinned second-growth stands with actual data points overlaid. As with the unthinned stands, the Waitengaue stand had unusual early volume development different when compared to other stands. The model fits well for all other stands.

8.6 COMPARISON BETWEEN PLANTED AND SECOND-GROWTH STANDS

The median projection for height, basal area and volume for each stand type and treatment were plotted (Figure 8.21). While initial height growth in natural stands was slow, the shape of the curves for unthinned and thinned stands were similar. At age 50, kauri in planted stands were over twice the height (20.0 m) of kauri in natural stands (unthinned 8.0 m, thinned 9.0 m). By age 80, kauri in planted stands were predicted from actual data to be 25.7 m. In natural stands at age 75 height is predicted to be similar at 14.4 m (unthinned) and 15.2 m (thinned).

For basal area, kauri in planted stand had significantly higher productivity than natural stands (Figure 8.21). At age 50, second-growth stands perform similarly (11.0, 7.0 m^2/ha) while planted kauri basal area was 65.0 m^2/ha. The second-growth stands perform similarly with unthinned stands having higher basal area throughout.

Volume in planted kauri stands was significantly higher than the two second-growth stand types at all ages (Figure 8.21). The thinned and unthinned second-growth stands performed similarly, although the thinned stands continue to have less volume/ha than the unthinned stands throughout.

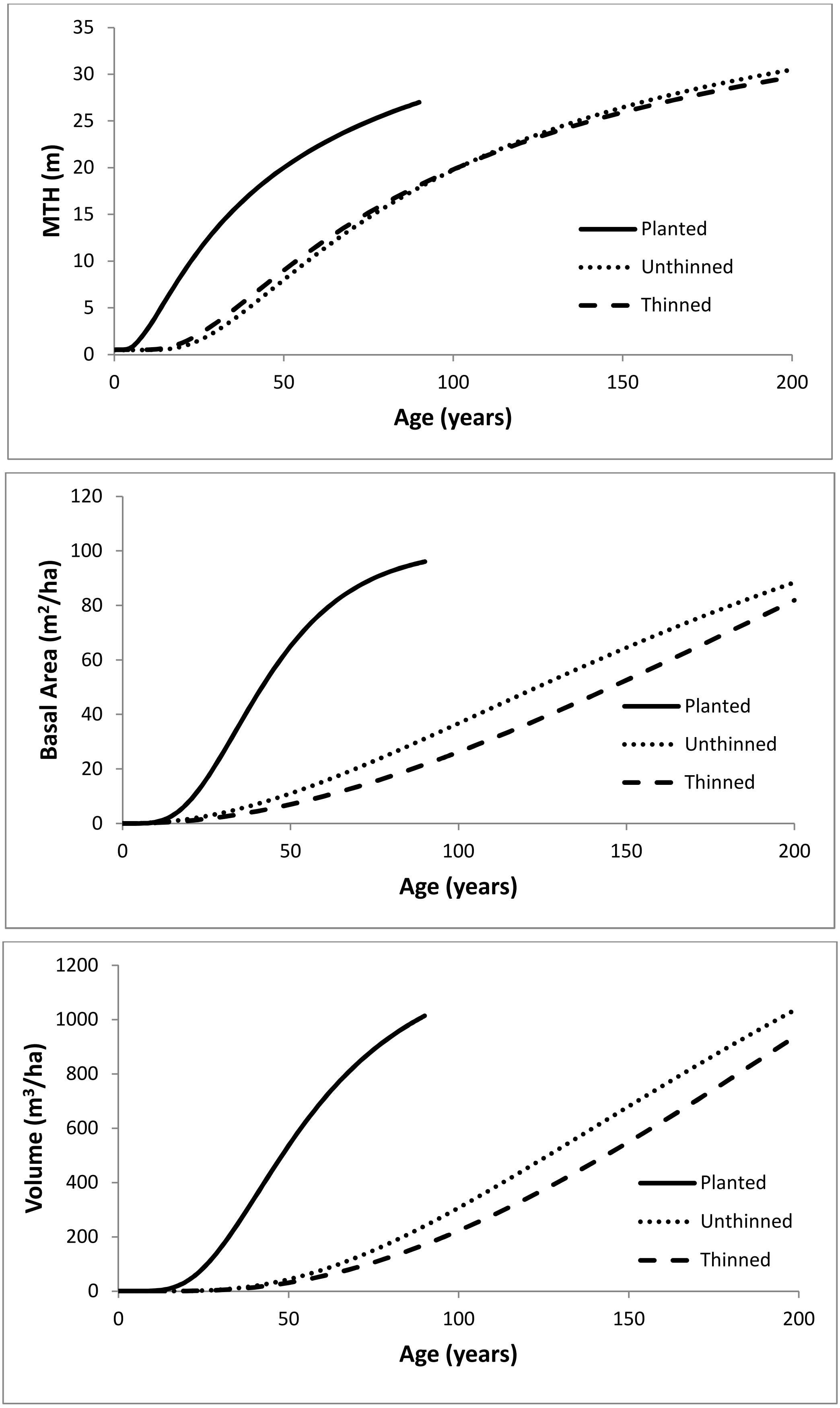


Figure 8.21. Comparison of height, basal area and volume between planted and second-growth kauri stands. For each model and each stand type the median prediction is shown.

8.6 COMBINED DATABASES AND MODEL VALIDATION

It was hypothesised that kauri in second-growth stands would perform similarly to kauri in planted stands once they emerged through an overhead canopy, and that growth and productivity of kauri in planted stands and second-growth stands could be fitted by one model. Therefore to test this hypothesis, all kauri growth data were combined into one dataset, and two further models of basal area were developed (Equations 8.4 and 8.5). These two nonlinear models were based on von Bertalanffy-Richards and Schumacher growth functions in difference form. Both equations included a local slope parameter, and incorporated a random parameter (*d*) that allowed for time of emergence through the canopy. Planted kauri stands were identified in the database by a dummy variable (1) and second-growth stands (0).

von Bertalanffy-Richards equation

$$\mathbf{G = \mathit{a}\times(1-(1-(G_{\mathit{i}}/\mathit{a})^{1/\mathit{c}})^{(T-ND\times \mathit{d})/T\mathit{i}-ND\times \mathit{d})})^{\mathit{c}}} \qquad \text{Equation (8.4)}$$

where;
G = basal area
G_i = initial basal area
a = asymptote parameter estimate (97.0049)
c = shape parameter estimate (6.1200)
d = time taken to emerge through the canopy (-19.1438)
T = age
T_i = initial age
ND = dummy variable where 0 = natural stand, 1 = planted stand

Schumacher equation

$$\mathbf{G = \mathit{a}\times EXP((((T-ND\times \mathit{d})/(T_{\mathit{i}}-ND\times \mathit{d}))^{\mathit{c}})\times LN((G_{\mathit{i}})/\mathit{a}))} \qquad \text{Equation (8.5)}$$

where;
G = basal area
G_i = initial basal area
a = asymptote parameter estimate (133.8)
c = shape parameter estimate (-1.5036)
d = time taken to emerge through the canopy (-16.7677)
T = age
T_i = initial age
ND = dummy variable where 0 = natural stand, 1 = planted stand

The models were run in SAS using the NLIN procedure and convergence was achieved for both. As with basal area modelling by stand type, the von Bertalanffy-Richards model gave the best fit. Residuals were calculated and plotted (Figure 8.22).

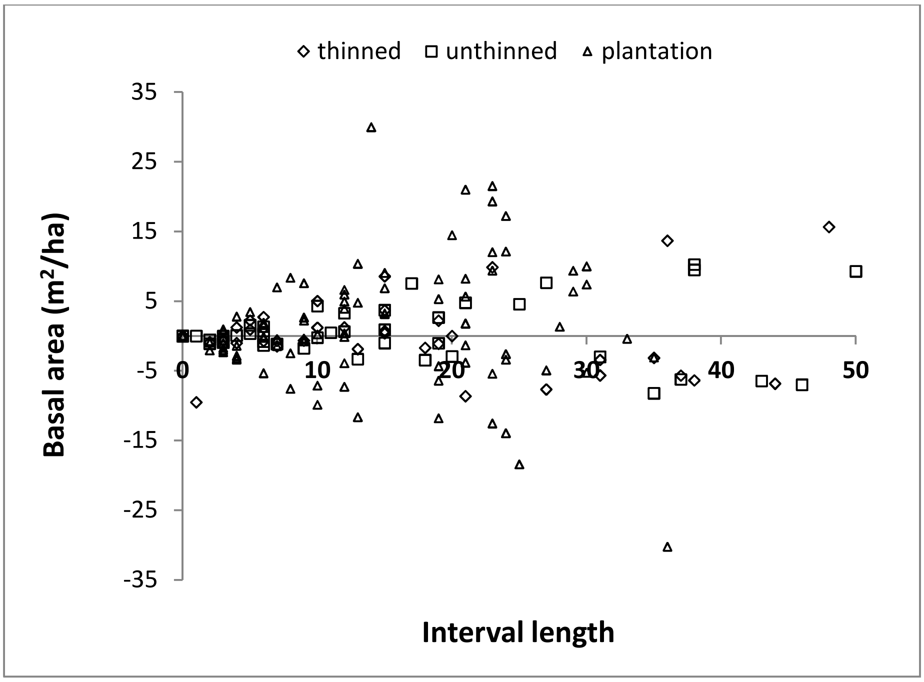


Figure 8.22. Residuals of basal area plotted against interval length using the von Bertalanffy-Richards model for basal area and incorporating a random variable (*d*) to allow for time of emergence through the canopy for natural stands.

Major conclusions drawn from combined databases were:

1. Incorporating a variable to allow for time of emergence through an overstorey canopy predicted that natural stands would grow faster than planted stands. This result was opposite to what was actually occurring in the stands. The model gave no better fit for the planted stands and the unthinned stands, but a slightly better fit for the thinned stands, when compared to the original models for each stand type separately (Table 8.9).

Table 8.9. Comparison of RSME's from basal area for planted, thinned and unthinned stands modelled separately and with a random variable (*d*) to allow for time of natural stands to emerge through the canopy. For the natural stands bias was reduced when incorporating a random variable when compared to modelling them separately.

Stand type	**Stands modelled separately**		**Stands modelled with random (*d*) variable**	
	RMSE	**bias**	**RMSE**	**bias**
planted	7.58	0.44	7.60	1.00
unthinned	3.29	1.53	3.90	0.44
thinned	5.80	1.93	4.83	0.08

2. One model (the Schumacher model for mean top height for kauri in planted stands - **Equation 8.1**, and the von Bertalanffy-Richards model developed for basal area for planted kauri - **Equation 8.2**) will fit all three site types. When using these models and coefficients for planted stands for asymptote (*a*) and shape (*c*) on data from natural stands the results for unthinned stands are similar, but improved for thinned stands (Table 8.10, Figure 8.23).

Table 8.10. Comparison of RSME's for basal area for all stand types modelled using the planted kauri basal area model.

Stand type	Stands modelled separately		All stands modelled with planted stand model	
	RMSE	bias	RMSE	bias
planted	7.58	0.44	7.58	0.44
unthinned	3.29	1.53	3.70	0.19
thinned	5.80	1.93	4.85	-0.004

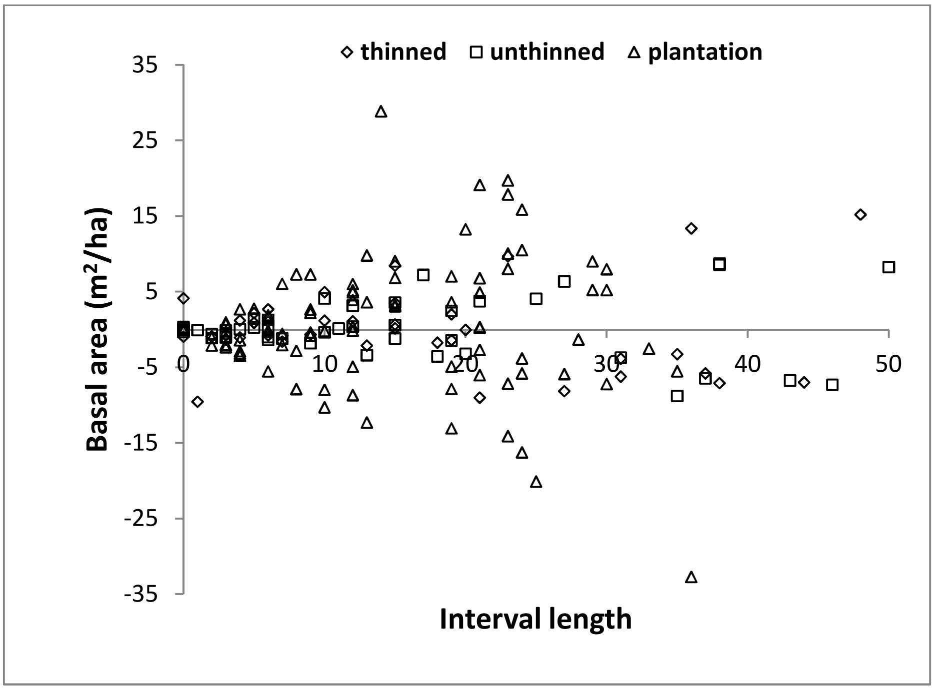


Figure 8.23. Residuals of basal area for all stand types produced with the planted kauri stand model and coefficients.

3. Volume models were fitted individually to all stand types, and then compared with a combined database for all site types (planted, second-growth unthinned and thinned) combined. Volume was fitted using log volume as a linear regression of log G and log

> MTH. For each stand type the model fitted well ($r^2$0.993 or better). The databases were combined and the volume model was refitted ($r^2$0.9973). The volume model developed for kauri in planted stands **(Equation 8.3)** is the model recommended for developing volume predictions for kauri on all three site types.

Validation of models was undertaken for kauri in planted stands only. The models for second-growth kauri were developed only as a means of making comparisons between planted versus natural kauri stands. As the number of planted kauri stands available for modelling the mean top height and basal area development was small (25 stands) it was not possible to construct meaningful training and test sets. Therefore to validate the MTH and G models for planted kauri, the one-at-a-time cross-validation method was used. The models were re-fitted to the data, leaving out one stand at a time. New parameter estimates were acquired and the models were refitted and RMSE and bias were calculated (Table 8.11). For both MTH and G the validation process resulted in an increase in RMSE, but bias is either similar or marginally smaller. The results indicate a good fit for models to predict height growth and productivity for stands planted on a wide range of sites throughout New Zealand.

Table 8.11. The planted stand models for mean top height and basal area were validated using the one-at-a-time cross-validation method. The models validated well using this method with small increases in RMSE, and bias similar for basal area and an increase for mean top height.

	MTH		**Basal Area**	
	RMSE	**bias**	**RMSE**	**bias**
Model	1.301	0.09	7.58	0.44
Validation	1.555	0.37	8.327	0.41

8.7 CONCLUSIONS

One model, the anamorphic Schumacher model for mean top height, for planted kauri - **Equation 8.1** $\mathbf{MTH = 0.5+a\times exp(((T/50)^c)\times ln((SI-0.5)/a))}$ **-** will fit all three site types with the coefficients (a = 44.5; c = -0.7903) giving a bias of 0.09 and RMSE of 1.301.

The polymorphic von Bertalanffy-Richards model developed for basal area for planted kauri - **Equation 8.2** $\mathbf{G = a\times(1-(1-((G_i/a)^{1/c})^{T/Ti}))^c}$ - will fit all three site types with the coefficients (a = 101.4; c = 5.6971) giving a bias of 0.44 and RMSE of 7.58).

The volume model fitted using log volume as a linear regression of log G and log MTH, developed for planted kauri **- Equation 8.3 $\mathbf{Vol = b \times G^{a} \times MTH^{c}}$ -** is the model recommended for developing volume predictions for kauri on all three site types using the coefficients (a = 0.956; b = 0.703; c = 0.883) giving a bias of 0.91 and RMSE of 14.91.

The models produced from this study indicate substantive differences in performance and productivity between planted and second-growth kauri. However, they have also been shown to be able to modelled in one database with the bias introduced most likely to be explained by within-stand competition in second-growth stands, and site quality.

The basal area model for kauri in planted stands was asymptotically stable, while the mean top height model was bounded at 45 m. The models produced for second-growth stands were asymptotically stable for unthinned stands. In thinned stands, the model had difficulty fitting one site but gave a good result for all other sites. In combined datasets the models were stable.

Kauri in planted stands were shown to be at least three times the height of kauri in natural stands at the site index age (50 years) and can produce up to 20 times the volume at age 50. The worst of the planted stands have performed better than the best of the natural stands for height and basal area growth and for volume productivity. Reasons for this were not examined in this study, but differences in site quality, times to emergence from the canopy, and stand structure are all potential explanations that can be tested in the future.

Mortality of kauri in planted stands averaged 0.56%/yr from planting to their last assessment, but was as high as 3.9%/yr for one stand where drought was a problem. Most mortality occurred before the first assessment for all stands and averaged 0.64%/yr. Mortality between the first and last assessment for all stands was 0.3%/yr, with no mortality occurring in 19 of the sample plots. No mortality was attributed to stand density.

Models developed in this study are relevant only to kauri that are in the “ricker” or monopodial (orthotropic) form irrespective of age, and for stands from 320-2000 stems/ha. The models are relevant to kauri planted on sites within and outside the species current natural range.

CHAPTER 9

DISCUSSION AND CONCLUSIONS

9.1 MODELLING

The models developed in this study performed well despite the limited size and scope of the contributing data. The models developed for kauri grown in planted stands, based on observations of 25 stands, were more robust than those for the second-growth natural stands that were based on seven stands. There was considerably more variation in performance and productivity of kauri in second-growth stands. Second-growth stands were frequently on atypical, upland sites where earlier pastoral activities could not be supported. Therefore, it was not surprising to find inferior growth, particularly when compared to planted stands established on lowland, fertile sites.

The volume MAI of kauri in second-growth stands predicted by Halkett (1982) of 5-9 m^3/ha/yr was not supported by the current models for either natural stand type. Volume MAI for both unthinned and thinned second-growth stands peaked at 5.5 m^3/ha/yr and was considerably lower than expected. The diameter and height growth of kauri in second-growth stands is most likely restricted by a combination of factors including shading from an overhead canopy and within-stand competition (Bieleski, 1959; Barton, 1982). These are the same factors limiting expansion of kauri from existing natural stands as a shade-tolerant but slow-growing seedling under natural forest conditions (Barton, 1983a). In the second-growth stands included in this study, all kauri above 5.0 cm were measured, but not all kauri were emergent or dominant trees. In some stands, particularly the unthinned stands, much of the kauri composition was sub-dominant, young saplings and poles beneath a canopy. Sub-dominant kauri would have suffered the effects of reduced light capture and efficiency discussed by Niinemets et al. (2005). The majority of natural stands were on upland sites (the average elevation was higher than for planted stands (117 m a.s.l. v. 174 m a.s.l.) and had poorer soils/fertility than planted stands. Soil fertility and deficiencies of nitrogen, phosphorous and other minerals were identified as contributing factors in reduced kauri height growth in 30 year-old planted kauri stands in Omahuta Forest (Nieuwland, 1979), and laboratory and field experiments (Peterson, 1961, 1962). Similar trends were seen in the closely related *Agathis robusta* (C.Moore ex F.Muell.) in southern Queensland, Australia (Richards, B. N. & Bevege, 1967).

Thinning and its impact on the diameter growth of kauri in second-growth stands also influenced volume increment. Kauri in thinned stands and kauri of larger initial diameter generally grew more rapidly in diameter than kauri in unthinned stands (Figure 9.1). The scale of the effect was determined by initial diameter, stand density of individual sites before and after thinning, and the emergence status of individual kauri in relationship to a competing canopy. This was best illustrated by the Whangaparapara stand where two thinning intensities were applied and compared to an unthinned stand. Diameter increment (current annual increment) in the heavily thinned treatment was better for all diameters than either the unthinned or light thinning (Figure 9.2). The light thinning treatment resulted in better diameter increment than the unthinned, but only approached the diameter increment of the heavy thinning for larger diameters; presumably emergent kauri. As kauri emerges through the overtopping canopy they may still be at high stand density and therefore continue to compete with each other for growing space and resources. However, kauri appear to be able to persist in this state for extended periods of time, and have some ability to respond when conditions improve (Barton & Horgan, 1980; Barton & Madgwick, 1987).

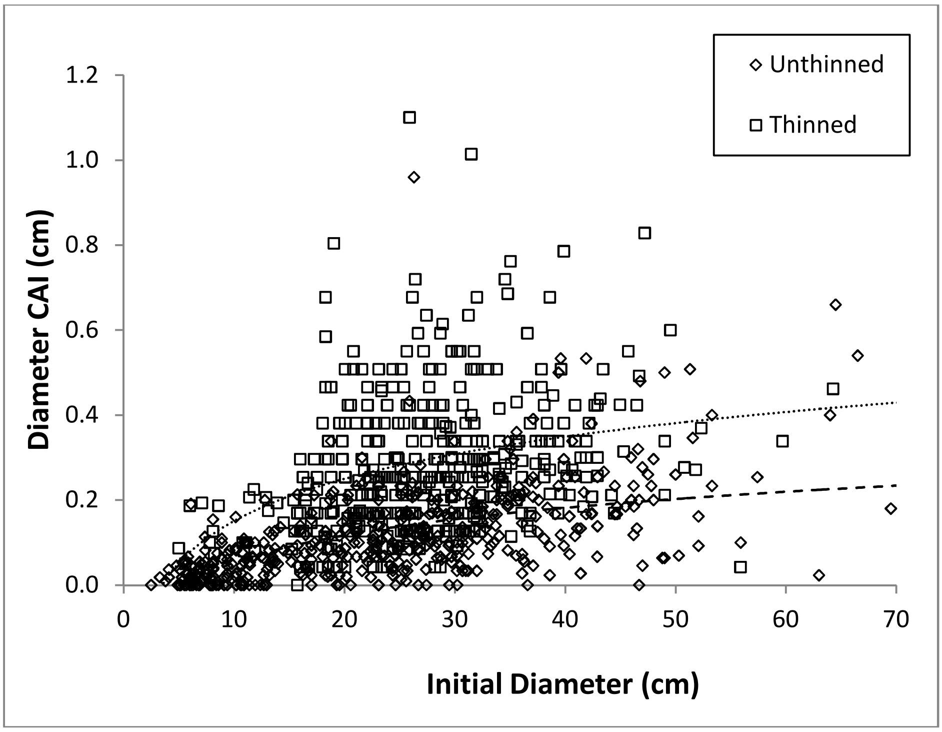


Figure 9.1. Current annual increment of kauri in unthinned and thinned stands plotted against initial diameter (all stands combined). Diameter CAI is determined by the initial diameter, stand density and/or the emergence status of individual kauri. Upper trend line represents thinned stands; lower (dashed) trend line represents unthinned stands.

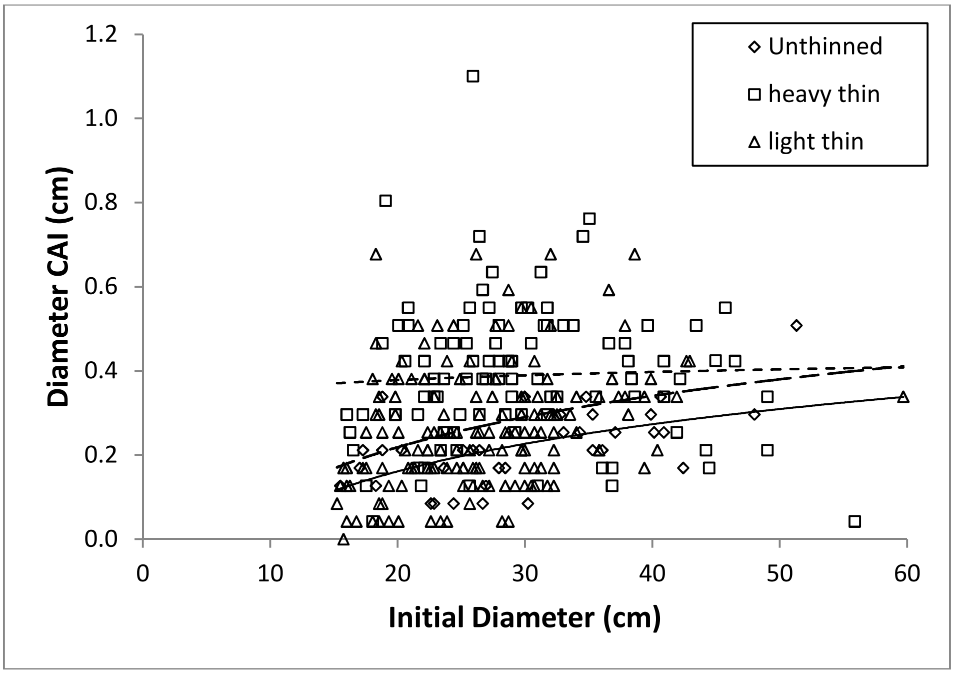


Figure 9.2. Comparison of the effect of two thinning intensities on diameter increment compared to the unthinned stand at Whangaparapara. The heavy thinning treatment resulted in better diameter current annual increment for all diameters while the light thinned and unthinned had slower diameter increment for smaller diameter kauri. The unthinned stand generally had slower diameter increment than the two thinned stands. Upper trend line represents heavy thinning; mid-trend line represents light thinning; lower trend line represents unthinned treatment.

The ages derived for individual kauri in natural stands in this study were based on breast height 5 mm increment cores. It can take some time for natural kauri to reach 1.4 m. There is likely to be some considerable variation, and it is likely that the response time would be site-specific. Burns & Smale (1990) found a mean age of 40 years for kauri seedlings to reach 1.4 m (range 30-56 years) at one natural stand on the Coromandel Peninsula. These values were higher than those reported by Ogden (1983) who estimated 26 years to reach 1.4 m for kauri in the Auckland region. Regenerating kauri in Russell forest were estimated to be 14 years old at 1.5 m (Lloyd, 1960). The MTH models developed during this study predict that natural stands would take 19-20 to reach 1.4 m (on average). The use of the 0.5 m intercept for both planted and second-growth stands and the time taken to reach 1.4 m in height explains the under-estimation of the emergence time in second-growth stands in the combined modelling approach.

9.2 COMPARISON WITH OTHER MODELS OF NZ KAURI

The models produced in this study for planted kauri stands were compared with the models for mean top height, basal area and volume produced by Herbert et al. (1996), and the basal area model produced by Chikumbo & Steward (2007). The height model of Herbert et al. (1996), based on two

Taranaki planted stands and measurements to age 60, fitted the current model reasonably well, but with a somewhat different shape (Figure 9.3). This difference in shape may be explained by the current model being based on the Schumacher growth function with data from 25 stands, while the Herbert et al. height model was based on the von Bertalanffy-Richards growth function using data from only two stands. In the current study, the von Bertalanffy-Richards growth function was shown to over-predict early height growth compared to the Schumacher growth function. The Schumacher growth function in bounded form fitted the actual data in the current study. The extrapolation by Herbert et al. (1996) from age 60 to 80 is supported by the current model based on measured data to age 83 (Figure 9.3).

The basal area model from the current study was compared with the two earlier basal area models of Herbert et al. (1996) and Chikumbo & Steward (2007). All basal area models were based on the von Bertalanffy-Richards growth function. In the current study and that of Chikumbo & Steward (2007), the growth function of von Bertalanffy-Richards was in difference form. Until around age 40, all models are in general agreement. From age 40 the models diverge (Figure 9.4). The predictions of Herbert et al. (1996) from age 40 years to 60 years are almost linear and had an assumption that diameter MAI was unlikely to fall below 2.0 mm/yr. From age 60 the extrapolated predictions of Herbert et al. (1996) were not supported by either the current study or that of Chikumbo & Steward (2007). The basal area model of Chikumbo & Steward (2007) is in general agreement with the current model.

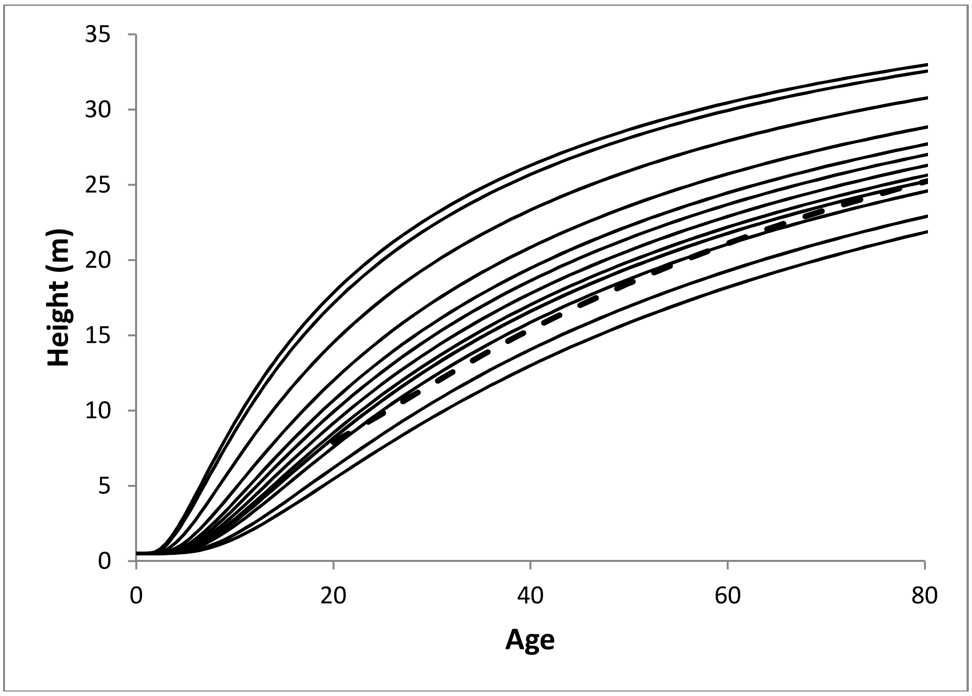


Figure 9.3. Family of curves from the current mean top height model with the model of Herbert et al. (1996) overlaid. The model of Herbert et al., based on two stands and measurements to age 60, is in agreement with the current model. (Current model = solid lines; Herbert et al. = dashed line).

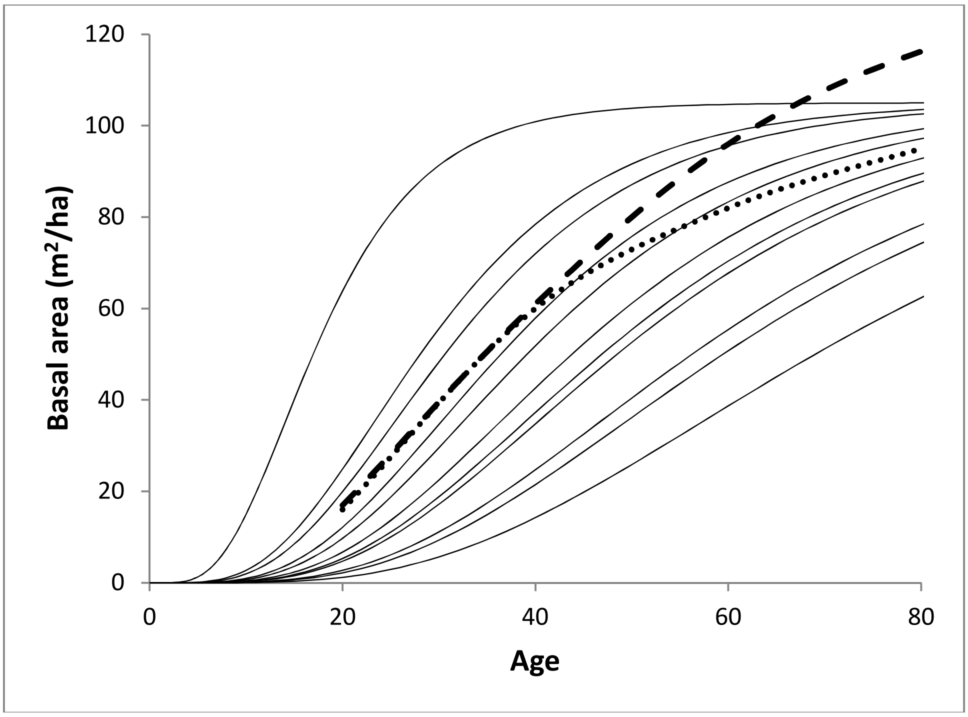


Figure 9.4. Family of curves from the current basal area model with the model of Herbert et al. (1996) and Chikumbo & Steward (2007) overlaid. (Current model = solid lines; Herbert et al. = dashed line; Chikumbo & Steward = dotted line).

The volume model from the current study was compared with that of Herbert et al. (1996) (Figure 9.5). The two models were based on predictions that were developed using different growth functions for height. While they predict similar values until around age 40, the shapes of the models were different. From age 40-60, and then extrapolated to age 80, Herbert et al. (1996) projected volume increment in an almost linear form. Their projections from age 50-60 are not supported by the current model, nor are the extrapolated values to age 80. In planted stands with either higher stand density or better performance (all stands above the dashed line representing the Herbert et al. predictions) there is an indication of an asymptote effect seen by age 40-50 at the oldest.

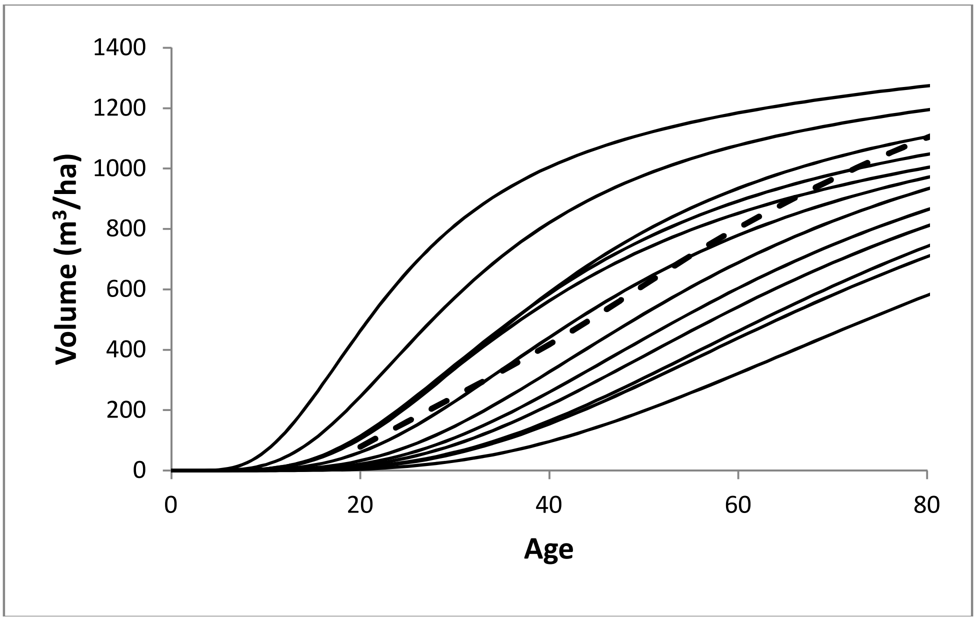


Figure 9.5. Family of curves from the current model of volume with the model of Herbert et al. (1996) overlaid. The model of Herbert et al., based on two stands and measurements to age 60, is largely in agreement with the current model to age 60. (Current model = solid lines; Herbert et al. = dashed line).

The volume model from the current study was also compared with a simple yield table of estimated average volumes for stands at c. 800 and 1000 stems/ha to age 80 years. The yield table was constructed from averaged values after calculating individual stand volumes for kauri in planted stands, but before the models of height, basal area and volume were developed. The volumes from the yield table were plotted against age and followed a similar trend, with increased separation in volume between projections as stand age increased, and where stand density was assumed to remain constant (Figure 9.6). When the volume model for planted kauri was completed, the mid-line projection was overlaid over the earlier yield table projections. While the projections of the yield table are reasonable at age 80 years against the models mid-line predictions, there are a number of important differences in the volume projections based on yield tables and on models of height and basal area developed from sigmoidal growth functions. These differences would be important when estimating timber volume recoveries and potential carbon sequestration through a stand's life. Until age 20 years the model predicts very little volume production (c. 35.0 m^3/ha) while the yield table estimates volumes of 134 and 168 m^3/ha. The volume model does not begin to approach the yield table estimates until age 40. At age 80, the volume predictions in the model begin to plateau, while the yield table indicates ongoing volume increment at an almost linear projection. The volume estimates derived from the volume model agree with the actual data.

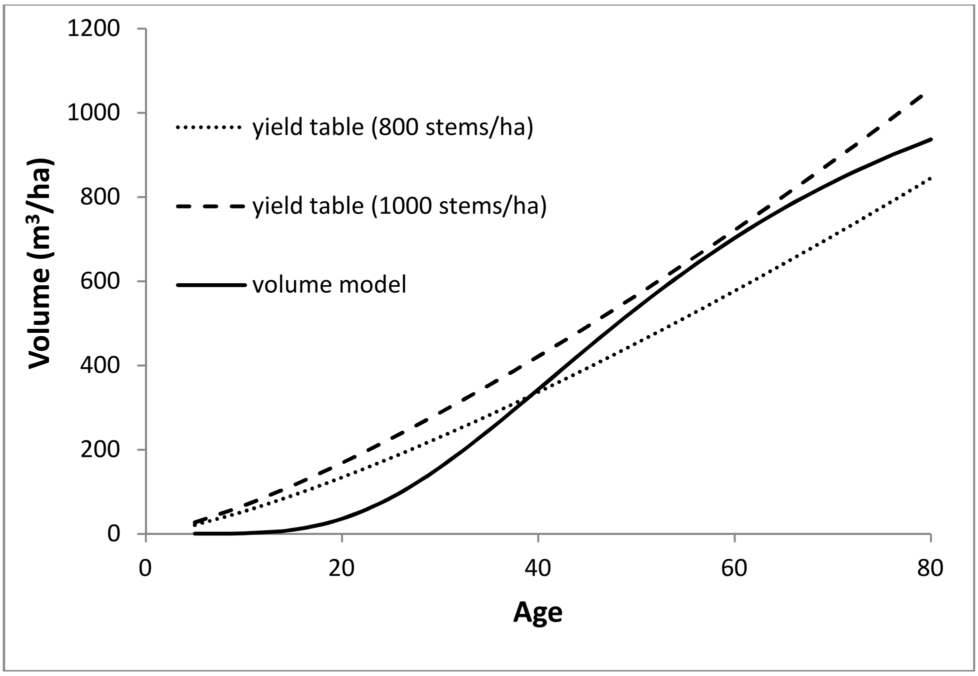


Figure 9.6. Estimates of volume production from planted kauri stands based on simple yield table estimates of averaged data at c. 800 and 1000 stems/ha compared with mid-line projections from the planted kauri volume model.

9.3 COMPARISON WITH OTHER SPECIES

9.3.1 Agathis

Growth and yield models have been developed for few other *Agathis* species. The exceptions are three species of kauri from Queensland, Australia. Models of volume production were developed from data from small plantations of *Agathis robusta* (two provenances), and one mixed stand of *Agathis atropurpurea* (B.Hyland) and *A. microstachya* (J.F.Bailey & C.T. White) that had been established in Zululand, South Africa. Data sets were described as small and unsuitable for "more sophisticated modelling" (Bredenkamp, 1981). Volume regression equations and estimates were developed for each species and provenance separately as a common volume regression for all species and provenances could not be fitted. The statement that a single regression equation could not be fitted to each species separately, but an equation was fitted to the mixed stand of *A. atropurpurea*/*A. microstachya* appeared to be contradictory. The two species grow in close proximity in northern Queensland with species boundaries determined by altitudinal range. They are easily confused and described as being more-or-less sympatric (Farjon, 2010). Volume regression equations were fitted according to the model:

$$\log_{10} \mathbf{V} = \mathbf{b}_0 + \mathbf{b}_1 \log_{10} \mathbf{DBH} + \mathbf{b}_2 \log_{10} Ht$$

where V = under bark volume to 75 mm diameter (m^3)

DBH = over bark diameter at 1.3 m height (cm)

Ht = Total tree height to apical tip (m)

Volume for each species was plotted by age with the current median projection for *Agathis australis* from the current study (Figure 9.7). New Zealand kauri volume production estimates most closely resemble that of the southern provenance of *A. robusta*. The volume regression equations project volume growth almost linearly for the northern provenance of *A. robusta* and the *A. atropurpurea/A. microstachya*. As with *A. australis*, predicted early volume development for the Australian species is slow, and except for early growth at around age 10, the volume of New Zealand kauri is not as high as the two Australian species.

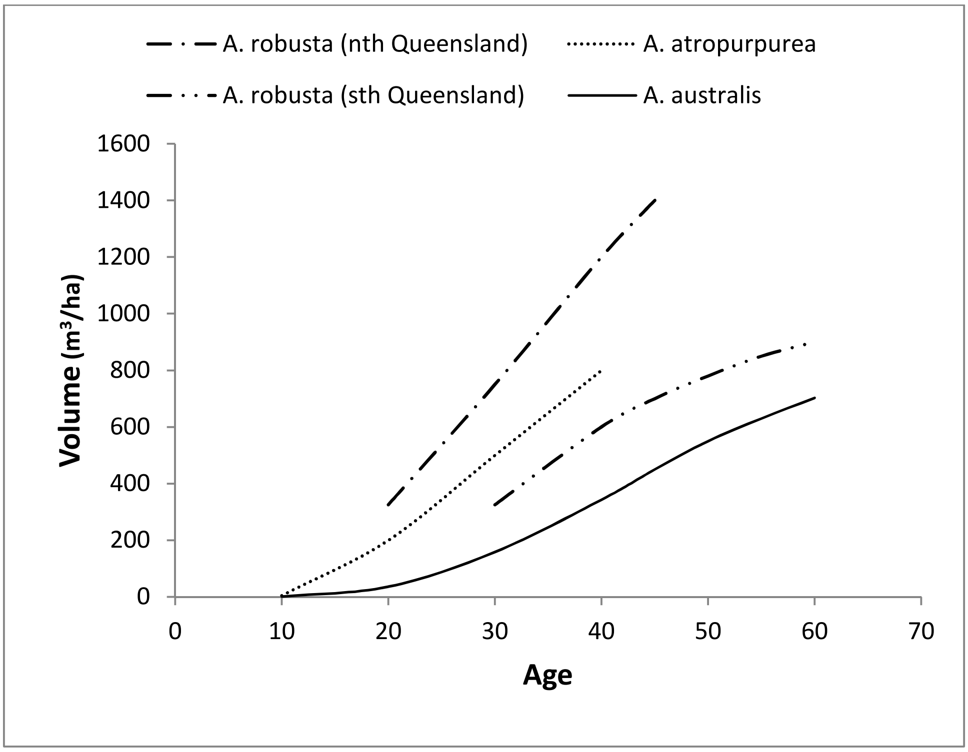


Figure 9.7. Comparison of volume models of *A. australis* (New Zealand kauri) with two provenances of *A. robusta*, and a mixed stand of *A. atropurpurea/A. microstachya*, from Queensland, Australia, grown in South Africa.

9.3.2 Podocarpus totara

Podocarpus totara, a common indigenous conifer throughout New Zealand, has had considerable research conducted on its production potential. Bergin (2001) investigated its potential to be managed as a plantation species, and Bergin & Kimberley (2003) produced a growth and yield model for plantation-grown totara from models of height and basal area based on the von Bertalanffy-Richards growth function. Totara plantations used by Bergin & Kimberley (2003) for modelling were up to 90 years of age. Totara and kauri mid-projections follow similar volume production trajectories in the first 20-25 years (Figure 9.8). From age 25-30 kauri volume predictions exceed that of totara until age 80. The models are projected to converge between ages

90-100 years. An analysis of the two data sets indicates that the greater volume production in planted kauri stands is almost entirely due to the superior height growth of kauri. At age 60, kauri mean top height is predicted to be 22.3 m, and for totara it is predicted to be 14.9 m.

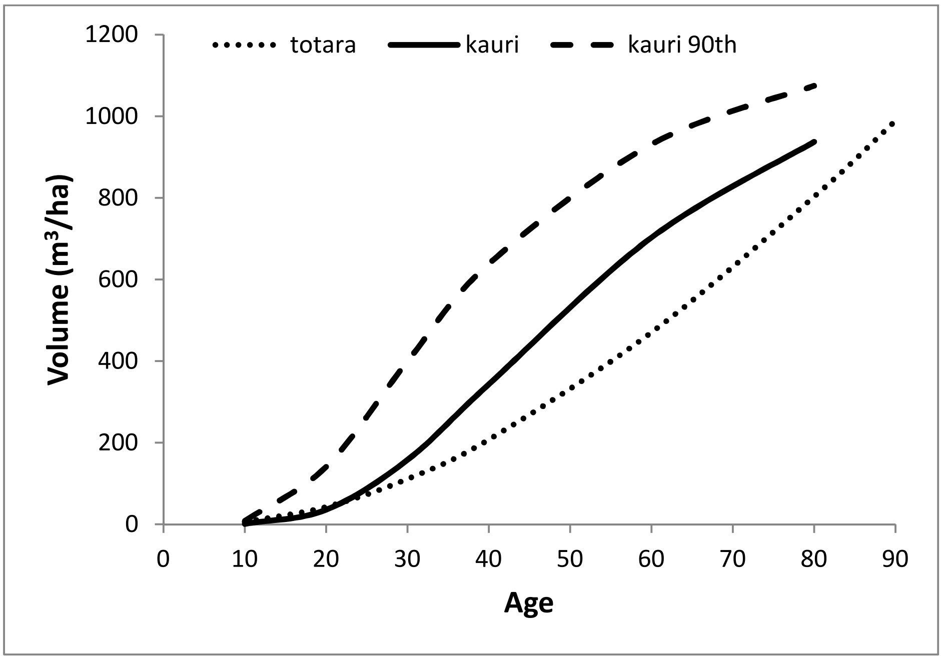


Figure 9.8. Comparison of volume production in planted kauri and totara stands at c. 1000 stems/ha. The two lower lines represent mid-line volume predictions for both species. The 90th percentile line is included to indicate performance of the best performing kauri stands. Data for totara is from Bergin & Kimberly (2003).

9.4 KAURI AND CARBON FORESTRY

In 2004, the biomass of kauri in planted stands was assessed on one site in the Taranaki region. Carbon sequestration was estimated to be 4.3 t C/ha/yr (pers. comm. Peter Beets, 2011), or 15.9 t CO_2/ha/yr. Applying the conversion factors from the Taranaki study to the mean prediction line from the volume model (based on whole-tree volume) yields an estimated carbon sequestration of 292 t C/ha at age 100, and 1080 t CO_2/ha for a stand at c. 1000 stems/ha (Figure 9.9). Carbon and CO_2 MAI would be as high as 3.3 t/ha/yr and 12 t CO_2/ha/yr. A mean 435 kg/m^3 density was used for all stands in this prediction. Carbon sequestration would alter if wood density across the planted population was found to substantively vary from this mean. Carbon sequestration calculated on the 90th percentile projection of the volume model would result in carbon sequestered rising to 316 t C/ha and 1168 t CO_2/ha. The amount of carbon estimated to be sequestered by planted kauri is minimal until age 25. By age 60 sequestered carbon is estimated to be 191 t C/ha and 707 t CO_2/ha.

Carbon sequestration MAI would peak at age 60 (Figure 9.10), while PAI would peak between 35-40 years of age when CO_2 is estimated to be 97 t CO_2/ha/yr.

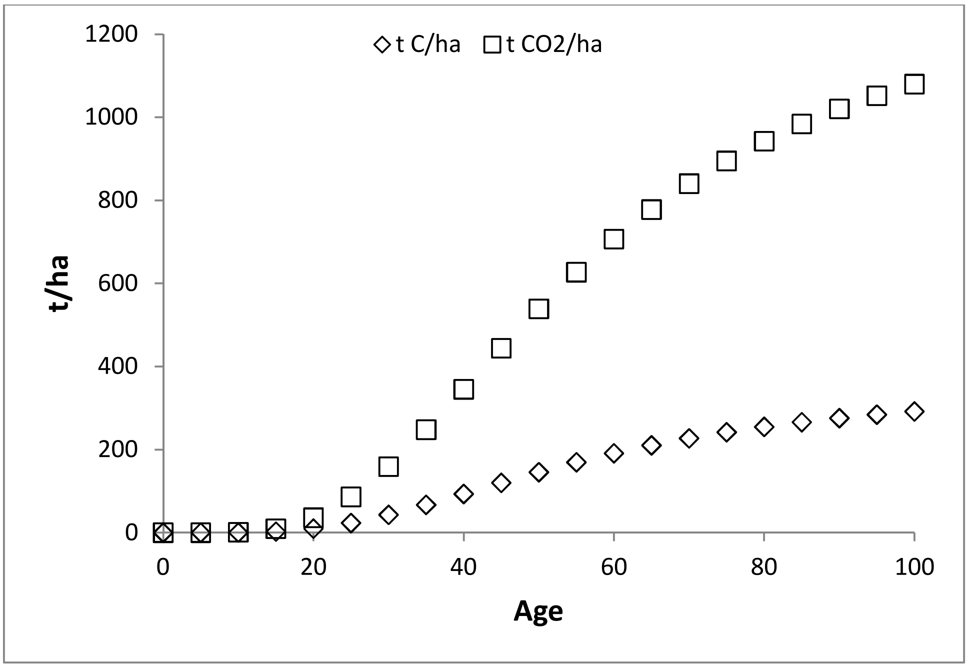


Figure 9.9. Estimated carbon sequestration in tonnes C/ha and tonnes CO_2/ha for kauri in planted stands based on whole-tree volumes and a mean 435 kg/m^3 for density.

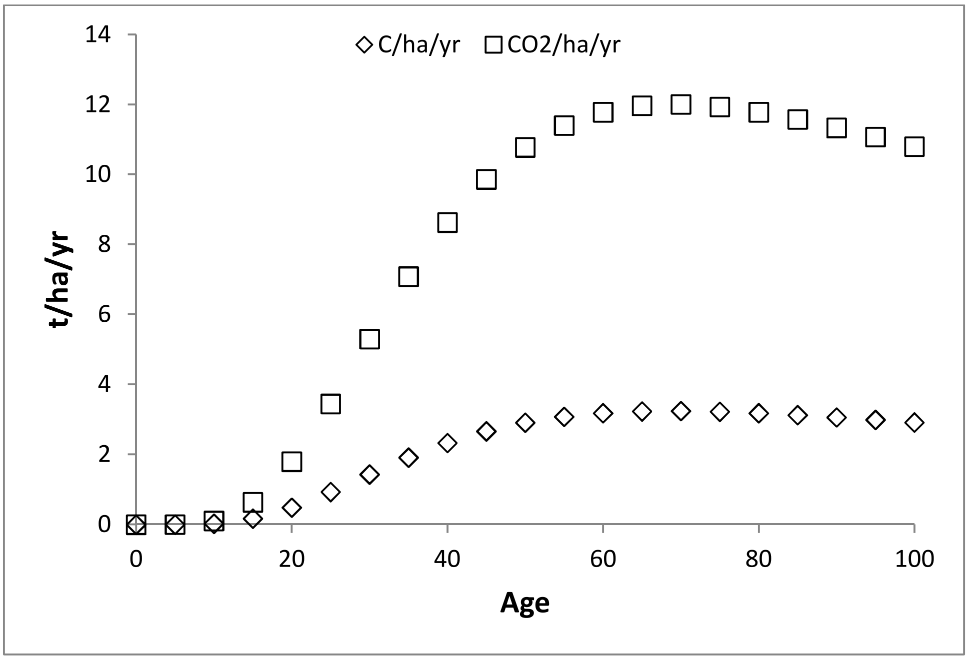


Figure 9.10. Estimated carbon sequestration MAI in tonnes C/ha/yr and tonnes CO_2/ha/yr for kauri in planted stands.

9.5 STAND 16

At age 12 (the last assessment), mean top height in **Stand 16** was 11.0 m and mean diameter was 22.3 cm. Height MAI was 0.92 m/yr since planting and diameter MAI was 1.85 cm/yr since planting. Basal area at age 12 was 24.2 m^2/ha (MAI 2.02 m^2/ha) while whole-stand volume was 118 m^3/ha (9.8 m^3/yr). Height increment in **Stand 16** was 2.4 times faster, and almost 3 times better for diameter increment than all other planted stands. At age 12 years its growth and productivity was similar or better than kauri planted stands that were up to 30 years of age. These results from **Stand 16** have indicated an ability within the kauri population to grow at rates that had not previously been recorded, when established on good quality sites. It is, however, unknown whether the observations from this stand represent the absolute maximum for kauri growth. Whether the growth rates observed in this stand can be attributed individually to site characteristics or genetics, or whether these growth rates will be maintained over a long rotation will be the subjects of further studies. Observations by the owner of the stand since its last measurement suggests that growth rates, particularly diameter, are continuing at those previously recorded.

Rather than try and increase the growth rates found in **Stand 16**, it would seem logical to learn from this stand, and use its productivity as a target for all new stands. In a workshop on planting and managing native trees for future production, McConchie (1999) suggested that timber properties of native species would be largely age-dependent and would be compromised by a push for excessively short rotations. In an attempt to prove the potential of kauri as a commercial forestry species and to improve the returns from planted stands, it would be a mistake to pursue growth rates at the expense of wood quality. The only study of wood quality of timber from planted stands 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 (Steward & McKinley, 2005). 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 (Table 9.1). The properties were uniform across the width of the stem. The DBH MAI 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 suggestions of McConchie (1999) may not be applicable to kauri as the growth rates observed did not negatively influence wood quality. The results produced by Steward & McKinley (2005) represented only one site and would need to be confirmed with studies of wood properties from other planted stands of kauri however.

Table 9.1. Comparison of wood properties of 68 year-old planted kauri with old-growth and second-growth kauri (from Steward & McKinley, 2005).

	Basic density (kg/m^3)	Stiffness (MoE) (GPa)	Shrinkage (%)	
			Radial	Tangential
Old-growth	520	13.0	2.3	4.1
Second-growth	472	10.8	2.6	3.9
Planted	451	13.6	2.9	4.1

9.6 HYPOTHESES

The study had three hypotheses in relation to kauri growth and productivity in planted and natural stands.

1. *that kauri grow faster and are more productive in even-aged planted stands than in natural second-growth stands.*
2. *that thinning of natural second-growth stands improves growth and productivity compared to comparable stands that are unthinned.*
3. *that kauri can be planted and grown in rotations for timber recovery as short as 60 years.*

The models of growth and productivity that were developed during this study indicate that kauri grown in even-aged planted stands are more productive than kauri grown in either managed (thinned) or unmanaged second-growth stands for a given age. These productivity gains are most likely a result of faster early establishment and growth, on what were generally better sites (soils, fertility, and lack of competition). Kauri at planting was estimated to be on average 50 cm tall. For newly germinated kauri in second-growth stands competition for root space, nutrients, moisture, and light from competing ground cover species would have caused establishment to be over an extended period. Even at the sapling stage in second-growth stands kauri were often still competing for these same resources. When they become emergent or dominant over a competing canopy, their growth and productivity become similar to kauri of a similar stature in planted stands, but will differ considerably in age. Height growth in planted stands was nearly three times that of second-growth stands at the site index age, 50. Volume and basal area were 9 and 17 times that of second-growth stands for mid-line predictions for each stand type. The best performing planted stands were more than 20 times more productive than second-growth stands, and the worst performing planted stands had higher productivity than the best natural stand. For mean top height, natural stands were not estimated to achieve the same or similar height reached in planted stands at age

100 until c. age 200. Basal area and volume were predicted to take until natural stands were more than 200 years old to achieve the same productivity as planted kauri stands at 100 years.

The development and productivity of kauri in natural second-growth stands was not improved at the stand-level by thinning. Increased productivity at the individual tree level, particularly for emergent or dominant kauri was observed. Mean top height and height growth were similar in thinned and unthinned treatments. Diameter growth was higher in thinned stands, but only marginally (0.03 cm DBH MAI). Basal area and volume development (MAI) were all better in the unthinned control treatments. Performance of second-growth stands was related to stand density more than the treatment applied, and to site quality and variability (particularly soil quality and fertility).

The diameter data from the current study of growth and productivity estimated that quadratic DBH at age 60 would be 37.4 cm and 45.7 cm for mean top DBH for all planted stands combined. Best performing planted stands would have DBH c. 55 cm at age 60. Wood quality studies of kauri in planted stands from two Taranaki sites in 2002 (Steward & McKinley, 2005), and a further additional site in 2004 (unpubl. data) examined the variables of wood density, shrinkage and stiffness of sapwood boards milled from 68-year old stems. For the variables of density, stiffness and shrinkage, values were found to be similar or better than old-growth heartwood, and were uniform pith to bark. If it is assumed that wood quality across all sites is the same or similar to that found in the study of Steward & McKinley (2005) then **harvesting for timber from kauri grown in planted stands could occur at age 60, or earlier**. A commercial harvest or thinning could occur as early as age 50, as mean top DBH was estimated to be 39.7 cm and quadratic mean DBH was estimated to be 31.7 cm, also well within the DBH range for logs tested from the two Taranaki sites. These rotation lengths compare to 40 year rotations for *Agathis dammara* Warb. in Indonesia (Bruijnzeel, et al., 1985), 35-40 years for *Agathis* sp. in South Africa (Bredenkamp, 1981), 40-45 years for *Araucaria cunninghamii* Aiton ex D.Don in Queensland (Huth, et al., 2009), 45-50 years (estimated) for *Agathis macrophylla* in Vanuatu and Fiji (Keppel, et al., 2009), and 40-45 years for *A. lanceolata* and *A. moorei* in New Caledonia (Direction Du Développement Rural, 2002) in plantations. A common theme with all these species was the reference to slow establishment and growth in the early years after planting.

The models for height, basal area and volume developed for kauri in planted stands should be used when modelling kauri growth and development in second-growth stands. The models developed represent kauri in the ricker form only. Models of growth and productivity for kauri in stands where a mature form predominates (i.e. a large spreading crown) will need to be developed separately if kauri is grown over longer rotations to produce heartwood or to store carbon, and where diameters of 1.0 m or more might be required. The establishment of kauri in planted stands has been shown not to be reliant on the use of nurse crops.

In the late 1800s the extinction of kauri was being suggested, not just as an outside possibility, but with predictions for the early 1900s. Happily, and perhaps despite the best efforts of the gum-diggers, pastoralists, and largely indifference from Government the kauri did not become extinct, and with good forethought some have begun the restoration of the species. If this study goes some way to finally breaking the erroneous and prejudicial thoughts about growing kauri for commercial outcome, then it will have achieved something useful.

9.7 CONCLUSIONS

This study has developed models of kauri growth and productivity in both planted and natural second-growth stands that can be used as a basis for comparing their performance and for making decisions about management and productivity.

1. Kauri has been shown to be able to be grown in even-aged single-species planted stands with expected rotations of 50-60 years on good quality sites, although growth in the early years is delayed. This tendency for slow early development was characteristic across all planted stands except Stand 16, and was shown to be characteristic for members of the *Agathis* genus. Kauri grown in planted stands outperformed kauri in natural stands for height (20.4 v 8.0 m) and basal area growth (64.9 v 11.0 m^2/ha), and volume production (500.0 v 43.7 m^3/ha) when compared at the same age.

2. Height growth of kauri was best modelled using the anamorphic Schumacher growth function where the asymptote was bounded at 45 m.

   $\mathbf{MTH = 0.5+a\times exp(((T/50)^{c})\times ln((SI-0.5)/a))}$ with the parameter estimates of ***a*** 44.5, ***c*** -0.7903.

   Kauri height growth was found to be independent of stocking in both planted and second-growth stands.

3. Basal area development of kauri was best modelled using the polymorphic von Bertalanffy-Richards growth function in difference form.

   $\mathbf{G = a\times(1-(1-((G_{\mathit{i}}/a)^{1/c})^{T/T\mathit{i}}))^{c}}$ with the parameter estimates of
   a 101.4, ***c*** 5.6971

4. Volume production of kauri was slow to develop in both planted and second-growth stands, and was best modelled using the equation

   $\mathbf{Vol} = \boldsymbol{b} \times \mathbf{G}^{\boldsymbol{a}} \times \mathbf{MTH}^{\boldsymbol{c}}$ with the parameter estimates of
   a 0.956, ***b*** 0.703, ***c*** 0.883

5. The models of mean top height and basal area developed for kauri in planted stands were validated using the one-at-a-time cross-validation method. The models validated well with small increases in RMSE compared to the models of all stands, and similar bias.

	MTH		**Basal Area**	
	RMSE	**bias**	**RMSE**	**bias**
Model	1.301	0.09	7.58	0.44
Validation	1.555	0.37	8.327	0.41

6. The models of mean top height, basal area and volume developed for kauri in planted stands are recommended for modelling the growth of kauri in natural second-growth stands.

ABBREVIATIONS

a.s.l.	(height) above sea level
BP	before present
CAI	current annual increment
c.	approximately
cm	centimetres
DBH	diameter at breast height (cm) (1.4 m above ground)
et al.	and others
ft	feet
G	basal area (m^2/ha)
ha	hectares
kg	kilogram
m	metres
MAI	mean annual increment
m^2	square metre
m^3	cubic metre
mg	milligrams
mm	millimetres
MTH	mean top height
NZFS	New Zealand Forest Service
^{o}C	degrees centigrade
^{o}S	degrees latitude
PAI	periodic annual increment
pers. comm.	personal communication
pers. obs.	personal observation
PSP	Permanent Sample Plot
s.d.	Standard deviation
s.e.	Standard error
t	tonnes
unpubl. data	unpublished data
yr	year

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APPENDIX I.

Performance and productivity of all plantation-grown kauri. (Values are at the last assessment. Sites are arranged youngest to oldest).

Stand	Age (years)	Height (m)	Height MAI (m)	Quad. Mean DBH (cm)	Quad. DBH MAI (cm)	Mean Top DBH (cm)	Basal Area (m^2/ha)	Basal Area MAI (m^2/ha/yr)	Volume (m^3/ha)	Volume MAI (m^3/ha/yr)	Stand Density (stems/ha)
8	14	7.0	0.5	8.3	0.59	13.4	5.02	0.36	14	1.01	904
7	18	7.6	0.42	12.6	0.70	16.3	2.72	0.15	10	0.53	218
9	30	13.0	0.43	19.8	0.66	27.2	19.42	0.65	108	3.59	612
11	30	13.8	0.46	23.7	0.79	27.8	21.16	0.71	128	4.26	481
10	44	19.9	0.45	32.9	0.75	36.6	46.49	1.06	392	8.91	545
22	46	20.2	0.44	25.4	0.55	33.8	85.44	1.86	680	14.78	1688
17	49	19.4	0.40	44.5	0.91	54.6	90.68	1.85	779	15.91	582
6	50	19.3	0.39	27.9	0.56	39.9	61.14	1.22	480	9.60	1000
21	51	19.8	0.39	27.1	0.53	33.0	103.60	2.03	867	17.01	1800
23	53	20.8	0.39	31.5	0.59	39.0	74.00	1.40	636	12.00	950
15	54	23.2	0.43	43.8	0.81	53.7	55.82	1.03	540	9.99	371
1	54	16.8	0.31	33.3	0.62	38.8	71.96	1.33	541	10.02	825
3	55	21.6	0.39	32.7	0.59	41.4	69.05	1.26	584	10.61	823
5	55	20.4	0.37	33.1	0.60	42.2	94.57	1.72	823	14.96	1099
25	55	23.8	0.43	30.6	0.56	37.3	64.48	1.17	885	16.10	875
14	59	19.3	0.33	49.6	0.84	57.2	54.00	0.92	449	7.61	280
2	60	23.0	0.38	34.9	0.58	40.2	82.40	1.37	789	13.15	860
18	63	24.3	0.39	27.0	0.43	37.3	105.63	1.68	830	13.18	1845
4	67	29.0	0.43	40.9	0.61	51.4	100.26	1.50	1184	17.67	765
20	73	25.3	0.35	32.7	0.45	39.3	70.14	0.96	726	9.95	831
19	74	24.3	0.33	36.6	0.49	44.7	68.10	0.92	681	9.20	647
12	79	23.2	0.29	50.6	0.64	61.5	74.51	0.94	746	9.44	371
13	81	23.0	0.28	51.9	0.64	61.8	63.40	0.78	623	7.69	300
24	83	22.3	0.27	41.9	0.50	49.9	86.97	1.05	818	9.86	630
All Stands	**54.0**	**20.0**	**0.39**	**33.1**	**0.63**	**40.8**	**65.5**	**1.16**	**596.4**	**10.3**	**804**

APPENDIX II.

Diameter and height growth, and basal area and volume development of kauri in all second-growth thinned stands at their last assessment. Sites arranged north to south.

Stand	**Mean age (years)**	**Mean height (m)**	**Height MAI (m)**	**Mean DBH (cm)**	**DBH MAI (cm)**	**Basal Area (m^2/ha)**	**Basal Area MAI (m^2/ha/yr)**	**Vol (m^3/ha)**	**Vol MAI (m^3/ha/yr)**
Herekino	161	21.4	0.13	38.6	0.24	99.9	0.62	1111.5	6.90
Papakauri	176	28.1	0.16	42.3	0.24	31.6	0.18	319.8	1.82
Kaiarara	120	19.3	0.16	26.0	0.22	43.1	0.36	335.8	2.80
Whangaparapara	118	23.0	0.19	34.4	0.29	18.1	0.15	173.9	1.47
Whenuakite	126	34.3	0.27	46.7	0.37	64.8	0.51	861.2	6.83
Mangatangi	114	22.8	0.20	16.2	0.14	50.1	0.44	401.2	3.52
Waitengaue	196	29.5	0.15	29.6	0.15	81.0	0.41	866.4	4.42
All Stands	**144**	**25.5**	**0.18**	**33.4**	**0.24**	**55.5**	**0.39**	**581.4**	**3.97**

APPENDIX II. CONT.

Diameter and height growth, and basal area and volume development of kauri in all second-growth thinned stands at their last assessment. Sites arranged north to south.

Stand	**Mean age (years)**	**Mean height (m)**	**Height MAI (m)**	**Mean DBH (cm)**	**DBH MAI (cm)**	**Basal Area (m^2/ha)**	**Basal Area MAI (m^2/ha/yr)**	**Vol (m^3/ha)**	**Vol MAI (m^3/ha/yr)**
Herekino	166	23.6	0.14	44.3	0.27	57.2	0.35	619.6	3.73
Papakauri	148	28.1	0.19	46.7	0.31	19.4	0.13	232.4	1.57
Kaiarara	121	16.8	0.14	32.5	0.27	18.6	0.15	135.8	1.12
Whangaparapara light thin	98	22.0	0.22	30.8	0.31	43.6	0.45	393.1	4.01
Whangaparapara heavy thin	98	23.3	0.24	35.6	0.36	34.2	0.35	323.5	3.30
Whenuakite*	-	-	-	-	-	-	-	-	-
Mangatangi	90	20.2	0.23	18.3	0.20	40.8	0.45	318.3	3.50
Waitengaue	184	28.0	0.15	34.5	0.19	62.5	0.34	675.4	3.67
All Stands	**129**	**23.1**	**0.19**	**34.7**	**0.27**	**39.5**	**0.31**	**385.4**	**2.99**

*no thinning treatment was applied to the Whenuakite stand.