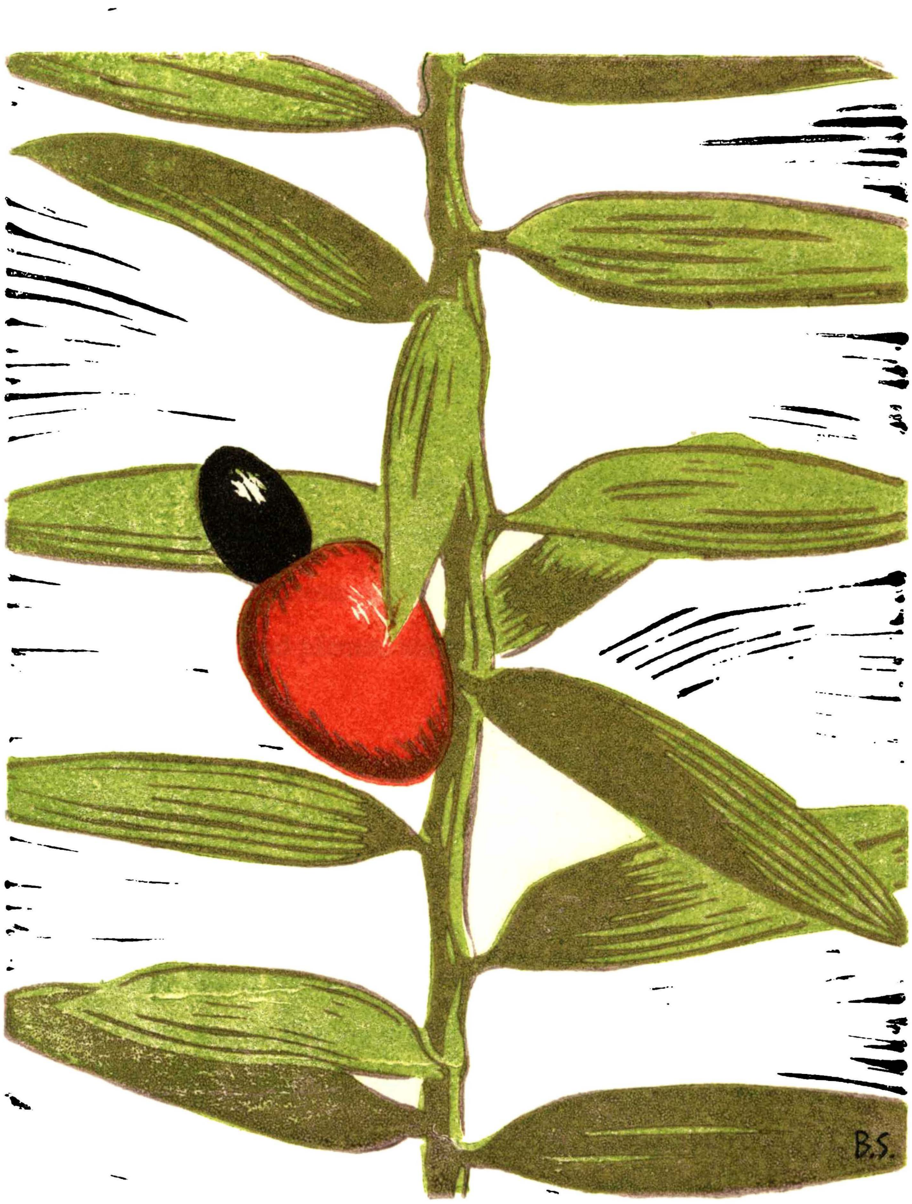
GROWTH AND MANAGEMENT OF PLANTED AND NATURALLY REGENERATING STANDS OF *PODOCARPUS TOTARA* D.DON

A thesis
submitted in partial fulfilment
of the requirements for the Degree
of
Doctor of Philosophy in Biological Sciences
at the
University of Waikato
by

D.O. BERGIN

University of Waikato

2001


B.S.

ABSTRACT

Podocarpus totara D. Don (totara), a highly valued, naturally durable coniferous tree species, is widely distributed in indigenous lowland forest throughout New Zealand. As harvesting from natural forests has declined there has been increasing interest in planting and managing totara for timber production. A 'new' indigenous forest resource not only gives landowners options for extraction of high value specialty timber in the long-term, but also fulfils a wide range of other non-timber objectives, such as increasing biodiversity and enhancing the cultural and heritage values of our flora. However, there is a lack of quantitative information on growth, productivity and wood characteristics of totara from planted stands. In addition, there is the potential to manage stands of totara that have regenerated naturally on farmland in many regions. Aspects influencing the growth of totara and relevant to management for timber production have been investigated, including genetic variation, age estimation techniques, growth and productivity of natural and planted stands, and tree form and wood quality.

Thirty-six provenances of totara planted on a coastal site were assessed almost 11 years later. Some genetic differences between provenances were apparent. Totara from northern latitudes grew faster and with better stem form than provenances from more southern locations. There is also considerable variation within provenances, indicating that improvement of growth and stem form is possible within local populations. Breeding trials that capitalise on the fairly homogenous genetic variation in totara are likely to provide significant improvement in productivity and wood quality, as has been found in other conifer species.

An assessment of increment cores from planted stands of totara of known age was undertaken to determine accuracy of this method for estimating age, and hence determining productivity of natural stands of unknown age. Using refinements of these techniques, increment cores were used to estimate age of a chronological sequence of naturally regenerating totara-dominant stands in three areas in Northland where they are a prominent feature on steep, hill country farmland.

Evaluations of these stands support previous work that totara fits the catastrophic regeneration mode typical of shade-intolerant species. Clearance of original forest cover has provided conditions in which totara can successfully colonise open, grazed, steep slopes dominated by weedy pasture and bare ground, often in mixture with other unpalatable species such as manuka, kanuka and gorse. With natural thinning, most eventually develop into single-species, semi-mature stands that are relatively uniform in stem size and form; such stands have good potential for management as a future wood resource.

An evaluation of the early performance of totara and other indigenous conifer tree species planted throughout the country indicates most stands have been established on sites unsuited to other land uses such as exotic forestry or farming. In addition, many stands received minimal after-planting care. A preliminary growth and yield model for totara based on a small number of established plantations indicates that while total stem volume growth is slow over the first 50 years, yield increases significantly over the following 50 years. A mean basal area of about 100 m^2ha^{-1} and mean volume of 800 m^3ha^{-1} are predicted at age 80 years.

Growth of totara in natural stands that developed on steep hill slopes on Northland farms is considerably slower than in plantations mostly established on better sites. Plantations had a mean volume of 470 m^3ha^{-1} at 60 years but natural stands were estimated to take another 40 years to achieve a similar volume. Widely-spaced trees have a high proportion of multiple stems and coarse branching to low levels while trees in high density stands have better form. The few log sections sawn into boards indicate no major problems in timber quality although heartwood development is usually low.

A descriptive model of totara following four pathways is presented showing growth and tree form development over time for natural and planted stands that have established under different conditions. A selected management regime and preliminary economic analysis for planting a stand of totara is also given. The timber and other benefits of planting and managing naturally regenerating totara stands are discussed along with constraints and suggestions for growing totara on new sites as a long-term specialty timber resource.

ACKNOWLEDGEMENTS

Access to natural totara stands with helpful discussions and practical assistance during the course of fieldwork were greatly appreciated from the following landowners in Northland: Noel Donelley, Tom MacBride, Doug Lane, Owen Lewis, Paul and Katarina Quinlan, Brian Cooper, Greg Brough, Geoff Cookson, Olive and Catherine Mackenzie, Ken Going and Mrs McKenzie-Pollock. The thinning trial was established in collaboration with indigenous forest silviculturist Owen Lewis and landowner Brian Cooper. Access to planted totara stands in other regions from the Auckland Regional Council, New Plymouth District Council, Jim Holdsworth, Fletcher Challenge Forests Ltd, Rayonier NZ Ltd, and Holt's Forest Trust was also appreciated.

The assistance of ***Forest Research*** staff Greg Steward, Ham Gifford, Jeremy Cox, Jessamy Herbert and Heidi McGlone in fieldwork, wood sample preparation and data entry is gratefully acknowledged. Dr Tom Richardson, Sheree Cato and Satish Kumar carried out the DNA fingerprinting of selected totara populations. Lorraine Tinsley (University of Waikato) carried out analysis of possum stomach contents. Thanks to Dr Douglas Hicks for advice on soils and helpful discussions.

I am grateful to Dr John Bathgate who, as my main supervisor, has provided excellent support and encouragement throughout the programme and, since his move to Indonesia, has continued to critically review and offer support during the final stages. I appreciate the input of my co-supervisors Dr John Herbert and Dr Chris Goulding who have contributed enormously throughout. Thanks also to Dr Rob Allen for helpful initial discussions. I am grateful to Professor Warwick Silvester for guidance during the final stages of thesis preparation.

I thank ***Forest Research*** for supporting me through this study as part of the indigenous plantation forestry programme funded by the New Zealand Foundation for Research, Science and Technology. I also thank my managers during the course of study: John Tustin, Dr Tom Richardson and Dr Luis Gea. Many at ***Forest Research*** provided their skills and advice willingly and always in good humour. My thanks go to: John Smith and Rita Tetenburgh who drafted the maps and scanned the photographs; Dianne Le Bas and Christine Leigh who assisted with formatting;

Pauline Green and Joy Smith who compiled draft and final versions of the document; and Bernard Salmon who drew the frontispiece and other tree drawings. Greg Steward has been tremendously supportive throughout my study, providing many lighter moments. I am also grateful to colleagues Dr Fiona Ede and Diana Gainsford for their day to day support and encouragement.

Thank you to the following for reviewing various chapters: Tony Beveridge, Dr Bruce Burns, Dr Mike Dodd, Mark Smale and Don McConchie. I have appreciated support and helpful discussions with David Hunt who edited each chapter during preparation. My wife Susan spent many hours helping me during the final stages of thesis preparation with compilation and proof reading for which I am very grateful.

My friend and colleague Mark Kimberley assisted with the statistical analysis and production of graphs and willingly shared his ideas. On many occasions, Mark provided encouragement and support throughout the planning, data analysis and writing stages for which I am most grateful.

Tony Beveridge has inspired me to work on the planting and management of indigenous tree species through his own enthusiasm, vigour and energy over the past 20 years during which I have had the privilege of knowing and working with him. Thank you Tony for continuing to share your passion and knowledge of indigenous forestry and your endless ideas and observations on the management of our indigenous timber tree species.

I am very grateful to the many other colleagues and friends who have given encouragement and support during this study. Thank you to Gerard Horgan for gleefully pointing out the 1913 Royal Commission on Forestry report which highlighted "the utter absurdity of suggesting such a tree as the totara for afforestation purposes". I only hope this thesis has gone some way to supporting an alternative view of the management of planted totara for timber production!

Finally, I could not have completed this thesis without the support and assistance of my family during the many months of fieldwork, data preparation and writing which have impacted so heavily on our family time. I am very grateful for the support, encouragement and optimism of my wife Susan and, for the most part, patience of our four children, Michael, Brendan, Anna and Natalie.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

With limitations on harvesting timber from natural forests in New Zealand in recent years, there has been increasing interest in the planting and management of indigenous tree species for wood production. Most old-growth indigenous forest is in Crown ownership and is now protected from logging (Whyte 2000), with only limited supplies available from indigenous forest in private or Maori ownership managed on a sustainable basis (Newton 2000). Interest, therefore, has been increasing in many sectors of the community, including landowners, iwi (Maori tribal groups), and forestry consultants, and within Government agencies in developing sustainable management systems for planting and management of indigenous timber species for market and non-market benefits (e.g., Hughes 1991; Silvester and McGowan 2000). A 'new' indigenous forest resource on previously milled and cleared land provides not only an option for wood production on appropriate sites, but also gives numerous other benefits. These include stimulating interest in New Zealand's natural heritage and culture, enhancing biodiversity in a range of landscapes and encouraging the practice of multiple-use forestry. A sustainable resource of indigenous timber trees gives future generations of New Zealanders options for meeting some of their cultural, social and economic needs. Other benefits include less reliance on imported specialty timbers often harvested from natural forests and encouraging the use of naturally-durable timbers for specialty uses rather than near-total dependence on locally-grown exotic softwoods treated with preservatives.

Totara (*Podocarpus totara* D.Don) is one of our major indigenous conifer species, widely distributed in lowland forest throughout the country. Other major conifers are rimu (*Dacrydium cupressinum*), kahikatea (*Dacrycarpus dacrydioides*), matai (*Prumnopitys taxifolia*), miro (*Prumnopitys ferruginea*), kauri (*Agathis australis*) and tanekaha (*Phyllocladus trichomanoides*). These species have been utilised for a range of purposes by both Maori and European settlers with totara providing some highly specialised end uses. Only small quantities of totara are now available from private or Maori land, or from Crown land under the stewardship of the Department of Conservation for infrequent Maori ceremonial uses.

1.1 USE AND DEMAND

The early Maori quickly appreciated the architectural and carving qualities of totara. For Maori, both the spiritual significance and practical use of totara had a "special mythical origin assigned to it" and a status "as the principal member of the company of rakau rangatira (superior or lordly trees)" (Best 1942). As a wood, totara was unexcelled, not only through its mana (status) but also through its physical properties. These included ease of working with stone tools, light weight and durability. It was extensively used for construction, decorative carvings, and most significantly, ocean-going waka taua (war canoes). Since the arrival of European settlers in the late 18th century, totara from old-growth stands has been an important special-purpose timber because of its outstanding features of durability, evenness of texture, ease of working, and lightness of heartwood (Hinds and Reid 1957). Consequently, it was widely used for exterior joinery as well as fence posts, battens, buildings, bridges, railway sleepers, foundation piles and shingles (Duguid 1990; Clifton 1990).

1.2 EXPLOITATION

Concern over exploitation of the indigenous forestry timber resource and dwindling old-growth forest in many regions was being expressed over a century ago. In the 1880s the indigenous forests were still regarded as virtually inexhaustible. By 1900, government officials and some sawmillers were coming to the view that the indigenous forests were likely to be cut out within 40 or 50 years (Roche 1990). It became obvious that the increasing demand for construction timber could not be sustained from clearfelling natural stands. In addition, there was a gradual acceptance of the need for forest reserves during the late 19th century. However, in practice, a distinctive geographical pattern emerged, as it was generally upland areas that were reserved, these being less suited to farming (Roche 1990).

A forest plantation industry based on introduced conifers became predominant but exploitation of the indigenous old-growth forest continued until the late 20th century. Pressures from informed public debate and environmentalists led to changes in forest policy (New Zealand Forest Service 1977). However, totara, along with other major podocarp tree species, was still being felled in Crown forests in the central North Island in the late 1970s. Environmental groups protested, some occupying crowns of large totara at Pureora Forest Park to prevent felling, one of the decisive public actions taken at this time highlighting exploitation of indigenous forest (Edmonds 1978; New Zealand Native Forest Restoration Trust 1992). Ultimately this led to public pressure on central government to cease logging of old-growth indigenous forest on Crown land in the North Island by the early 1980s and on Crown land in the South Island by 2001.

1.3 EARLY PLANTATION TRIALS

Efforts to establish plantations of indigenous species, including totara, date back to the 1870s. However, comparisons between indigenous, European, North American and Australian species indicated that New Zealand species such as totara grew too slowly (Roche 1990). In a species-by-species account of forestry trees for planting, Mathews (1905) accepted earlier pronouncements from others rejecting commercial afforestation with indigenous species on the grounds of their slow growth (Balfour 1865, Blair 1879, Kirk 1889; cited in Roche 1990). The encouraging results that had been attained for exotic species, principally radiata pine (*Pinus radiata*) and other *Pinus* species, Douglas-fir (*Pseudotsuga menziesii*), and various eucalypts (*Eucalyptus* spp.) and poplars (*Populus* spp.), contrasted with the disappointing growth rates of indigenous species. This provided the impetus for a fledgling exotic plantation forest industry in New Zealand.

The perception that indigenous species were inherently slow-growing and, therefore, of little value for planting and managing for timber production was reinforced in the Royal Commission on Forestry's report of 1913. In a discussion of the economics of planting trees that take 80 years to mature, the report, in its conclusion referred to " the utter absurdity of suggesting such a tree as the totara for afforestation purposes" (Royal Commission on Forestry 1913, p.xxx). This was based on early experimental plantations of selected indigenous and exotic species in New Zealand. Nevertheless, some 546,500 seedlings of totara had been planted in State Plantations up to 1909 along with only three other indigenous species listed – 4280 kahikatea, 200 Hall's totara (*Podocarpus hallii*) and 200 rewarewa (*Knightia excelsa*) (Department of Lands 1909). Why totara was planted in such high numbers compared with other indigenous species probably reflects the ease with which totara seed could be collected, seedlings raised in nurseries, and the early indications that it could grow on a wide range of cleared and open sites, albeit relatively slowly. One totara plantation established between 1905 and 1909 was located at Puhipuhi in Northland. The seedlings were grown at the local Ruatangata Nursery just north of Whangarei (Department of Lands 1909) where over 100 ha of cleared land were planted (McQuire 1956, Forest Research Institute File F.S. 28/4/5). This clearly demonstrated that some landowners and managers early last century recognised both the dwindling natural resource of totara and the need to rejuvenate it. This particular plantation was accidentally burnt a few years later with only small remnants existing today. These remnants, however, have shown the excellent potential of the species for growing in plantations. Had these earlier generations continued planting totara and other indigenous timber trees, there could well have been plantations approaching 100 years of age and suitable for harvesting in the near future.

Despite the increasing focus of the forestry industry on exotic species (O'Loughlin 2000), some planting of indigenous tree species continued either as small operational programmes of the New Zealand Forest Service, in parks and recreational areas by local authorities, on private land or as part of research programmes of the Forest Research Institute. Sporadic planting of nursery-raised and wilding kauri seedlings was carried out from the early 1930s to the 1960s although seedlings survival and growth varied widely (Halkett 1983). From the late 1950s, half a million seedlings of indigenous species were planted out on a range of forest and scrub sites. This included a number of large trials of the native conifers rimu, totara, kahikatea with some matai and tanekaha established in several regions including the West Coast, Hawkes Bay, central North Island, and north Auckland (Beveridge 1977). During the late 1970s and early 1980s up to 50,000 kauri seedlings were raised at the New Zealand Forest Service for planting in Northland, Great Barrier, South Auckland and the Coromandel Peninsula. Over the same period, up to 40,000 podocarps were being planted in the central North Island forests of Pureora and Whirinaki (Beveridge 1979). In addition, numerous small plantations of single or mixed stands of a wide range of indigenous timber trees were planted on private land and in public reserves and urban parks throughout the country (Pardy *et al.* 1992). These stands have often been established on fertile lowland sites and have been well-maintained indicating the potential growth of the major indigenous tree species in planted stands up to 100 years of age.

1.4 WHY RESEARCH TOTARA?

Totara has been of great importance in the past to both Maori and early European settlers. The cultural importance of totara for Maori has not lessened in current times (Simpson 1988). With limited availability of totara from old-growth forest, interest by significant sectors of the community for information on totara for a range of objectives, including wood production, justifies an in-depth investigation of its potential for planting and management. There is also a large resource of naturally regenerating second-growth stands developing on previously cleared sites in many regions throughout the country on private or Maori land. These have the potential to be managed as a long-term wood supply.

Previous studies and observations have identified a wide range of features that make totara a species worthy of further evaluation for growing as a specialty timber tree. These include: cultural and heritage values; durability and machining qualities of the wood; wide natural distribution; tolerance of a wide variety of sites; ease with which seedlings can be raised in a nursery; good growth rates;

potential genetic gains in both growth and form; and amenability to tending. However, previous research has not adequately demonstrated the feasibility of growing totara as a special purpose wood supply.

1.5 OBJECTIVES OF THIS THESIS

The overall objective of the thesis is to determine the potential for growing and managing totara as a long-term sustainable timber supply. The aim is to develop a descriptive model of the growth and development of totara under different establishment and management regimes with recommendations for a strategy for developing a future timber resource. A broad approach has been taken whereby several research areas investigating aspects of the growth and development of totara, in both planted stands on a range of sites and in naturally regenerating stands on pastoral hill country, are considered. Specific objectives for these research areas include:

- to compare the growth and stem form of a range wide sample of provenances relating any variability to geographic and climatic factors, and to determine the potential for breeding improved strains of totara;
- to describe and quantify the characteristics of naturally regenerating stands of totara on farmland including their development over time and potential for management;
- to quantify growth rates of totara of known age on a range of sites and to develop a preliminary growth model; and,
- to determine correlations between tree form and branching characteristics with stand parameters including stand age and stocking and the effects on wood quality for both planted and young natural stands.

Various aspects relevant to the long-term management of totara for specialty timber production under a range of ecological, silvicultural, and economic considerations are also discussed. These include the role of totara in sustainable land use particularly in hill country; even-aged or uneven-aged stand management; and management of totara as single-species stands or in mixed-species stands.

1.6 OUTLINE OF THESIS

The following aspects of the growth of totara have been studied in both planted and naturally regenerating stands. These include: establishment; early growth; stand development; tree form and wood quality. Provenance differences and aging using growth rings have also been studied for planted stands. An outline of the thesis is given below with reference to papers published, in press or in preparation relating to each chapter.

Chapter 2 A review of the current knowledge of the ecology and silviculture of totara relevant to management for timber production is given. This has been published as:

- Bergin, D.O. 2000: Current knowledge relevant to management of *Podocarpus totara* D.Don for timber. *New Zealand Journal of Botany 38*: 343-359.

Chapter 3 As totara covers a wide latitudinal and altitudinal range, an investigation of genetic differences between geographically separated populations (provenances) in growth and tree form was undertaken. This is useful for developing a strategy for genetic improvement of the species where timber production is an objective. This chapter investigates the variability among provenances of totara collected from throughout the country planted on a North Island site over 10 years ago. A paper has been submitted to an international journal:

- Bergin, D.O.; Kimberley, M.O. (reviewed): Provenance variation of *Podocarpus totara* D.Don ten years after planting on a coastal site in northern New Zealand. *Forest Ecology and Management.*

Chapter 4 To assess growth and development of naturally regenerating stands, reliable techniques for aging stands of unknown age are required. The reliability of using growth rings to estimate tree age based on planted stands of totara of known age has been determined. A paper for an international journal has been written:

- Bergin, D.O.; Bathgate, J. (reviewed): Determining age using growth rings on increment cores from planted totara (*Podocarpus totara* D.Don) stands. *Tree Ring Bulletin.*

Chapter 5 Chapters 5 and 6 cover the establishment and development of naturally regenerated stands of totara on farmland. This chapter describes the early successional pattern from pasture to totara on a typical hill country site in Northland. A journal paper is in preparation:

- Bergin, D.O. (in prep): Regeneration of *Podocarpus totara* D.Don on pastoral hill country, Northland, New Zealand. *New Zealand Journal of Botany.*

Chapter 6 Development of natural stands on farmland in three districts of Northland is investigated. In each district, age sequences of naturally regenerated stands were sampled to describe stand development over time, including growth rates and stem form. A journal paper is in preparation:

- Bergin, D.O. (in prep): Development of naturally regenerating stands of *Podocarpus totara* D.Don on pastoral hill country, Northland, New Zealand. *New Zealand Journal of Botany.*

Chapter 7 Both chapters 7 and 8 describe the performance of planted stands of totara. Chapter 7 discusses the early performance of a selection of establishment trials and general plantings. These have included totara and the other major indigenous conifer tree species. The plantings were established up to 50 years ago throughout New Zealand, covering a wide variety of sites. They provide insights into the ecological characteristics of totara compared with the other conifers. Two papers related to this chapter have been written:

- Bergin, D.O. (in prep): Early performance of planted totara (*Podocarpus totara* D.Don) — a comparison with other indigenous conifer tree species. *New Zealand Journal of Forestry Science.*

- Beveridge, A.E.; Bergin, D.O. 2000: The role of planting native trees in the management of disturbed forest. *In* Silvester, W.; McGowan, R. (eds.) *Native trees for the future. Potential, problems, possibilities.* Proceedings of a forum held at The University of Waikato, Hamilton, 8-10 October 1999. 51-60.

Chapter 8 The growth performance of selected plantations of totara that range in age from 10 years to nearly 100 years is investigated. These stands indicate the potential growth rates of planted totara, and have been used to develop a preliminary growth and yield model. A journal paper has been written:

- Bergin, D.O.; Kimberley, M.O. (reviewed): A preliminary growth and yield model for totara (*Podocarpus totara* D.Don) based on planted stands. *New Zealand Journal of Forestry Science.*

Chapter 9 Branching and stem form characteristics for both naturally regenerated stands and plantations of totara are described and quantified with a preliminary investigation of wood quality. A journal paper has been prepared:

- Bergin, D.O.; Bathgate, J. (in prep): Stem form and branching characteristics in natural and planted stands of totara (*Podocarpus totara* D.Don). *New Zealand Journal of Forestry Science.*

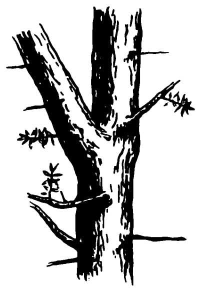
Chapter 10 Finally, Chapter 10 discusses conclusions drawn from these studies of the growth of planted and naturally regenerating stands. This leads to a descriptive model of the development and growth of totara where wood production is the major objective. Some management considerations of totara are discussed and potential management regimes are offered. Suggestions for future research from both an ecological and management perspective are given. Publications relating to this chapter include:

- Bergin, D.O. 2000: Growth and management of planted and regenerating stands of totara (*Podocarpus totara* D.Don). *In* Silvester, W.; McGowan, R. (eds.) *Native trees for the future.*

Potential, problems, possibilities. Proceedings of a forum held at The University of Waikato, Hamilton, 8-10 October 1999. 28-36.

- Bergin, D.O.; Bathgate, J.B. 2000: Managing planted and regenerating stands of totara on farmland. *New Zealand Tree Grower*, August 2000. 11-12.

Nomenclature follows Allan (1961), Connor and Edgar (1987), Moore and Edgar (1970), Healy and Edgar (1980), Webb *et al.* (1988), Edgar and Conner (2000), Brownsey and Smith-Dodsmith (1989) and Chamber and Farrant (1998). Abbreviations and conventions used, and definitions are given in Appendix 1.1. Alphanumeric codes used for each plot established in planted and natural stands, with a brief description of plot location and land tenure, are listed in Appendix 1.2.



CHAPTER 2

CURRENT KNOWLEDGE RELEVANT TO MANAGEMENT OF TOTARA FOR TIMBER

2.1 INTRODUCTION

There is good potential for management of totara as a special purpose timber species because of its extensive use in the past by both Maori and European settlers, high cultural value, and an ability to grow in many regions on a range of sites with good growth rates. Totara was the most commonly planted indigenous species a century ago (Department of Lands 1909) and a small number of stands, some of which date back to the turn of last century, indicate its potential for growing in plantations (Pardy *et al.*1992). It is often found growing as bushy, multi-stemmed, open-grown young trees on farmland as well as in single- or mixed-species stands, with good form where stem density is high. It has proven wood quality, including natural durability of heartwood. However, there is a lack of quantitative information on growth, productivity and wood properties either in plantations or in managed natural second-growth stands. This chapter reviews previous work on the ecology and silviculture of totara that is relevant to management of the species in plantations or in naturally regenerating stands on previously cleared sites.

2.2 CHARACTERISTICS OF TOTARA

2.2.1 Taxonomy

Totara is a member of the Podocarpaceae, one of five families within the order Coniferales. The other four families within the Coniferales are Araucariaceae, Cupressaceae, Pinaceae and Taxodiaceae. Of these, Podocarpaceae and Araucariaceae are found mostly in the Southern Hemisphere although some podocarps are found as far north as Japan and the Himalayas (Enright *et al.* 1995).

In the Southern Hemisphere, there are some 124 species representing 18 genera within the Podocarpaceae, with 53 species found only in the Southern Hemisphere (Enright *et al.* 1995). The geographical distribution of the podocarps includes Africa, South America, various Pacific islands, New Zealand, Australia, New Guinea, Phillipines, parts of Indonesia and southern taxa species in parts of mainland South East Asia. For many taxa, ecological studies are largely non-existent including most of the Podocarpaceae of south-east Asia and tropical South America. In contrast to the dominance of cone bearing plants of most conifers in the Northern Hemisphere, the female 'cone' in many Southern Hemisphere species is reduced to one or a few scales bearing a single ovule and is a feature of the Podocarpaceae including the podocarp species in New Zealand. The seeds are either borne on an often fleshy receptacle such as with totara, or enclosed in a fleshy fruit or drupe and thus the seed is adapted to bird dispersal.

In New Zealand, the Podocarpaceae is represented by eight genera and 17 species, and probably all the species are endemic (Ogden and Stewart 1995). These include *Dacrycarpus* (one species), *Dacrydium* (one species), *Halocarpus* (three species), *Lagarostrobus* (one species), *Lepidothamnus* (two species), *Podocarpus* (four species) and *Prumnopitys* (two species) (Dawson 2000) as well as *Phyllocladus* (three species). Members of the Podocarpaceae family are found from sea-level to subalpine shrublands throughout New Zealand.

2.2.2 Related species and hybridisation

Totara is one of four closely related *Podocarpus* species. The other three are:

- *Podocarpus hallii* Kirk (Hall's totara), a tree commonly 20 m high but sometimes up to 30 m, and up to 2 m diameter, with thin, often papery bark. It occurs throughout the country usually, but not always, at higher altitudes than totara. It occurs on a wide range of soil types, and tolerates colder and wetter sites than totara. Seedlings and saplings are much more shade tolerant than totara.
- *Podocarpus nivalis* Hook. (snow totara), a prostrate shrub with wide-spreading branches up to 3 m tall which grows at upper forest margins and in subalpine scrub.
- *Podocarpus acutifolius* Kirk, a dwarf, needle-leaved shrub or small tree up to 9 m high which occurs on stony alluvium in north Westland.

Species of *Podocarpus* hybridise freely in the wild, resulting in a range of leaf and habit forms which are determined by their predominant parentage (Webby *et al.* 1987). A distinctive variety (*P. totara* var. *waihoensis*), which is an introgressed hybrid of totara and *P. acutifolius*, occurs in lowland Westland (Wardle 1972). Totara also hybridises with Hall's totara. A high degree of hybridisation was described by Bergin and Kimberley (1992) where these two species occur in Pureora Forest, central North Island at 500-550 m a.s.l., near the upper altitudinal limit of totara (Figure 2.1). At such a site, a mixture of bark types has been observed on the same tree with stringy bark characteristic of totara on one side of a trunk and papery bark characteristic of Hall's totara on the other (A.E. Beveridge pers. comm.). In regions where both totara and Hall's totara are present, there can be some crossing between the two species, even at low altitudes. Difficulties in distinguishing between the two species has also been observed in the South Island (e.g., Banks Peninsula and near Invercargill) where many trees may be hybrids (D.A. Norton pers. comm.). Thus, it is likely that hybrids between the two species occur in some extensive areas of naturally established second-growth stands on farmland which have the potential for management for timber.

Figure 2.1: Hybridisation between totara and Hall's totara at Pureora Forest, central North Island. Ovoid shaped seed of totara is on left and the narrow-ovoid, pointed seed of Hall's totara on right with seed of hybrids in between. Seed in upper row are attached to the succulent receptacle which ranges in colour from yellow and orange to red.

2.2.3 Tree dimensions and longevity

Totara is able to survive as a canopy or emergent tree for many centuries. In general, totara is a tree up to 30 m high with a trunk up to 2 m in diameter with thick, stringy, furrowed bark on older specimens (Allan 1961). Burstall and Sale (1984) described three totara and one Hall's totara in their list of 100 "great trees" of New Zealand; the largest is the Pouakani totara in Pureora Forest, south Waikato, with a diameter of 3.6 m and a height of 39 m, and they suggest that, if the trunk were sound, it would contain 77 m^3 of timber. Another totara, also in Pureora Forest, has a similar diameter but is shorter at 27 m, while the third listed totara is located at A'Deanes Bush, Hawke's Bay, at 2.6 m diameter and 34 m high. The Hall's totara is in Dean Forest, Southland. It has a diameter of 2.6 m but has had its top blown out. Because of the brittle nature of the crown and inevitable breakage of branches and stems in storms, it is likely that the original heights of many giant totara trees will have been reduced.

Large old totara are usually hollow, making age estimation difficult but larger specimens of totara could be 1000 years old or more. Ancient totara in the Whirinaki Forest, central North Island, have been estimated to be over 800-years-old (Ebbett 1992). Enright and Ogden (1995) indicate typical longevity is 600 years for totara.

2.2.4 Seedling and sapling morphology

The seedlings of totara bear two, occasionally three, relatively long-lived, curved cotyledons 15 mm long and 2 mm wide (Philipson and Molloy 1990). These can be retained on seedlings for up to four years (A. E. Beveridge pers. comm.). The leaves are flat, linear, and sharply pointed, 24-40 mm long x 2-2.5 mm wide. They are arranged on the stem in a spiral, except for the first two leaves which are opposite and at right angles to the cotyledons. Dormant buds eventually terminate the growth of the stem and also occur in the axils of some of the leaves in no apparent regular pattern. A few of these buds grow out during the first growing season to produce more or less horizontal lateral branches.

Terminal resting buds on the main stem or on lateral branches can resume growth up to four times in a growing season depending on conditions, leaving a circle of bud scales at the base of each flush. The facility for some shoots to produce a second flush of growth in the same season is maintained to the adult stage (Philipson and Molloy 1990). Flushing of totara of all ages from seedlings grown in the nursery to poles and semi-mature trees on farmland has been observed from spring to autumn. In the nursery, up to four flushes are possible for vigorous seedlings but there are usually only up to two flushes for natural seedlings (A.E. Beveridge pers. comm.). Considerable phenotypic variation, particularly in habit of branching and stem form, was observed in the 1970s and early 1980s in tens of thousands of totara seedlings raised in the Forest Research Institute Nursery for planting in selectively logged forest in the central North Island (Bergin and Kimberley 1992).

2.2.5 Foliage and form at later stages

Seedlings develop into laxly-branched saplings without any abrupt change in foliage or habit. At semi-mature and mature stages, trees have broader, shorter leaves 10-30 mm long x 1-4 mm wide and are more or less in two opposite rows.

With adequate side shade, or in gaps, totara seedlings and saplings can maintain generally straight stems, with mostly a single leader. In semi-mature and mature trees, the main leader often becomes eclipsed by the strong growth of laterals, producing the more rounded crown of the mature tree. In open growing conditions, larger seedlings and saplings can be multi-stemmed with several branches competing as leader. At wide spacing in plantations and in open conditions, trees become multi-leadered and heavily branched and form large rounded crowns that are characteristic of second-growth totara on farmland (Bergin and Pardy 1987). In northern parts of its range, totara within the forest grows tall with narrow light crowns whereas in southern localities, the trees are usually shorter with large boles, basal buttresses, and more heavily branched crowns (Philipson and Molloy 1990). The stems of mature large trees have been observed to produce epicormic shoots up to 2 m long at Whirinaki Forest, particularly where the crown has died back (A.E. Beveridge pers. comm.).

2.2.6 Phenology and seeding

Totara is dioecious. Best (1942, P.5), in his book Forest Lore of the Maori, describes how the Tuhoe term the male trees of totara as 'karaka' and the female trees as 'kotukutuku'. On male trees, 10-15 mm long, yellow-green catkins occur in abundance on short branchlets over crowns in spring and release pollen from mid to late spring depending on locality (McEwen 1982). On female trees, glaucous ovules are borne on short stout stalks in October-November near the base of new shoot growth. Ovules are fertilised 2-3 months after pollination and the fruit ripens in autumn. The 3-5 mm long ovoid, green, nut-like seeds are seated on red, orange, or occasionally yellow, swollen and succulent receptacles on tips of modified branchlets. Receptacles usually bear one ovule but sometimes two. Seeding usually occurs from March to April with fallen seed turning brown within a few weeks but remaining viable for some time. Compared with the other tall podocarp tree species, totara produces reasonable quantities of seed in most years although large old trees can have poor seed crops. Planning for large-scale planting programmes using totara is relatively easy as locally-sourced seed can usually be collected in most years for the raising of seedlings. Fallen seed can be recovered from beneath female trees up until late winter and successfully germinated (Bergin and Kimberley 1992). Method of seed collection varies depending on the size of seed trees and quantities of seed required. Where seed is sought from large trees, sheets of hessian or similar material can be laid beneath seeding trees on the ground or suspended on poles to catch falling seed during the autumn. Seed can be collected by hand from lower branches of smaller trees. Once seedfall has ceased in late autumn or winter, seed, which by this time has turned brown and lost receptacles, can be picked up from the ground around the base of female trees. Although large quantities of seed can be found at the base of seeding female trees, it is also widely distributed by a range of both native and exotic bird species in flight or from perches.

2.2.7 Root structure

Totara root systems are irregular and variable, even within one soil type (Hinds and Reid 1957). They comprise a framework of large surface or subsurface laterals, often extending well beyond the crown spread, with obliquely-descending peg roots and nodulated-like feeding roots in humus near the surface.

Root systems of bare-rooted seedlings are vigorous and distinctly golden in colour when fresh, with abundant nodules on lateral roots and occasionally on main roots (Herbert 1976). The nodules, which in fact are modified extensions of the lateral roots specific to Podocarpaceae, may be infected with phycomycetous mycelia (Baylis *et al.* 1963). There has been extensive research on the significance of these nodule-like roots. Bond (1967) showed that an endophytic fungus was necessary for growth of totara in poor soils deficient in available phosphorus and calcium. McSweeney (1982) considered that the evidence for extensive nodules on totara root systems fixing nitrogen is inconclusive.

Foweraker (1929) highlighted the ability of totara to produce a new root system after inundation with river silt. McSweeney (1982) recorded from a survey of matai/totara flood plain forests in South Westland that both matai and totara can produce new root systems from their trunks after silt is deposited around them, and this was also confirmed by observations of local farmers. The new root systems appear higher up the erect inundated boles. McSweeney (1982) also observed that new root systems could be produced high up horizontally lying trunks uprooted by windthrow and that some trees carried long distances down rivers had developed new root systems and were growing. Campbell (1984) also reports growth of roots from trunks of trees in the Orongorongo Valley, Wellington, where bases of mature totara buried by over 3 m of alluvium spread by streams have produced another root system near the surface of the gravel. This capability of producing new root systems high up stems indicates that the species should be easy to raise from cuttings (L. Gea pers. comm.).

2.3 DISTRIBUTION

Totara occurs discontinuously in most regions of the country in lowland and lower montane forest (Allan 1961). It is most abundant in the central North Island and discontinuous in the South Island. While Allan (1961) indicates totara is present on Stewart Island, Wilson (1982) considers only Hall's totara occurs on the island, although some have thicker bark and resemble totara. The National Forest Survey estimated the national resource of totara timber in 1955 by land tenure and indicated that it was a significant component of forests in all regions in the North Island and most regions in the South Island (Masters *et al.* 1957).

Totara occurs from sea level to about 600 m in the North Island and up to 500 m in the South Island (Bergin and Kimberley 1992). It was often found with matai on well-drained flood plains where both species were widespread before European settlement, as well as on deeper pumice deposits in the central North Island (McSweeney 1982). With fertile soils highly suited to agriculture, most of the flood plain forests have been cleared.

Simpson (1988) suggested that totara has great ecological vigour as it regenerates widely, is adapted to a range of climates and sites, is relatively resistant to grazing and is found in many forest types throughout the country. However, this resource has largely disappeared from most areas and Simpson (1988) outlined the loss of totara that has occurred during both Maori and non-Maori settlement. During Maori occupation, totara stands declined because it was felled for various purposes and was also inadvertently destroyed by forest fires. Since European arrival, land where totara was dominant was favoured for farming, which resulted in forest removal and utilisation of timber for construction and fencing.

Today, remnants of totara that occur in old-growth forests in the central North Island are in conservation areas protected from harvesting (e.g., remnants in Whirinaki Forest and Pureora Forest). It also occurs in pockets of forest on flood plains (e.g., Te Maire Scenic Reserve) and remnants on slopes (e.g., A.H. Reed Memorial Reserve, Whangarei). Totara growing on private land and available for management for timber production under the current Forest Act amended in 1993 (Newton 2000) occurs in a wide range of forest types. These include regeneration in almost pure stands of totara and Hall's totara in some regions, particularly Northland and Westland. Both totara and Hall's totara also occur in admixture with rimu, miro, and occasionally kahikatea and matai throughout both the North and South Islands, including Taranaki, Wanganui, Westland and Southland (A. Griffiths pers. comm.).

In many farming districts throughout the country, there is a considerable resource in second-growth totara-dominated stands which are often prominent features of the rural landscape. Such stands occur as established groves or small stands of semi-mature trees on hill country, and on flat lowland as forest along riparian strips. Most second-growth stands range in age from 50-120 years and are the result of land clearing over that time and subsequent regeneration in grass or manuka (*Leptospermum scoparium*)-dominated scrub. Seedling regeneration occurs along fencelines and in hedgerows. Regeneration in grass on steep hill slopes can develop into small stands of saplings and poles within 20 years on some sites if they are not grazed heavily or cleared regularly by landowners.

Duguid's (1990) account of the botany of the Horowhenua region, North Island, which includes totara in a range of forest types, is likely to describe the situation in many other regions, particularly in the North Island. Duguid described the composition of the original vegetation cover, its destruction during human settlement and the remnant vegetation patterns. In this region, totara grew on coastal sand country, plains, and foothills of the Tararua Range, but was particularly abundant on alluvial gravel terraces on the plains and foothills. Although early Maori occupation would have resulted in some clearance, particularly of the sandy coastal strip, sawmilling began in the 1840s and logging for a wide range of timber use followed by land clearance was "actively and ruthlessly pursued" through the 1880s and 1890s (Duguid 1990). However, in some of these areas totara has regenerated freely after logging and is still well represented in remnants on the plain and foothills, but it has almost disappeared from the dune belt (Duguid and Druce 1966). In contrast, Hall's totara only occurs in the Tararua Ranges where it is still common in intact forest.

2.4 CULTURAL VALUES AND TIMBER USE

2.4.1 Maori values and use

Totara timber was appreciated very quickly by early Maori settlers for its suitability in construction and carving, as shown by its use in the oldest house yet found from the 12th century at Moikau, Palliser Bay (Davidson 1987). This and other rectangular houses were constructed of small, shaped totara posts; later examples of larger houses also used totara extensively. Best (1942) discussed both the spiritual significance and practical use of totara for the Maori. He described the "special mythical origin assigned to it" and totara's status "as the principal member of the company of superior or lordly trees (rakau rangatira)". As a wood, totara is unexcelled not only through its mana (status) but also through its physical properties, including ease of working with stone tools, light weight and durability. Best (1942 p. 107) described how "by means of small hardwood wedges the great totara is split into smaller pieces". Thus, it was used extensively for construction of buildings (especially house posts), for decorative carvings and, most significantly, for construction of the ocean-going war canoe, waka taua.

Maori used the bark of totara for roof thatching by using long strips of the semi-detached outer bark that could be readily obtained from mature trees without killing or injuring the tree (Best 1916). The thick fibrous bark also played an important role in the construction of the fortified pa (village), including the outer defences as well as the buildings within (Clifton 1990). When trees were felled for house-building or construction of canoes, the inner bark was used for making patua (vessels for carrying and storing food) (Best 1942). Simpson (1988) also indicated that the bark was used as splints in pohatiti (kelp bags used for storage and transport of muttonbirds). Simpson (1988) also noted that with the resurgence of interest in carving there is now an increasing demand for totara at a time when supplies are scarce.

2.4.2 European use

Since the arrival of European settlers (early 18th century), totara has been an important timber species because of its outstanding features of durability, evenness of texture, ease of working and lightness of heartwood timber from old-growth stands (Hinds and Reid 1957). Consequently, it was widely used for exterior joinery as well as for fence posts and battens, buildings, bridges, railway sleepers and shingles (Duguid 1990). Garratt (1924) recorded that the wood was much in demand for house, bridge and wharf construction, poles, railroad-ties, paving blocks, cooperage and wood-pipe staves.

Totara heartwood is amenable to all types of machining, including joints, and finishes off very smoothly; it was considered superior in many uses to kauri. The timber is excellent for carving and can be used for joinery and furniture, finishing well with a coating of oil or wax (Dermott 1985).

Sapwood is moderately resistant to pressure treatment with copper-chrome-arsenical (CCA) preservatives (Clifton 1990). Heartwood is resistant to chemical preservation and is unnecessary as the natural durability of the wood makes it suitable for all uses except extreme hazard situations. Principal uses for high grade heartwood were sashes and doors, tanks, vats, boat sheathing and building (Hinds and Reid 1957). Lower grades were used for large quantities of fence posts and battens, survey pegs, transmission poles and house piles. Sapwood of totara is durable in exterior woodwork of buildings and is not susceptible to attack by the borer *Anobium*. In recent years, where small supplies were obtainable, totara has been made into a range of hand-crafted products such as boxes, bowls and platters supporting a local craft industry in many regions. Recycled posts and battens have also been made into a range of products, including outdoor furniture.

2.5 SITE PREFERENCES

Totara is found on a wide range of soils with the best stands on well-drained lowland alluviums (Esler 1978) and on some pumice soils of the central North Island. Totara is more tolerant of dry soils and seasonal drought than other podocarps, but it is intolerant of poorly drained soils (Hinds and Reid 1957). Simpson (1988) confirmed the wide site tolerances of totara, indicating that it once grew throughout the country on coastal sand dunes, swamp margins, alluvial valleys and plains, volcanic areas and hill slopes. Totara is often the most common indigenous tree that regenerates naturally on farmland after clearance in many regions of the North Island where it occurs as single trees or in second-growth stands on hilly country, and sometimes in mixture with kahikatea along riparian areas and on river flats. Evidence that seed is dispersed widely by birds can be seen where seedlings are often found growing along fencelines having germinated from seed dropped or defecated by perching birds. Seed is also dispersed in flight by tui and starlings (A.E. Beveridge pers. comm.).

2.6 REGENERATION STRATEGIES

2.6.1 Seed dispersal and destruction

The bulk of the totara seed crop ripens from mid March to May in central North Island (Beveridge 1964). The ripe, nut-like seed is green in colour while still on the tree, and although the seed coat turns brown after seedfall, it is still viable. Planted totara bear seed after 20 years on upland sites in the central North Island (A.E. Beveridge pers. comm.). Beveridge (1973) studied periodicity and abundance of seed crops in podocarps at Pureora Forest and found that totara produced light but consistent seed crops over several years in areas with few or no brushtail possums (*Trichosurus vulpecula*). He also found that occasionally trees produced empty seed even if borne on ripe, fleshy receptacles.

In an intensive seed study of podocarps over several years in central North Island forests, Beveridge (1964) found that the most active dispersers of podocarp seed, including totara, are kereru (*Hemiphaga novaeseelandiae*), tui (*Prosthemadera novaeseelandiae*), and bellbirds (*Anthornis melanura*). These birds swallow both fleshy receptacles and seed of podocarps but digest only the pulp and the seeds pass intact through the digestive tract. Beveridge also found that the only bird observed destroying totara seed was the yellow-crowned parakeet (*Cyanoramphus auriceps*). However, his experiments showed that totara seed, unlike the other major podocarp species, was not eaten by rats (*Rattus rattus*), although receptacles were quickly consumed. Burrows (1994) also observed keruru and bellbird feeding on fruit of totara in Banks Peninsula.

Beveridge (1964) concluded that seed of most podocarp species is distributed beyond 40 m primarily by birds and also possibly water. He suggested that bird dispersal is vital for the regeneration of podocarps in areas of scrub where there are no seeding trees. In a study of the regeneration of podocarps on Mount Tarawera, Rotorua, Burke (1974) found that totara seeds had dispersed up to 4.8 km from the nearest surviving trees and concluded that bird dispersal was responsible.

2.6.2 Regeneration

2.6.2.1 Podocarp regeneration studies

There are numerous descriptive studies of natural regeneration of the podocarps in high forest and scrubland as well as theories attempting to explain regeneration patterns. A feature in many New Zealand conifer-hardwood forests is a scarcity of conifer seedlings, saplings, and poles, and a predominance of mature trees. This has been reported for several indigenous conifer trees including totara and is often referred to as the podocarp "regeneration gap" (Holloway 1954; Wardle 1963). They suggested that dense podocarp stands are relicts surviving from the past when climatic conditions were more favourable for establishment of seedlings. However, Ogden (1985) listed several independent studies emphasising that all-aged populations should not be expected in stands which have not been disturbed recently. Rather than the "climax" model which assumes continuous regeneration, he suggested a "mosaic regeneration" model as more appropriate where regeneration occurs in disturbed areas on a localised scale rather than on a regional scale as would be expected with past climatic changes.

McSweeney (1982) suggested that totara is more a true forest pioneer than matai. In a survey of the matai/totara flood plain forests of South Westland, he concluded that there was strong evidence of totara's inability to regenerate beneath a closed canopy or even in small canopy gaps. Totara regeneration is most vigorous in large windthrow gaps, forest margins, and open scrub and grassland, whereas matai can regenerate beneath a continuous forest canopy.

Along many previously disturbed forest edges and scrub ecotones in Pureora Forest, central North Island, there is often regeneration of totara. Leathwick (1987) found that young rimu, matai and totara are common in scrub communities on gently rolling country adjacent to mires and bordering high forest in the Waipapa Ecological Area, Pureora Forest. Totara regeneration often occurs in manuka-, kanuka- (*Kunzea ericoides*), or kamahi- (*Weinmannia racemosa*) dominant scrub, particularly where natural canopy gaps occur or when the nurse species dies back (A.E. Beveridge pers. comm.).

Most totara seed germinates in the late spring and summer after seedfall (Beveridge 1964). Although podocarps germinate readily on a wide range of forest sites, many places are unsuitable for further growth such as dense leaf litter from tree ferns and broadleaved species, and in dense shade from ground vegetation (Beveridge 1973). In a summer survey of regeneration in Whirinaki Forest in recently selectively logged and unlogged dense podocarp forest, Smale *et al.* (1985) found over 20,000 mostly cotyledonary seedlings ha^{-1} of rimu, matai, kahikatea, miro and totara on the forest floor. A lack of advanced regeneration indicated that most seedlings were ephemeral.

Beveridge (1973) described in detail the conditions under which podocarps regenerate in Pureora Forest. He found that podocarp regeneration is scarce under dense-canopied forest but occurs more frequently beneath a gradually opening canopy of large broadleaved trees and in fire-induced scrub. Cyclic regeneration can be seen in scattered podocarp forest where tree ferns invade or increase in gaps created by large windfallen, overmature podocarps. Then epiphytic hardwoods, particularly kamahi in the relatively wet climate of Pureora Forest, develop on tree ferns or fallen logs which leads to eventual suppression and death of the tree ferns as the hardwood trees develop to a large size. These are favoured by birds for perching in, particularly kereru, which deposit seed from which podocarp seedlings regenerate. The next generation of podocarps then develops as the kamahi crowns thin and die. Beveridge (1973) also found regeneration of podocarps in old cutover forest and along logging tracks after controlled selective logging of virgin forest with few remaining large pioneer totara with many seedlings eventually developing without tending.

2.6.2.2 Comparison between conifers and angiosperms

In a study of the relationship between seedlings and saplings of four podocarp species in a coastal forest fragment in Westland, Norton (1991) supported earlier suggestions (Cameron 1954; Beveridge 1964; Herbert 1986) that large angiosperm canopy trees play an important role in the regeneration of podocarp tree species. Norton (1991) detailed a number of factors that may be involved in an abundance of totara and other podocarp seedlings and saplings under large hardwood trees, particularly kamahi, and a relative paucity of podocarp regeneration under totara and rimu canopy trees. These include the role of birds perching in large, branched kamahi depositing seed on the ground (McEwen 1978), and the greater irradiance levels on the forest floor beneath large angiosperm trees compared with podocarp canopies, which may facilitate the regeneration of the podocarps (Cameron 1954).

Conifers are generally slower growing and achieve greater final sizes and longevities than associated angiosperms (Ogden and Stewart 1995) described by Bond (1989) as a contest between the slow (conifer) tortoise and the fast (angiosperm) hare. Ogden and Stewart (1995) argue that the mixed conifer-angiosperm forests are two components that occupy different strata and regenerate in response to canopy disturbances of different scales. Veblen (1992) described three types of regeneration pattern according the scale and severity of natural forest disturbance and Burns (2000) has discussed these regeneration modes in relation to a selection of New Zealand conifer and angiosperm tree species:

- 'Catastrophic regeneration' – occurs after some stand-destroying event such as fire, flood, windstorm or avalanche that has created a large gap up to 1 ha in size in which seedlings of shade-intolerant species but tolerant of exposed conditions regenerate such as totara, kahikatea and to some extent kauri.
- 'Gap phase' – found where regeneration occurs in small to intermediate sized gaps caused by the death of one or a small group of trees such as rimu, puriri (*Vitex lucens*) and mangaeo (*Litsea calicaris*) that are of intermediate shade tolerance but where seedlings may need to persist for long periods in shade under a canopy.
- 'Continuous' – occurs where seedlings that are shade tolerant and grow to maturity without an opening in the canopy such as the relatively slow growing tawa (*Beilschmiedia tawa*).

2.6.3 Allelopathic effects

Other authors have suggested that the lack of regeneration of podocarps under mature trees of the same species may be due to factors associated with soil conditions. Burke (1974) found that seedlings of Hall's totara survived better some distance away from the parent tree and suggested that the parent may have a harmful influence on the survival of its progeny. Molloy *et al.* (1978) found that water-soluble extracts of fresh green leaves of kahikatea, totara, and matai had a toxic effect when applied to first-year and older kahikatea seedlings. The allelopathic effect of the podocarps is supported by Perry *et al.* (1995) who found that undiluted ethanol extracts from foliage of podocarps including totara inhibited both germination and hypocotyl elongation of lettuce (*Lactuca sativa*). Perry *et al.* (1995) concluded a great deal of experimentation, including identification of active compounds in extracts from podocarps and their quantification and significance to regeneration in the forest environment, is still required.

2.7 GROWTH RATES AND FORM

2.7.1 Seedling growth

Beveridge (1962) recorded up to 30 cm height growth in one year for totara seedlings transplanted from the forest into potting mix at a nursery adjacent to tall podocarps in Pureora Forest. Addition of fertiliser significantly improved height growth compared with unfertilised seedlings both in nursery beds and in containers. Wildings approximately 10 cm high could be raised on this upland site to a planting height of 50 cm in 12 months in a plastic house where there was shelter from wind and frost.

Totara seedlings can be grown in a nursery from seed to a planting height of 50-70 cm within three years of sowing on cool upland sites (Beveridge *et al.* 1985). Considerably faster growth rates can be achieved in nurseries in warmer lowland locations; seedlings have grown up to 70 cm within two years of seed sowing (M. Dean pers. comm.).

2.7.2 Planted stands

Podocarps are slow starters after planting out. On cool upland sites, annual height growth of totara has accelerated after the second year averaging 20 cm on a range of microsites. Tall seedlings (60-80 cm) planted on good sites have reached 2 m in height within five years with survival exceeding 90% (Beveridge *et al.* 1985).

In a nation-wide survey of indigenous trees planted mainly on fertile lowland sites (Pardy *et al.* 1992), over a dozen stands and shelterbelts planted with totara ranging in age from 20 to 80 years were assessed. Predicted mean annual height increment for totara based on height/age regression curves was 38 cm at age 20 years with the rate slowly reducing to 32 cm at age 40 years and 24 cm at age 80 years. Average height of totara was estimated at 10, 16, and 18 m at ages 25, 50, and 75 years respectively. The predicted annual diameter growth (at 1.4 m above ground level) over all ages was 8 mm, with estimated diameters of 19, 36, and 55 cm at ages 25, 50 and 75 years, respectively. On individual sites, increments varied by 20% or more, depending on site and silvicultural factors. However, volume production per ha could not be estimated reliably because of the small size and variable species composition of many of the stands surveyed.

2.7.3 Natural stands

Stem analysis of conifer poles regenerating in a scrub ecotone resulting from fire in West Taupo forests showed extremely slow growth rates. All podocarp species took 50-100 years to reach 15 cm diameter on these cool upland sites where there would have been strong competition mostly from kamahi (Beveridge 1973). This compares with 20-25 years in planted stands on a range of fertile lowland sites (Pardy *et al.* 1992).

Cameron (1959) evaluated the growth rate of indigenous conifers in North Auckland by measuring the width of growth rings. Depending on the forest type, diameter at breast height over bark for totara ranged from 9 to 12 cm at age 50, 18-25 cm at age 100 years, 35-53 cm at age 200 years, and 58-80 cm at age 300 years. Similar growth rates were reported for 54 totara in South Westland measured by McSweeney (1982) using ring counts from discs taken from windthrown or logged trees. McSweeney (1982) found a strong linear relationship between diameter and age (annual growth rings) for totara from trees aged from less than 50 years to nearly 400 years.

Relatively slow growth rates have been recorded in other studies on upland sites. Katz (1980) found that totara averaged 5 mm diameter growth and 20-25 cm height growth per year in a rimu-dominated 80-year-old pole stand that had regenerated under scrub on former Maori-cleared sites in the Whirinaki River valley, central North Island. Total basal area at 1.4 m above ground in an unthinned plot was 71 m^2 ha^{-1}.

2.7.4 Stem form

Totara in high forest often forms a tall straight bole with no branching at lower levels. In contrast, isolated totara on farmland or trees planted in shelterbelts invariably form large-crowned trees with large live branches to near ground level.

Pardy *et al.* (1992) found that height and tree form were greatly influenced by stand density. In a survey of planted indigenous tree species they found that a dense totara stand in Northland, planted at 1.2-1.5 m spacing, had excellent stem form with a high proportion of interior trees having clear boles of 5-10 m and small, lightly branched crowns. Conversely, 50-year-old totara planted 4-6 m apart at Cornwall Park, Auckland, had short large-diameter stems with multiple leaders and large persistent branching to near ground level.

2.8 INJURIOUS AGENCIES

Of the podocarp species, totara is the most susceptible to injury by unseasonal frost on young shoot growth and to defoliation by insects. There was a high incidence of insect attack by defoliating caterpillars on seedlings raised in a nursery at Pureora with severe damage to new foliage (Beveridge 1962). Most severe damage was caused by tortricids destroying the terminal bud of small seedlings which gave rise to production of long horizontal side shoots or multiple leaders. Geometrids appeared to do less damage to the form of seedlings where the leaves were usually eaten but not the buds. Phasmids, often abundant in crowns of mature podocarps, can also damage totara seedlings significantly. Some unthrifty totara seedlings were also attacked in the Pureora nursery by the smut fungus *Corynelia tropica*, the reproductive bodies occurring as yellow patches on leaves.

Seedlings and small saplings are frequently damaged by cicadas from bark lesions caused in egg laying and unidentified leaf miners and stem-boring insects. Light browsing of seedlings and saplings by deer is frequently followed by heavy infestation of *Corynelia tropica*, death of terminal shoots and severe malformation (Hinds and Reid 1957). Similar infestations occur after frost damage (A.E. Beveridge pers. comm.). Lloyd (1949) reported that totara seedlings and saplings (and other podocarps) were severely damaged by cicada oviposition in both branches and stems which sometimes led to breakage. He found widespread cicada damage in situations where there was ample light and suggested that it could be a serious silvicultural problem for successful regeneration of totara and other podocarps, especially where the canopy is opened up by logging or releasing. However, cicada damage is only a problem at the seedling and sapling stages while bark is thin.

The native two-toothed longhorn beetle (*Ambeodontus tristus*) bores in dead softwood and heartwood of a number of softwood species but is not as commonly found in totara as it is in rimu and kahikatea (Hosking 1978). Hinds and Reid (1957) reported that heart rot is found in old totara trees which are usually hollow.

This honeycomb decay (sometimes referred to as kaikaka) only occurs in the heartwood and is especially common in the central North Island.

In the central North Island, Beveridge (1973) found that seedling growth flushes that had not hardened off were frequently damaged by both late and early frosts at altitudes of 500-550 m above sea level. Such damage significantly affected annual height increment in most years on these frost-prone sites.

Browsing of totara by possums has been observed and recorded often, particularly on new flushes of totara. Autumn flushes in central North Island forests probably form a significant early winter diet (A.E. Beveridge pers. comm.). Possums have also been observed to reduce seed crops by ingesting seed with receptacles. In enclosure trials, where planted podocarp seedlings were fenced to prevent browsing, possums were found to eat the young shoots and bark of planted seedlings (Forest Research Institute 1980a). In a major study of the diet of possums in Orongoronga Valley near Wellington, Mason (1958) found that totara foliage was eaten by possums and trees were sometimes severely damaged. She also found that possums ate fruit and seeds of totara.
McSweeney (1982) found that totara does not appear to regenerate under grazing pressure in South Westland. In the absence of grazing, totara regeneration is sparse in dense forest but does occur along forest margins and in adjoining scrubland. It is evident that totara can become established on farmland in many regions throughout the country, especially where there is light grazing. It is, therefore, not uncommon to find seedlings and saplings of totara regenerating in grazed pasture where there is a nearby seed source. Most successful regeneration occurs in relatively undisturbed areas such as along fencelines or on steep banks where there is less trampling by stock (Bergin and Pardy 1987).

2.9 NUTRITIONAL AND PHYSIOLOGICAL ASPECTS

Significant growth responses to nutrition were demonstrated by Hawkins and Sweet (1989a) for three podocarp species, rimu, kahikatea and totara. Totara seedlings had the greatest dry weight after eight months of growth and showed the greatest response to increasing levels of nutrient compared with the other two species.

In a further study of temperature response of several tree species, Hawkins and Sweet (1989b) found that significant differences in growth occurred between five temperature regimes examined. As with the other species tested, totara achieved maximum growth at day temperatures of 22°C and at night temperatures of 22°C or 27°C. Totara and the other conifers tested experienced maximum net photosynthesis rates in one of the 27°C regimes.

Of five podocarp species grown in different levels of light intensity under shade cloth and various canopy vegetation types, totara and kahikatea had the greatest height growth response in the highest light levels (Ebbett and Ogden 1998). They suggested that totara and kahikatea have the greatest ability to respond to elevated light levels where large canopy openings in forest gaps have occurred as a result of catastrophic disturbance.

When comparing the effect of a major drought on five stressed and five healthy plants of several indigenous tree species in Canterbury, Innes and Kelly (1992) found that drought-stressed totara produced shorter leaves during the year of the drought. As the drought persisted, stressed totara shed many leaves, while remaining leaves either became yellow-green or died. Most plants eventually died. Of five species tested, Innes and Kelly (1992) found that totara grew in the moister sites and had relatively high mean internal water potentials suggesting that totara is a drought avoider rather than a drought tolerator.

2.10 PROVENANCE DIFFERENCES

In a study of seedling growth and form between provenances of totara from 42 sites throughout New Zealand, Bergin and Kimberley (1992) demonstrated that some genetic differences exist in stem form, height growth and leaf characteristics. In particular, provenances from southern latitudes (e.g., Dean Forest, latitude 45°52') grew more slowly than those from further north (e.g., Otaki, latitude 38°07'). Provenance mean growth was positively correlated with mean summer temperature of the locality of seed source. Although stem form and branch length varied between provenances, this was not related to any provenance site variable. Bergin and Kimberley (1992) recommended that because considerable provenance variation does exist within totara, large-scale planting for ecological purposes should use seed of local origin. However, where the objective is to establish plantations of totara for the long-term supply of specialty timber, there is considerable scope for an in-depth breeding programme that would allow selection of provenances with fast growth and good tree form. Also of interest is the effect of introgression of Hall's totara genes on growth and form of hybrid totara.

In a separate study, Hawkins *et al.* (1991) found a strong positive correlation of cold hardiness with altitude of seed source. They suggested that environmental pressures for frost hardiness in totara have resulted in the evolution of populations of totara adapted to current local climates.

2.11 WOOD CHARACTERISTICS

The heartwood of totara is an even pinkish brown and the sapwood whitish brown. The wood is typically straight grained and therefore easily split. It has a fine, even texture which cuts smoothly across the grain. Kiln drying is not recommended as it dries slowly and unevenly (Hinds and Reid 1957). It is normally air dried although this may take many months (e.g., 25 mm wide boards require nine months). Once dry, heartwood is dimensionally very stable (Harris 1961). Totara is not a strong timber and the dry heartwood is relatively brittle; it is therefore better suited as posts and piles rather than as beams (Clifton 1990). Extractives in heartwood seriously retard drying of normal primer paint, otherwise painting qualities are excellent. Before the development of water-based paints, special primers that were low in oils to compensate for the natural extractives in the wood were required for totara.

In a study of the natural durability of the heartwood of a range of New Zealand grown timbers of both exotic and indigenous species, totara was listed as one of only five species (three exotic and two indigenous) assigned as very durable. It has an expected service life in excess of 25 years when used in a ground-contact situation (Forest Research Institute 1982).

Traditional supplies of totara have been from trees several hundred years old logged from old-growth forests where the bulk of the stem comprised heartwood surrounded by a narrow band of sapwood. In contrast, relatively fast growing second-growth stands that are less than 100 years old have a high proportion of sapwood (Bergin and Pardy 1987). Although heartwood does have superior wood qualities for many traditional uses, the sapwood can be used for furniture and joinery and can also be used for exterior woodwork as long as it is not in contact with the ground. However, because of the reduced durability, lower density and lighter colour of sapwood, the uses and, therefore the financial value of timber from fast growing trees is likely to be reduced.

The economic viability of growing species such as totara in relatively short rotations is likely to be low until an adequate proportion of heartwood has developed. Numerous studies in several countries on a range of species indicate that heartwood formation can be influenced by a range of factors, e.g., tree age (Yang and Hazenberg 1991; Bhat *et al.* 1988), growth rates (Worbes 1988), silvicultural manipulation (Margolis *et al.* 1988; Pazdrowski 1988), site factors (Ahn et *al.* 1986) and provenance (Schultze-Dewitz and Gotze 1987; Purnell 1988; Magnussen and Keith 1990). However, there has been little research into what influences heartwood formation in New Zealand species, including totara.

2.11.1 Growth rings

Many researchers have experienced difficulties in counting rings in totara. Hinds and Reid (1957) state that growth rings are poorly defined with latewood having slightly darker bands. In limited collections of cores taken from mature totara at approximately breast height, Dunwiddie (1979) found severe problems with ring wedging and lobate growth in both totara and Hall's totara. Lloyd (1963) noted apparently false rings in five specimens.

In a preliminary investigation of several New Zealand timber tree species, Bell (1958) found the ring records difficult to read for totara, suggesting that there may be up to three rings in one year. He also found totara was prone to lack of uniformity and circularity where perfectly normal rings on one side of a cross-section would disappear completely part way round. Bell (1958) recommended use of entire cross-sections for ring studies as cores from different radii are likely to give different ring counts. Norton and Ogden (1987) found that errors in age estimates are likely to be accentuated if based on increment cores due to irregular or lobate diameter growth. Missing rings on single radii can be as high as 10% of the total number of rings present.

McSweeny (1982) used basal discs from windthrown or logged trees in South Westland for counting rings. He did not use increment cores because of the difficulties with compressed ring sequences, as well as the possible risk of damage to live trees. After drying and sanding discs of totara, McSweeney (1982) found very distinct growth rings with no evidence of discontinuous or false rings.

Cameron (1959) acknowledged the possibilities of false rings having been counted as annual rings and that more than one ring could have been produced in one year when he undertook measurement of growth ring widths of totara and other indigenous softwoods in North Auckland. In warmer regions, such as Northland, it is not known what effect multiple flushes in one growing season may have on growth rings compared with the effect of continuous growth on growth ring development of trees in cooler wet climates.

2.12 SILVICULTURE

2.12.1 Seed collection

Seed with receptacles attached can be collected from lower branches of female trees in autumn, or from the ground using fine mesh nets placed beneath seeding trees in late autumn and early winter. There are no special requirements for preparing seed for storage or sowing. Viable seed can be stored for 6-18 months in moist cool conditions (Forest Research Institute 1980b). The seed is green when ripe. Fallen seed turns brown over several weeks but still remains viable for several months after seedfall. Receptacles may be attached to fallen seed but soon shrivel away. Raking up of the upper layer of forest litter (duff) after seedfall in autumn in the vicinity of seeding totara trees and then spreading over seed-raising boxes or beds has resulted in germination of totara seedlings (Herbert 1976). Seed collected from throughout the country for a provenance study of totara (Bergin and Kimberley 1992) was collected from mid autumn to late winter. The most productive collections involved hand-picking fallen brown seed from beneath female trees in early winter. Formed seed was checked during collection by cutting seed in half. Sound seed was regarded as those containing a full white- or cream-coloured endosperm. Shrivelled or empty seed was also present in many collections.

2.12.2 Nursery practice

2.12.2.1 Seedlings

Germination of totara seed after a spring sowing is often irregular and sporadic, even occurring several months to a year after sowing (Forest Research Institute 1980b). Hinds and Reid (1957) indicated that fallen totara seed in forest sites has a long natural dormancy of 70-140 days during winter months before germination occurs. Totara seed of 40 collections from throughout the country mostly germinated 6-10 weeks after spring sowing with a second flush of germination occurring about 4 months later (Bergin and Kimberley 1990).

Totara may be raised either as bare-root or container-grown seedlings. Tall seedlings (50-80 cm) which can be produced in two years are preferred for planting on difficult sites where vigorous weed growth is expected (Bergin and Pardy 1987).

2.12.2.2 Cuttings

The reported ability of totara to produce new roots from parts of the tree trunk covered by alluvium after flooding (e.g., Fowraker 1929; McSweeney 1982), and that large trees can produce epicormic shoots from trunks exposed to increased light when adjacent trees have been felled or windthrown (A.E. Beveridge pers. comm.; own observation), provides some evidence that totara is amenable to production from cuttings. Totara has been raised successfully from cuttings on a small scale, readily forming roots even where live stem and leaf material was taken from very old trees (T. Faulds pers. comm.). This will be important in the propagation of clones of trees with superior growth and form.

2.12.3 Planting

On upland sites, totara is best planted in late winter or early spring. However, in warmer districts, autumn planting may be preferred so that seedlings are better established before summer droughts (Bergin and Pardy 1987). Planting pattern and density will depend on objectives of planting and site. Small-group-planting in canopy gaps to take advantage of overhead light is a preferred method for degraded high forest, cutovers, and bush remnants on farms (Beveridge 1973). A flexible planting pattern in forest gaps will allow selection of better microsites for totara such as disturbed soil away from root systems of large trees, but relocation of scattered groups for releasing will be difficult. Group- or line-planting is appropriate for establishing podocarps in scrub sites depending on height of the canopy (Forest Research Institute 1980a). Although totara and kahikatea are the podocarp species most successfully established on open sites (Forest Research Institute 1980a), establishing a cover of hardy indigenous shrub species such as manuka, kanuka and kohuhu (*Pittosporum tenuifolium*) as nurse species will improve survival and growth, and reduce the risk of frost damage. On open sites totara planted in pure stands which remain untended develop poor form unless they are planted at a high density. Hinds and Reid (1957) also noted that while full overhead light is required for growth of totara, without side shelter, stem form is poor, resulting in a large proportion of multi-leadered trees in plantations.
In general, the application of fertilisers has not boosted growth and survival significantly in trials on upland sites and has been less important to the growth of totara than the choice of suitable planting sites (Bergin and Pardy 1987).

In a survey evaluating the performance of planted indigenous trees up to 100 years of age located throughout the country, the main problem after planting was competition from grass, ferns and shrub hardwoods. Totara is also intolerant of overtopping vegetation whereas Hall's totara seedlings can tolerate persistent shade. Lack of releasing is the main reason for failure of plantings of totara and other species, affecting both survival and growth (Pardy *et al.* 1992). Where weed growth is vigorous, releasing of planted totara from overtopping vegetation is necessary for the first 2-5 years after planting, with additional releasing where necessary to ensure a canopy gap is maintained to allow optimum growth (Bergin and Pardy 1987).

2.12.4 Tending

Some tending to ensure seedlings are not overtopped by competing vegetation is required until they reach about 2 m in height when they can grow in competition with other vegetation. Tending of planted stands of a wide range of indigenous tree species, including totara, has generally been minimal (Pardy *et al.* 1992). Pruning up to 3 m was carried out in a 23-year-old planted totara stand in Hawke's Bay with no apparent detrimental effect on external stem quality or tree health. There are clear indications from both planted and natural stands that stem form and branch development can be influenced by spacing but there have been no detailed assessments of these factors.

Katz (1980) found that previous thinning of an 80-year-old rimu-dominant naturally regenerated stand in the central North Island some 30 years earlier had resulted in an initial increase in basal area increment for both totara and rimu for 8-10 years after thinning. He found that totara adjacent to large trees had excellent form with clean, straight boles extending to the base of the green crown. This was 12 m above ground where canopy height of the stands was just over 14 m. Although nearly 80% of the totara had single stems, most were heavily branched and their form would have benefited from pruning.

2.13 MANAGEMENT FOR TIMBER

2.13.1 Rotation

Under optimum natural conditions, Hinds and Reid (1957) suggested that totara can grow 2-4 rings cm^{-1} and 23-30 cm annual height increment. However, in natural stands where suppression has occurred, slower growth rates of 4-8 rings cm^{-1} are more usual. They indicated that totara are mature at 250-400 years but may remain sound for 800-900 years. Most large totara felled at Pureora Forest in 1978 were found to be hollow (A.E. Beveridge pers. comm.).

Katz (1980) suggested that if rimu-dominant pole stands (including some totara) which had regenerated on Maori clearings in the central North Island around 1900 were regularly thinned, a 5 mm per annum diameter increment should be possible. Rotations of 145 years could then be achieved to get an average 60 cm diameter at breast height for merchantable stems on these cool upland sites. Similarly, Beveridge (1973) suggested that for rimu, also in the central North Island, it would take at least 150 years to obtain a second crop of merchantable sawlogs after an initial regeneration period of 50 years. Trials indicated similar early growth rates of seedlings and saplings of totara, rimu and kahikatea planted in gaps in selectively-logged forest of the central North Island (Beveridge *et al.* 1985). However, growth rates on lowland sites can be expected to be significantly faster than on upland sites (Pardy *et al.* 1992) and consequently a shorter duration could be expected for podocarps to reach merchantable size.

2.13.2 Long-term management

In examining types of silvicultural treatments that aim to establish regeneration, Baur (1964) describes sustained yield management in even-aged and uneven-aged systems. Even-aged management is practiced over extensive areas by some form of clear-cutting or shelterwood system whereas uneven-aged management is achieved by periodic partial harvesting. The latter system has the advantages of removing only the mature larger stems leaving the smaller stems to grow on in a range of size classes; the continued protection the soil against erosion compared to clearfelling options; better protection against climatic hazards; and aesthetic reasons where retaining high forest is desirable. Disadvantages of maintaining an uneven-aged stand include the desirable timber species may be light-demanding, logging is more complex and more frequent and therefore more expensive, and residual trees can be damaged during logging operations (Baur 1964).

Smith (1962) describes in detail the selection systems aimed at creating or maintaining uneven-aged stands. Amongst many variations in selection methods, single-tree selection leaves a small canopy gap in which only very shade tolerant species regenerate whereas the group-selection method gives greater flexibility in canopy size to encourage regeneration or growth of planted desirable species and the development of even-aged aggregations (Smith 1962).

For totara, as well as for most if not all future indigenous timber production in New Zealand, preferred long-term management of indigenous forest for timber production is likely to be options that retain the values of high forest. This will favour selection management systems on most sites rather than clear felling. Most stands of indigenous trees planted over the last century located throughout the country on mainly lowland sites, and surveyed by Pardy *et al.* (1992), were planted with more than one objective in mind. These included providing amenity areas, enhancing scenic views, revegetation or restoration of previously forested sites, long-term timber supply from woodlots, providing shelter, developing or enhancing wildlife habitat, and reafforestation of erosion-prone hill country or landfill sites. Because of the long rotations for indigenous trees, conventional economic analysis cannot support the establishment of plantations of indigenous tree species unless other non-timber objectives such as aesthetic and heritage benefits are considered (Forest Research Institute 1997). These non-timber benefits are likely to reward owners in many ways before the option of removing timber has to be considered. In addition, the value of plantations of key indigenous tree species, including totara, is likely to increase as indigenous and imported decorative timbers become harder to obtain (Bergin and Pardy 1987).

Consideration of both timber and non-timber benefits therefore has implications for harvesting methods and in particular the need to determine whether totara can be selectively managed and what are the best management practices that will promote effective growth of the relatively light-demanding seedlings. The regeneration strategies of podocarps described by Beveridge (1973), Herbert (1986), and Smale and Kimberley (1993) indicate that effective podocarp regeneration occurs only when the over-topping canopy thins out. Early intervention in developing stands, by canopy thinning or releasing of seedlings, is required to optimise growth whether in natural stands or in planted stands.

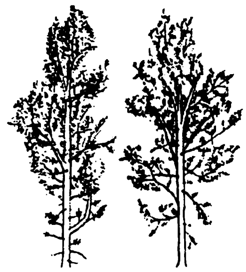
For a densely stocked stand, Cameron (1959) suggested that the podocarps could be grown in even-aged plantations on better sites with fertile soils and achieve good growth rates. He cautioned, however, that any planting would only be successful where weed growth is controlled. This was confirmed in the survey by

Pardy *et al.* (1992) where failures of planted indigenous trees were usually due to inadequate weed control in early years. Cameron (1959) was concerned that there were problems with regeneration on clear-felled areas where indigenous plantations are managed as an even-aged system. He discussed the concept that forest management can be either intensive or extensive, i.e., densely stocked forests for high-volume timber production or low-stocked forest for small intermittent yields. Forests can also be managed either as even-aged stands covering extensive areas or as uneven aged systems of silviculture where forests are a mosaic of small or large groups of even-aged trees.

Several selection logging trials established by the Forest Research Institute from the early 1960s to the early 1980s in low to dense podocarp forest in the central North Island investigated methods and intensities of extraction (eg., Herbert and Beveridge 1977; Smale *et al.* 1987). The last selection management trial established used refined extraction methods where relatively low volumes of timber were extracted from small groups or as individual trees with the aim of retaining high forest values (Beveridge 1984; Smale *et al.* 1985). James and Norton (2001) argue that natural forest management of rimu-dominant forest in Westland is an example of ecologically based sustainable management of a temperate rainforest. Management has involved the use of heavy-lift helicopters to minimise the impact of harvesting and the modelling of forest yield based on tree numbers and the forest's expected tree mortality rates. The forest plan aims to harvest biomass that should be recovered through growth before another harvest cycle; to harvest single or small groups of trees; to select trees that are senile or unthrifty; and to maintain a healthy forest ecosystem that continues to sustain the full range of biodiversity that occurs within the forest.

Benecke (1996) describes well-established sustainable management of mixed species uneven-aged forest under selection silvicultural systems carried out in Europe for over 100 years. In examples from Switzerland, Bavaria, Slovenia and the Black Sea regions of Turkey, ecological silviculture is guided by natural succession processes of the forest type to achieve near-natural forest composition and structure while providing timber through low-impact harvesting (Benecke 2000). The aim is to maintain a continuous cover of a mixed-species and an uneven-stand structure that will allow sustainable harvesting of timber whilst retaining associated environmental and social values of the high forest. Rotation length is not recognised. Rather emphasis in on stand stability, encouraging natural regeneration, and harvesting trees based on their health and growth vigour and their status in the stand structure with no strict adherence to "target" diameter.

A consideration of both the ecological characteristics of totara and societal demands in terms of acceptable harvesting practice will be important determinants of appropriate long-term management options for planted and managed naturally-regenerating stands. While in-depth analysis of this is beyond the scope of this thesis, an analysis of the growth and performance of totara will provide some insights into the long-term management of the species.



CHAPTER 3

PROVENANCE VARIATION IN TOTARA TEN YEARS AFTER PLANTING ON A COASTAL SITE

3.1 INTRODUCTION

As totara covers a wide latitudinal and altitudinal range, an investigation of genetic differences between geographically separated populations (provenances) in growth and tree form would be a useful first step in development of a strategy for genetic improvement of the species where timber production is an objective for planting and management. In 1985, a study was initiated to investigate the variability between provenances of totara. Seed was collected from trees at 42 sites from naturally occurring stands throughout the country covering most of the species' range. Seedlings were grown for three years under uniform nursery conditions. Results of seed and germination assessments and growth performance of seedlings from each provenance at the end of the 3-year nursery phase were reported by Bergin and Kimberley (1992). The study showed significant differences in stem form, height growth and leaf characteristics between widely-separated provenances of totara. Early growth was correlated with germination success after sowing. In the third year, height increment was negatively correlated with provenance latitude, i.e., provenances from southern latitudes grew more slowly than those from further north.

After the nursery study, seedlings of all provenances were planted on three sites in the North Island for long-term monitoring. Only one site where establishment was successful has been intensively assessed since planting. This is a coastal site near the north of the natural range of the species, and the results on growth and form nearly 11 years after planting are reported here.

3.2 OBJECTIVES

The main objective of this study was to compare the growth and form of a range-wide sample of provenances of totara on three North Island sites using seedlings raised during the nursery phase of the study and to relate any variability to geographic or climatic factors. A further objective was to identify superior provenances for growth and form to enable selection of strains of totara for timber production. A secondary objective was to monitor the early performance of large plantations of totara, established on open, grassy sites.

3.3 MATERIAL AND METHODS

3.3.1 Material

Details of sites where seed collections were undertaken in 1985 for each of the totara provenances and the methods used are given in Bergin and Kimberley (1992). Attempts were made to collect seed from 8-10 seed trees where trees were at least 100 m apart from communities representative of the natural forest of the area and within a 200 m altitudinal range. In practice, however, these requirements were often difficult to fulfil. Totara is dioecious requiring additional effort in identifying female trees, and seed crops on large trees in high forest were found to be small and difficult to collect from. In many districts, the only adequate quantities of seed found were on isolated trees or trees in small groves on farmland. At most sites, good collections were therefore made from 5-30 trees in these naturally regenerated stands. However, 12 provenances comprised seed from only three seed trees or fewer (Appendix 3.1).

Of the 42 original seedlots collected, 36 provenances had germinated well enough to allow planting on one main site. There were sufficient seedlings of 30 provenances for planting on a further site with some provenances available for planting at a third site. Surplus seedlings were used as buffers to the main trial plots where necessary. The 3-year-old bare-root seedlings raised at the Forest

Research Institute nursery ranged from 50 cm to 1 m in height at the end of the 3-year nursery phase of the provenance study and were ready for planting out in spring 1988.

3.3.2 Trial area description

Two main trial areas were selected for planting some 4000 seedlings, including buffers. These were in the Tapapakanga Regional Park at 35 m a.s.l. on the Firth of Thames, owned by the Auckland Regional Council (Figure 3.1), and on private land 450 m a.s.l. in the Whirinaki River valley near Minginui, 90 km east of Rotorua in the central North Island. In addition, a small demonstration block was established at the research headquarters in Rotorua, 300 m a.s.l. All sites were in grass at time of planting and had been fenced to exclude grazing stock. Only the Tapapakanga trial area has been monitored and maintained regularly. Survival at the Whirinaki site was severely reduced by frost damage and heavy grazing and the Rotorua site was partially disturbed by adjacent earthworks.

Locations of each provenance planted at Tapapakanga are shown in Figure 3.1 with seed tree characteristics and geographic and climatic details for each provenance given in Appendix 3.1. The trial at Tapapakanga is on a west-facing slope of a small valley and occupies approximately 1 ha, with slope varying from 5-20°. Soils are heavy clays formed from weathered andesite, forming only a shallow topsoil layer on the steeper slopes. Vegetation at planting was dominated by kikuyu grass (*Pennisetum clandestinum*) which had been recently grazed before the site was fenced off from stock. As for nearby Auckland, mean summer temperature is 16° and annual rainfall is approximately 1500 mm, usually evenly distributed through the year, although summers can become dry. The site is less than one kilometre from the coast at an altitude of 35 m a.s.l. and frosts are rare. The valley is, however, exposed to occasional north-easterly storms.

3.3.3 Trial design

Thirty-six provenances, planted in a randomised complete block design comprising eight 24 m x 24 m blocks, were established. Four-tree row-plots of each provenance were planted randomly within each block, i.e., 32 trees per provenance. Trees were planted at 2 m x 2 m spacing (2500 stems ha^{-1}) with at least one row of buffer trees planted around outside edges of the trial.

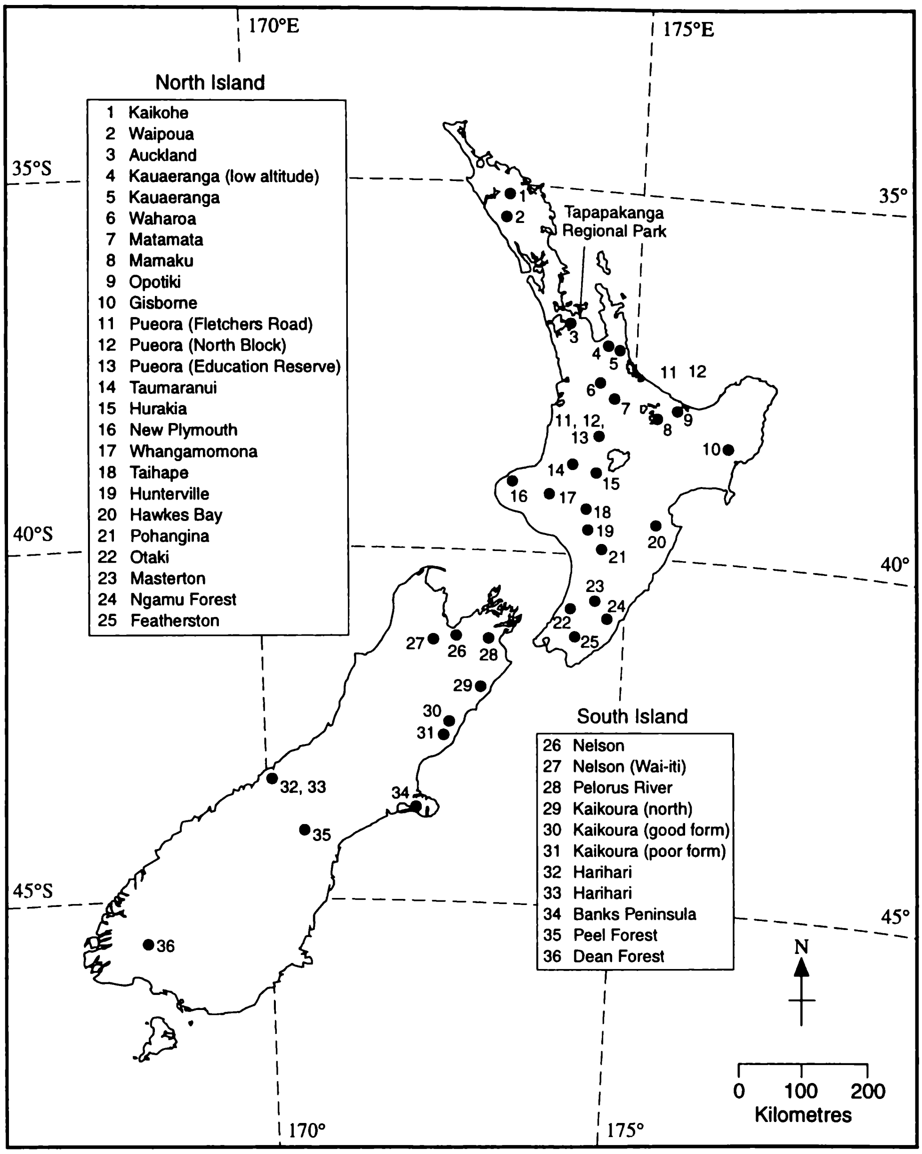


Figure 3.1: Seed collection sites for totara provenances located throughout New Zealand and location of the provenance planting trial site at Tapapakanga Regional Park, near Auckland.

3.3.4 Site preparation and planting

All blocks were laid out with numbered 5 cm x 5 cm ground-treated wooden pegs placed at each block corner and numbered 2.5 cm x 2.5 cm wooden pegs identified row-plots within blocks. Planting spots were sprayed with Roundup herbicide three weeks before planting to give a 1 m diameter area free of competing grass. Planting holes were then dug with a motorised post-hole borer to ensure consistent preparation of planting pits. Over 1200 bare-root totara seedlings were planted in September 1988 within three days of lifting from nursery beds. A mixture of indigenous hardwood species was planted around the periphery of the trial to provide shelter along the upper exposed margins.

3.3.5 Maintenance

Maintenance over the first five years included hand-clearing of rank kikuyu grass from around each seedling to leave a 1 m diameter cleared area. Grass growth was vigorous until canopy closure started to occur about 7 years after planting. Seedlings were vulnerable to overtopping until at least 1.5 m high, 3-4 years after planting.

3.3.6 Nursery assessment of seedlings

Nursery measurements are reported in Bergin and Kimberley (1992) but are included here for the purposes of relating to later field measurements. The following variables were recorded during the three years while seedlings were being raised in the nursery:

- "pulled-up" height (upper parts of leaders of totara seedlings tend to droop) measured annually for 3 years;
- a subjective rating of stem form on a three-point scale immediately prior to lifting:
    - good (1) – single, relatively straight stem with good apical dominance;
    - intermediate (2) – single stem but not upright and/or with double leaders;
    - poor (3) – straggly appearance with poor apical dominance and/or multiple leaders;
- a subjective rating of branching on a three-point scale immediately prior to lifting:
    - light branching (1) – only small branches present;
    - medium branching (2) – small branches numerous with or without one or two steep angle large branches;

— coarse branching (3) – numerously branched bushy habit with steep angle large branches often competing with leaders.

3.3.7 Field assessments

Field trial assessment was undertaken 6 years and then 10 years 8 months after planting. The latter was effectively 11 growing seasons as measurement took place in late autumn (May) of the 11th year after planting, and is hence often referred to as the assessment at 11 years.

- ***6 years after planting:***
  - Heights and survivals
  - a subjective rating of stem form (good = 1, intermediate = 2, poor = 3) following the same criteria used in the final nursery-based assessment immediately prior to lifting and planting.
- ***10 years 8 months after planting:***
  - root collar diameter of all trees;
  - DBH (diameter at breast height; 1.4 m above ground on uphill side of trees) of all trees; the DBH of all multiple leaders where they occurred at this level were recorded; for the purpose of analysis, the DBH of trees with more than one leader was based on the summed basal areas of all leaders;
  - height of the tallest tree in each four-tree plot.

At 10 years 8 months, owing to the closed canopy and dense crowns, it was impossible to continue using the subjective stem form assessment technique used in the previous measurement. However, where trees had more than one leader, the number and height to the base of each leader was measured. These measurements were used to derive three measures of stem form:

- percentage of trees with multiple leaders;
- mean number of leaders per tree;
- a score indicating the height to the base of the first leader (0 = 0-1 m, 1 = 1-2 m, 2 = 2-3 m, 3 = 3-4 m, 4 = no multiple leaders).

3.3.8 Data analysis

The SAS UNIVARIATE procedure was used to check the distributions of heights and diameters (SAS 1990). They were found to be approximately normally distributed. Analyses of variance (ANOVA) and least significant difference (LSD) tests were used to test the significance of provenance differences for the following variables: survival at age 6 and 11 years; height at planting (i.e., age 3), age 6 and age 11 years; root collar diameter at age 11 years; DBH at age 11 years; stem form at age 6 years; trees with multiple leaders, number of leaders per tree and height to first double leader, all at age 11 years; and height increments between ages 3 and 6 years and between ages 6 and 11 years. Correlations were not presented for height increments after planting as trends did not differ markedly from height correlations. Using SAS, all analyses were performed using plot means with the block treated as fixed effect. Pearson correlation coefficients were calculated between provenance means for the above variables and between these variables and latitude, altitude, mean temperature and rainfall of provenance sites.

3.4 RESULTS

3.4.1 Survival and growth

Provenance means for all characteristics assessed at the Tapapakanga site are shown in Tables 3.1 and 3.2. Overall mean survival had stabilised at 90% by age 6. By age 11 years average survival was 89% with all but one provenance exceeding 80%, the exception being the Gisborne provenance at 69%. Generally, trees appeared in good health in successive assessments and no disorders were noted. Most mortality occurred within the first 3 years of planting mainly caused by suppression of young plants by vigorous regrowth of kikuyu grass between annual maintenance visits. Temporary overtopping by grass may also have hindered early growth of some plants.

There were highly significant differences ($p < 0.01$) between provenances in height growth at time of planting, and at ages 6 and 11 years, and in root collar diameter, DBH, (Table 3.1) and for multiple leaders at age 11 years (Table 3.2). Overall, average height at planting was 85 cm and 6 years later was 2.9 m. Average height of the tallest tree per plot was 5.5 m 11 years after planting.

Overall, average root collar diameter was 12.7 cm and DBH was 9.7 cm, 11 growing seasons after planting. Mean annual increment for height was 42 cm and DBH was 8.8 mm. Provenance mean height and diameter at breast height varied significantly from 4.8-6.5 m and 6.9-11.2 cm respectively, almost 11 years after planting.

As was found with the nursery phase in 1988 (Bergin and Kimberley 1992), the Otaki provenance continued to be the fastest growing in terms of height, exceeding 6.5 m, almost 11 years after planting (Table 3.1). Other fast-growing provenances where mean annual height increments were approaching 50 cm included Waipoua, Kauaeranga (lower-altitude collection site), Mamaku and New Plymouth. The Gisborne and Dean Forest provenances were the slowest growing at under 5 m high by age 11 and had the smallest mean DBH.

Seed was collected from more than one stand of trees in four provenance locations (Kauaeranga, Pureora, Kaikoura, Harihari). Most showed no significant differences in growth after planting out (Table 3.1). The exception was Kauaeranga, where trees sourced from the low altitude site (30 m a.s.l.) grew significantly faster ($p < 0.05$) than trees sourced from the higher altitude site (140 m a.s.l.).

Pearson correlations between provenance means of seedling height during the nursery phase (1986-88) and after planting (age 6 and 11), and diameter (age 11) are shown in Table 3.3. There were no significant correlations between provenance mean height at ages 6 and 11 years, root collar diameter at age 11 years, and DBH at age 11 years with nursery heights in 1986 and 1987. As reported by Bergin and Kimberley (1992), the first two years of height growth in the nursery appeared to be related to seed quality and not to height growth in the third year (1988) when genetic factors began to predominate. This trend became stronger at the assessment 6 years after planting at the Tapapakanga trial site and has continued at a similar level with the latest assessment of the seedlings almost 11 years after planting.

Table 3.1: Mean survival and growth characteristics for each of the provenances of totara as assessed 10 years 8 months (referred in table as 11 years) since planting in 1988.

No.	Provenance	Survival age 6 (%)	Survival age 11 (%)	Height at planting (m)	Height age 6 (m)	Height age 11 (m)	Root collar diameter age 11 (cm)	DBH age 11 (cm)
1	Kaikohe	91	91	0.86	3.0	5.8	13.0	10.3
2	Waipoua	94	94	0.87	3.2	6.1	13.5	10.8
3	Auckland	94	94	0.79	3.0	5.9	12.8	9.7
4	Kauaeranga (low altitude)	91	88	0.87	3.1	6.2	14.5	10.8
5	Kauaeranga	84	84	0.89	2.7	5.5	11.8	8.9
6	Waharoa	97	97	0.85	3.0	6.0	13.5	10.2
7	Matamata	94	94	0.85	2.9	5.7	13.5	10.4
8	Mamaku	88	88	0.84	3.1	6.1	13.6	11.1
9	Opotiki	94	94	0.88	3.2	5.6	13.3	10.6
10	Gisborne	75	69	0.79	2.1	4.9	9.4	7.2
11	Pureora (40A Fletchers Rd)	94	94	0.84	3.0	5.9	12.1	9.6
12	Pureora (40B Nth Block)	91	91	0.87	2.9	5.3	12.2	9.4
13	Pureora (40C Education Res)	94	91	0.91	2.9	5.7	12.7	9.9
14	Taumaranui	94	94	0.94	3.2	5.9	14.6	11.2
15	Hurakia	84	84	0.81	3.0	5.5	12.0	9.1
16	New Plymouth	100	100	0.85	3.1	6.1	12.7	10.3
17	Whangamomona	84	84	0.82	2.9	5.3	12.4	9.9
18	Taihape	94	94	0.82	2.4	5.1	11.0	8.4
19	Hunterville	97	94	0.86	2.8	5.7	12.1	9.2
20	Hawkes Bay	88	84	0.66	2.8	5.5	11.9	8.7
21	Pohangina	94	94	0.96	3.2	5.4	13.3	10.7
22	Otaki	94	94	1.04	3.2	6.5	13.1	10.6
23	Masterton	81	81	0.87	2.9	5.6	12.9	9.3
24	Ngaumu Forest	100	100	0.93	3.1	5.4	12.7	10.2
25	Featherston	84	84	0.86	3.0	5.1	13.9	10.8
26	Nelson	84	81	0.83	3.0	5.8	13.6	10.3
27	Nelson (Wai-iti)	84	84	0.75	3.0	5.6	13.5	10.3
28	Pelorus River	94	94	0.79	2.8	5.4	12.0	9.6
29	Kaikoura (north)	88	88	0.78	2.8	5.5	13.0	9.9
30	Kaikoura (good form)	84	84	0.90	2.6	5.0	12.3	9.2
31	Kaikoura (poor form)	81	81	0.88	2.4	5.0	11.5	8.9
32	Harihari (76A)	82	82	0.85	2.6	5.1	12.7	8.7
33	Harihari (76B)	89	89	0.91	2.7	5.3	13.7	9.8
34	Banks Peninsula	88	88	0.86	2.9	5.3	13.1	10.0
35	Peel Forest	84	84	0.85	2.6	5.1	12.7	9.1
36	Dean Forest	91	91	0.64	2.3	4.8	10.1	6.9
	General mean	90	89	0.85	2.9	5.5	12.7	9.7
	LSD	15	16	0.09	0.3	0.7	1.8	1.5
	%Variance	1.9	2.5	35.7	32.8	18.7	17.9	22.1
	F-test - provenance	1.16 (0.26)	1.21 (0.21)	5.46** (<0.0001)	4.89** (<0.0001)	2.82** (<0.0001)	2.74** (<0.0001)	3.29** (<0.0001)

LSD Least significant difference ($p=0.05$). Provenance differences are statistically significant if they are greater than the LSD value.
%Variance Provenance variance as a percentage of provenance plus residual variance;
F-test * Significant at $P < 0.05$; ** Significant at $P < 0.01$ (P value in brackets)

Table 3.2: Mean stem form characteristics for each of the provenances of totara as assessed almost 11 years since planting in 1988.

No.	Provenance	Stem form [#]age 6	Trees with multiple leaders age 11 (%)	Number of leaders per tree age 11	Height to first double leader age 11 (m)
1	Kaikohe	2.03	65.6	1.72	1.86
2	Waipoua	1.69	45.8	1.68	2.07
3	Auckland	1.9	54.2	1.64	1.95
4	Kauaeranga (low altitude)	2.06	52.1	1.71	2.03
5	Kauaeranga	1.95	55.2	1.77	1.81
6	Waharoa	1.72	47.9	1.57	2.20
7	Matamata	1.94	56.3	1.75	1.78
8	Mamaku	1.96	49.0	1.78	1.80
9	Opotiki	2.04	64.6	1.71	1.68
10	Gisborne	2.32	67.9	1.71	1.44
11	Pureora (40A Fletchers Rd)	1.85	60.4	1.76	1.82
12	Pureora (40B Nth Block)	1.66	46.9	1.53	2.14
13	Pureora (40C Education Res)	1.99	54.2	1.61	1.85
14	Taumaranui	1.98	55.2	1.76	1.72
15	Hurakia	1.78	46.9	1.47	2.19
16	New Plymouth	1.75	25.0	1.28	2.44
17	Whangamomona	1.69	39.6	1.48	1.97
18	Taihape	2.07	57.3	1.74	1.94
19	Hunterville	1.84	50.0	1.56	1.91
20	Hawkes Bay	2.1	42.7	1.43	2.02
21	Pohangina	1.96	66.7	1.73	1.75
22	Otaki	2.03	77.1	2.05	1.27
23	Masterton	1.83	55.2	1.65	2.08
24	Ngaumu Forest	2.02	65.6	1.75	1.50
25	Featherston	2.27	84.4	2.23	1.11
26	Nelson	1.96	46.9	1.63	1.95
27	Nelson (Wai-iti)	2.09	52.1	1.68	1.96
28	Pelorus River	2.05	60.4	1.77	1.83
29	Kaikoura (north)	2.19	57.3	1.83	1.65
30	Kaikoura (good form)	1.77	74.0	2.01	1.39
31	Kaikoura (poor form)	2.25	70.8	1.83	1.56
32	Harihari (76A)	2.46	65.5	2.05	1.30
33	Harihari (76B)	2.36	73.2	1.89	1.36
34	Banks Peninsula	2.04	74.0	2.07	1.54
35	Peel Forest	2.04	66.7	1.93	1.47
36	Dean Forest	2.15	47.9	1.67	1.82
	General mean	1.99	57.6	1.73	1.78
	LSD	0.46	25.5	0.40	0.59
	%Variance	4.3	8.6	9.0	10.9
	F-test - provenance	1.37 (0.092)	1.76** (0.0078)	1.79** (0.0062)	1.98** (0.0015)

#	Stem form subjective assessment: 1 = Good; 2 = Intermediate; 3 = poor;
†	Assessed as height to first double leader
LSD	Least significant difference (p=0.05). Provenance differences are statistically significant if they are greater than the LSD value.
%Variance	Provenance variance as a percentage of provenance plus residual variance;
F-test	* Significant at $P < 0.05$; ** Significant at $P < 0.01$ (P value in brackets)

In April 2000, within 12 years of planting, many trees at the Tapapakanga site were fruiting. Both male cones and female fruits comprising green seed and ripe receptacles were present. Cutting of a small sample revealed a mixture of seed with full white-cream-coloured endosperm contents and some seed that was empty, indicating that viable seed was probably being produced. Naturally regenerated seedlings of totara were common, particularly around the edges of trial blocks where there was increased light. Seedling populations comprised both recently germinated seedlings likely to be less than 12 months old, as well as seedlings up to 20 cm high, likely to be up to 2 years old indicating that planted trees were producing viable seed within 10 years of planting.

Table 3.3: Correlation matrix of provenance means for growth variables between seedlings assessed during the nursery phase (1986-88) and performance of trees 6 years (1994) and almost 11 years (1999) after planting. P values are given in Appendix 3.2.

	Height 1986 (nursery)	Height 1987 (nursery)	Height 1988 (nursery)	Height 1988 (trial)	Height at age 6 (trial)	Height at age 11 (trial)	Height increment, 1987-1988 (nursery)	Root collar diameter at age 11 (trial)
Height 1987 (nursery)	0.90**							
Height 1988 (nursery)	0.75**	0.92**						
Height 1988 (trial)	0.63**	0.81**	0.92**					
Height at age 6 (trial)	-0.12	0.06	0.35*	0.46**				
Height at age 11 (trial)	-0.13	-0.03	0.26	0.35*	0.76**			
Height increment 1987-1988 (nursery)	-0.04	0.16	0.54**	0.54**	0.75**	0.69**		
Root collar diameter at age 11 (trial)	-0.12	0.09	0.31	0.45**	0.78**	0.59**	0.59**	
DBH at age 11 (trial)	0.02	0.20	0.45**	0.54**	0.89**	0.69**	0.69**	0.91**

* Significant at $p < 0.05$
** Significant at $p < 0.01$

3.4.2 Stem form

Branches from neighbouring trees were beginning to overlap 6 years after planting. Canopy closure for some blocks or part blocks had occurred by the second major assessment almost 11 years after planting. Trees were invariably bushy with green crowns to within 1 m of the ground making detailed assessment of stem form and branching difficult. Across all provenances, 58% of trees had multiple leaders with an average of 1.73 leaders per tree (Table 3.2). Average height to first double leader for all provenances was 1.78 m above ground ranging from 1.1 m to nearly 2.5 m. Lower branches below 0.6 m on most trees had died; many had rotted away or were brittle and easily broken off leaving relatively clear lower stems. Grass had thinned out from beneath most planted blocks or had disappeared, leaving bare ground with the onset of canopy closure.

The general mean score of stem form in 1994, 6 years after planting (Table 3.2), had not changed from that reported for stem form of seedlings at the end of the nursery phase in 1988 (Bergin and Kimberley 1992). Six years after planting, provenances with good stem form generally had faster growth rates and were from the northern half of the North Island. These provenances with a stem score <1.75 included Waipoua, Waharoa, Pureora (North Block), New Plymouth and Whangamomona. The three variables used to assess stem form at age 11 indicated a similar trend to better form for the faster growing northern provenances. In general, the provenances that scored well for stem form at age 6, continued to exhibit better tree form at age 11. These provenances had lower mean percentage of trees with double leaders (<50%), a lower mean number of leaders per tree (< 1.6 leaders) and a greater average height to the first double leader (> 2 m). The Hawkes Bay seed source was also amongst the better-formed provenances.

Where seed was collected from more than one stand of trees in a provenance location (Kauaeranga, Pureora, Kaikoura, Harihari), there were generally no major differences between stands within provenances in stem form scores and measurements of trees at age 6 and 11 years after planting (Table 3.2). Although seed collections of the Kaikoura provenances from trees of good and poor form showed a significant difference in growth and form between seedlings from parent trees at the end of the nursery phase, there were no longer any significant differences in growth and form after planting out. Similarly, there were no differences in form traits of seedlots from shorter semi-mature seed trees in the Pureora provenance (Fletcher's Road) and the other Pureora seed collections sites from tall, straight trees located in high forest. Bergin and Kimberley (1992) suggested that any genetic differences in stem form of the original parent trees were likely to be masked by the large variation in habitat conditions and this is likely to be continuing.

Correlations for stem-form variables between the nursery phase and later assessment of planted trees are given in Table 3.4. There were significant correlations between branching assessed in the nursery in 1988 and the three traits involving multiple leaders and number of double leaders at age 11. Each stem form trait at ages 6 and 11 was correlated with the other stem form traits ($p < 0.01$). The significant correlation of multiple leader traits at age 11 with those at age 6 and earlier, indicate that assessments of multiple leaders are effective as parameters for quantifying stem form based on subjective scores of stem form used in earlier assessments.

Table 3.4: Correlations of provenance means for stem form traits in the nursery (1988) and planting trial assessments 6 years (1994) and almost 11 years (1999) after planting. P values are given in Appendix 3.3.

	Nursery variables		Planting trial variables		
	Stem form 1988	Branching 1988	Stem form at age 6	Trees with double leaders at age 11	Number of leaders per tree at age 11
Branching 1988 (nursery)	0.68**				
Stem form at age 6	0.30	0.26			
Trees with double leaders at age 11	0.34*	0.45**	0.57**		
Number of leaders per tree at age 11	0.27	0.43*	0.55**	0.89**	
Height to double leader at age 11	-0.35*	-0.52**	-0.68**	-0.89**	-0.89**

* Significant at $p < 0.05$
** Significant at $p < 0.01$

3.4.3 Correlation with geographic and climatic variables

Correlations between provenance mean height and diameter traits, and geographic and climatic parameters are given in Table 3.5. Height at age 6 and 11 years and DBH at 11 years were both negatively correlated with latitude ($p < 0.01$) and positively correlated with mean summer temperature of the seed collection site ($p < 0.01$). R^2 values, however, indicate that at least two-thirds of the variation in provenance growth traits were not explained by latitude and summer temperature.

There was no correlation of growth with rainfall or altitude of provenance localities. During the nursery phase of the provenance trial, height increment in the third year was negatively correlated with provenance latitude (Bergin and Kimberley 1992). This trend has strengthened following planting in the main trial where trees raised from seed collected from northern latitudes grew faster in height than trees raised from seed collected from southern latitudes (Figure 3.2). There was no apparent difference in correlation of growth and geographic variables between provenances where seed was collected from less than six parent trees (listed in Appendix 3.1) compared with provenances where seed was collected from six or more seed trees.

Table 3.5: Correlations between provenance mean height and diameter, and geographic and climatic parameters of provenances. P values are given in Appendix 3.4.

	Height at planting	**Height at age 6**	**Height at age 11**	**Root collar diameter at age 11**	**DBH at age 11**
Latitude	-0.19	-0.45**	-0.58**	-0.20	-0.38*
Altitude	0.06	-0.06	-0.14	-0.25	-0.16
Mean summer temperature	0.15	0.43**	0.54**	0.32	0.41*
Total annual rainfall	0.17	0.04	0.02	0.16	0.07

* Significant at $P < 0.05$
** Significant at $P < 0.01$

There were significant correlations between stem form at age 6 and all stem form variables used at age 11 with latitude (Table 3.6). There was no correlation between stem form traits and mean summer temperature or rainfall, although there is a negative correlation between stem form at age 6 and altitude.

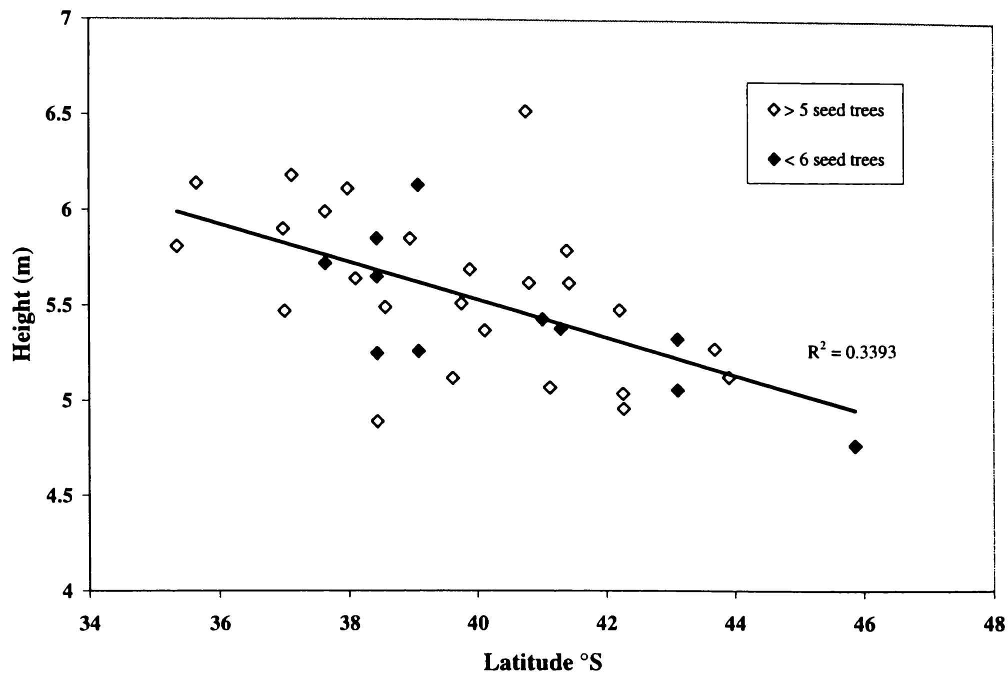


Figure 3.2: Relationship between mean height at age 11 and latitude of provenance for totara.

Table 3.6: Correlations for provenance means between stem form characteristics (assessed in the nursery and the planting trial), and geographic and climatic parameters of provenances. P values are given in Appendix 3.5.

	Nursery variables		Planting trial variables			
	Stem form 1988	Branching 1988	Stem form at age 6	Trees with double leaders at age 11	Number of leaders per tree at age 11	Height to double leader at age 11
Latitude	0.27	0.29	0.48**	0.35*	0.43**	-0.49**
Altitude	-0.02	-0.04	-0.41*	-0.15	-0.25	0.23
Mean summer temperature	-0.10	-0.20	-0.21	-0.11	-0.19	0.25
Total annual rainfall	-0.15	0.04	0.16	0.02	0.11	-0.12

* Significant at $p < 0.05$
** Significant at $p < 0.01$

As with the correlation of faster growth of more northern provenances, a similar, if weaker north-south trend is evident for tree form (Figure 3.3). Here there is a negative correlation between height to the first double leader assessed as a measure of stem form at age 11 and latitude of provenance seed source. As with growth, there was no apparent difference in correlation of tree form and latitude between provenances where seed was collected from less than six parent trees compared with provenances where seed was collected from six or more seed trees.

The poorest stem form 6 years after planting was from the two Harihari sources. These were collected from the introgressive hybrid *Podocarpus totara* var. *waihoensis* described by Wardle (1972) which is a natural hybrid of totara and the closely related, tall shrub *P. acutifolius*. *P. totara* var. *waihoensis* resembles totara but grows to a smaller stature and has narrower, more acute leaves.

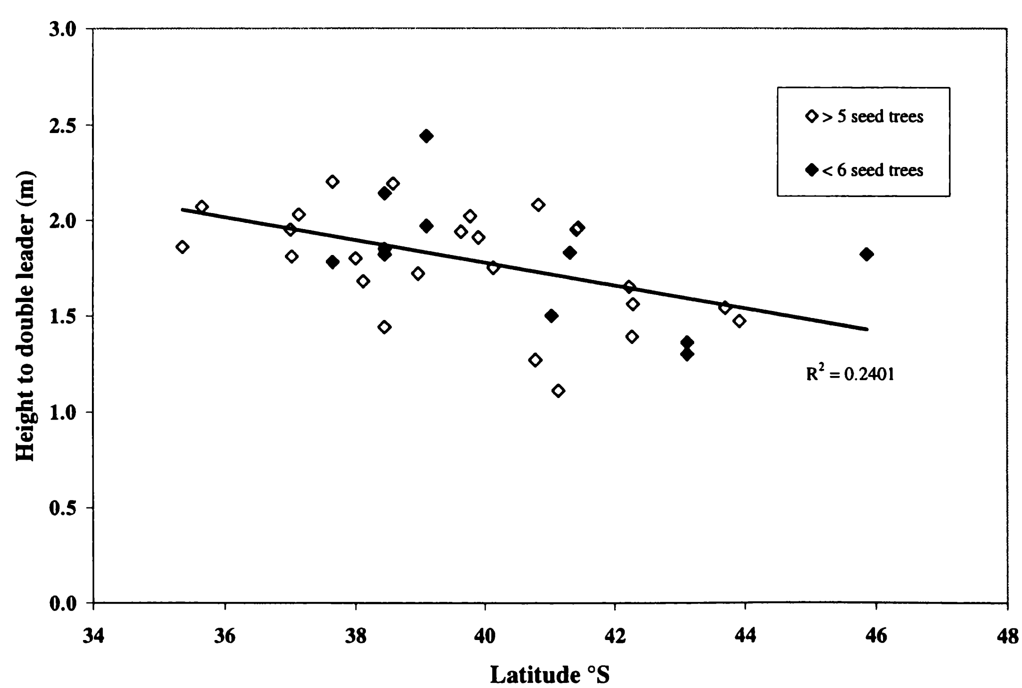


Figure 3.3: Relationship between mean tree form determined by height to first double leader at age 11 and latitude of provenance for totara.

3.5 DISCUSSION

This provenance trial at Tapapakanga Regional Park has allowed the comparison of long-term differences in growth of totara. The frost-free, fenced lowland site has been intensively maintained and monitored since establishment. It is intended that the trial will remain indefinitely to allow evaluation of long-term growth and form differences of totara. Nursery-based provenance trials have been carried out with only five other New Zealand indigenous timber tree species, viz., the beeches (*Nothofagus*) (Wilcox and Ledgard 1983; Ledgard and Norton 1988). A small dense planting of beech provenances remains at Rangiora, north of Christchurch (David Norton pers. comm).

Growth rates of totara on this ex-pasture site at Tapapakanga are exceptionally high compared with other plantings of totara with canopy closure at this density of 2500 stems ha^{-1} occurring 8 years after planting (Figure 3.4). In almost 11 years, the average height is in excess of 5.5 m and DBH is 9.7 cm. This compares with a predicted average height of 4.1 m and DBH of 4 cm based on a survey of planted totara stands throughout the country (Pardy *et al.* 1992). Unlike many of the other planting sites, there was no evidence of possum browsing, minimal insect defoliation, no frost damage and little competition from weed growth at Tapapakanga. The fastest-growing trees have almost 60 cm annual height growth and 1 cm DBH growth per year. Mean survival at Tapapakanga of nearly 90% 11 years after planting matches average survivals reported for numerous podocarp planting trials where survival usually exceeds 80% (Beveridge *et al.* 1985). Selection of appropriate sites for planting podocarps and keeping seedlings free of weed competition in the early years have been critical in ensuring good performance.

Figure 3.4: The totara provenance trial 8 years after planting on a previously grazed farm site, Tapapakanga Regional Park, south of Auckland. Canopy closure is beginning to occur with the stand planted at a density of 2500 stems ha^{-1}.

Although significant provenance differences are evident at age 11 for both height and diameter growth and for stem form (Tables 3.1 and 3.2), provenance differences in height have become less significant with age (F value of 2.82 at 11 years compared with F value of 5.46 at planting). It should be noted, however, that the final height measurement was based on only the largest tree per plot. Similarly, although the negative correlation between height increment and provenance latitude that was evident in the third year nursery growth (Bergin and Kimberley 1992) has persisted and even strengthened, there is still much variation in the height and diameter growth rates of provenances that is not accounted for. This suggests that even at this level of provenance selection, there are opportunities to select fast-growing provenances from within parts of New Zealand, which with progeny testing in a breeding programme, are likely to yield fast-growing progenies.

Diameter at age 11 was more highly correlated with height at age 6 years than with current height (Table 3.3). This tendency for diameter to be correlated more with preceding height than with current height has also been observed for radiata pine by Burdon and Miller (1992a).

Ideally, provenance seed collections should be from a large number of parent trees to ensure that the genetic diversity of the local species population is fairly represented. One-third of the provenances evaluated in this study were based on seed collected from a small number of parent trees where growth could be based on only one or two inbred individuals. Inbreeding and the corresponding reduction on growth have been reported for a number of species including conifers (e.g., Williams and Savolainen 1996). However, analysis of provenances based on collections from 1-5 parents compared with provenances from a larger sample of parents did not significantly change provenance differences in growth reported here.

The phenomenon of negative correlation between growth and provenance latitude reported here for totara is common among species that occupy a wide latitudinal range, with slower-growing but hardier ecotypes being better adapted to colder latitudes, e.g., *Pinus strobus* (Wright 1970) and *Juniperus virginiana* (Schoenike 1969; Henderson *et al.* 1979). Apart from significant differences in height and DBH growth for the low and high altitude seedlots for the Kauaeranga provenance, there continued to be no correlation of growth traits with altitude across all provenances in the planting trial. This contrasts with other species such as *Pseudotsuga menziesii* var. *glauca* (Rehfeldt 1979; Rehfeldt 1983; Herman and Lavender 1968), *Sequoiadendron giganteum* (Guinon *et al.* 1982), *Pinus contorta* (Rehfeldt and Wykoff 1981), *Larix occidentalis* (Renfeldt 1982) and ponderosa pine (*Pinus ponderosa*) (Callaham and Liddicoet 1961). The lack of correlation with altitude may reflect the seed dispersal characteristics of totara. The principal means of seed dispersal is by birds (Beveridge 1964; Burke 1974) and is likely to result in seed dispersal within the altitudinal range of totara, but less likely to cover the latitudinal range. On the other hand, as totara is wind pollinated, wide-scale dispersal would allow mixing of local gene pools.

Despite this, there is some evidence of better frost hardiness from higher altitude seed sources. Hawkins *et al.* (1991) found that frost hardiness of totara was positively correlated with altitude of seed origin for a limited selection of central to southern region North Island provenances, ranging from 30-540 m a.s.l. in altitude. They used seedlings from the same seed material in this provenance trial. Totara forms hybrids with the closely related Hall's totara (Webby *et al.* 1987) where the latter is often, but not always, growing at greater altitudes than totara. Both species occur together in some areas such as at Pureora Forest Park, close to the upper altitudinal limit of totara (Bergin and Kimberley 1992). Therefore, it may be possible that introgression of Hall's totara genes in totara at higher altitudes has occurred, giving greater frost hardiness.

Coefficients of variation between provenance means for height at the end of the nursery stage was 8.6% for totara (Table 3.7). This level of provenance variation is between that found in red beech (*Nothofagus fusca*) and that in silver beech (*N. menziesii*) but less than that found in the mountain-black beech (*N. solandri*) species complex (Wilcox and Ledgard 1983). Wilcox and Ledgard found red beech populations to be weakly distinct genetically, in keeping with its rather narrow ecological range; silver beech was genetically variable in seedling growth and morphology, reflecting its wide ecological range. Although totara has a wider latitudinal range, and within some regions, a wider altitudinal range than silver beech (Wardle 1984), it is not as genetically differentiated in terms of height and diameter growth as silver beech. Both totara and the beech species are wind pollinated which would contribute to mixing of gene pools within each species, but there are differences in their seed dispersal mechanisms that may contribute to the differences in their genetic diversity. Bird dispersal of totara seed is likely to encourage greater mixing of gene pools than the beeches which have wind-dispersed, but relatively heavy seed that does not normally travel more than 40 m from the seed source (Wardle 1984).

Table 3.7: Comparison of coefficients of variation (CV) for provenance means for heights and diameters between totara and beech species. Coefficients of variation for the beeches were determined by Wilcox and Ledgard (1983) at the end of the nursery stage 2½ years after sowing.

	Height of totara		Height of beech species					
			Silver beech		Red beech		Mountain-black beech complex	
	Mean (cm)	CV	Mean (cm)	CV	Mean (cm)	CV	Mean (cm)	CV
3-years-old (end of nursery stage)	81	8.6	77	15.0	102	5.0	86	27.8
6 years after planting (Tapapakanga trial)	290	9.4	-	-	-	-	-	-
11 years after planting (Tapapakanga trial)	550	7.4	-	-	-	-	-	-

In a separate study, leaf samples were taken from 180 totara established in the Tapapakanga trial site for DNA analysis (Tree Grower 1995). Ten totara populations ranging from Kaikohe in the north to Dean Forest in the south were sampled and Random Amplified Polymophic DNAs (RAPD markers) were used to determine the genetic variation using extracted genomic DNA (Williams *et al.* 1990). The study revealed significant genetic differences between the various populations in relation to the geographic separation of the seed sources. However, 90% of the total genetic marker diversity was attributable to the differences among individuals within populations. It was suggested that the distribution of genetic variation is typical of predominantly outcrossing organisms such as totara. It was further proposed that recent fragmentation of formerly widespread and more contiguous totara populations, and the subsequent reduction in gene flow, may lead to shifts in this pattern of genetic variation over time (T.E. Richardson pers. comm.).

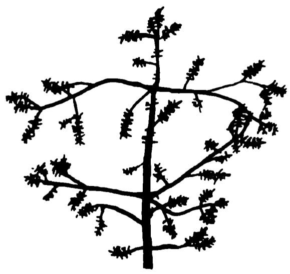
The DNA study supports the pattern of phenotypic variation described in the current study on provenances planted at the Tapapakanga site where there are significant growth and tree form differences amongst populations of totara. With the fragmentation of indigenous forest cover in New Zealand following the arrival of man (O'Loughlin 2000), there may indeed be scope for isolated populations of totara to develop greater genetic differences in the future. In addition, with introduced predators and decreased indigenous forest cover (King 1984), there has been a significant reduction in populations of some indigenous birds including kereru (Soper 1976), and in some regions such as Northland, bellbirds (e.g., Bull *et al.* 1978), that are known dispersers of podocarp seed (Beveridge 1964). Reduced bird dispersal of totara seed may also influence genetic variability by reducing the mixing of gene pools. Browsing of totara by possums has been widely observed (e.g., Mason 1958), and may also be influencing vigour and seed production on some sites.

There are a number of factors that potentially contribute to the large degree of variation in the growth rates of provenances that is not accounted for by geographic or climatic parameters. Contrary to arguments that forest fragmentation may increase genetic diversity, there is an abundance of newly regenerated stands of totara in many farming regions of New Zealand. Owing to its pioneering nature, totara readily colonises marginal pastoral hill country and is sometimes common along riparian areas in lowland sites (Bergin 2000). In addition, the Tapapakanga trial shows that totara can produce viable seed and regenerate at an early age. A further consideration is that of pollen dispersal which is equally important in gene flows (T. Shelbourne pers. comm.). Wind pollination of totara over potentially considerable distances is also likely to decrease local genetic differentiation. Although there has been greatly reduced indigenous bird populations in recent times, the influence of increased populations of introduced fruit-eating birds since human settlement such as starlings (*Sturmus vulgaris*), blackbirds (*Turdus merula*) and to a lesser extent thrushes (*T. philomelos*), may be a factor in ensuring continued effective dispersal of seed, particularly around the fringes of indigenous forest remnants. Some indigenous bird species that are common in parks, gardens and forest remnants such as tui are effective dispersers of totara seed (A.E. Beveridge pers. comm.).

Although results indicate a reasonably strong relationship of height growth to latitude of origin, with the inference that low latitudes tend to give more vigorous provenances, data is based on one coastal trial site that is well to the north within the natural range of the species. Latitudinal transfers have been the important geographic determinant of performance of some species in the Northern Hemisphere, such as Scots pine (*Pinus silvestris*) and Sitka spruce (*Picea sitchensis*) where transfers to lower latitudes can severely depress height growth. Any opposing effects of transfers to higher latitudes tends to incur risks of climatic damage (R.D. Burdon pers. comm.). Some caution is therefore required in recommendations implying faster growth for provenances of totara from low latitudes other than for around the latitude of the test site.

3.6 CONCLUSIONS

Accepting that the provenance trial is located at only one site, there is considerable scope for selection of improved strains of totara for both growth rates and stem form. Although northern populations generally grow faster and with better form than southern populations, results from both the field trial performance and the DNA marker study indicate that not all variation is due to geographic or climatic factors, and that there is considerable variation amongst populations from the same region. As the experiment did not have a family structure, it is impossible to determine how much of the variation within provenances are genetic, though some of this is likely to be so, based on experience with other conifers (T. Shelbourne pers. comm.). If totara is to be grown for timber, a strategy that is likely to produce better quality trees is the establishment of clonal seed orchards by grafting superior trees chosen from the best-performing provenances in this trial. Totara can be grown successfully from cuttings and from scion wood grafted onto rootstock (T. Faulds pers. comm.). Field trials with a family and provenance structure are required to estimate genetic parameters and the potential gains from selection and development of seed orchards.



CHAPTER 4

DETERMINING AGE USING GROWTH RINGS FROM PLANTED STANDS OF TOTARA

4.1 INTRODUCTION

Counting the number of growth rings on the lower part of the stem has proved to be a useful method for determining the approximate age of many temperate forest tree species (Fritts 1976). In softwoods, the wood formed late in the growing season results from the production of tracheids with thicker walls, and is termed latewood. When the trunk is cut transversely, these seasonal increments termed growth rings, appear as a series of more or less concentric circles about the pith (Jane 1970). Although growth rings are often used to determine the age of a tree, they are not always formed every year.

Jane (1970) describes the differences between seasonal rings formed annually and false rings. With annual growth rings, the boundary between latewood (laid down as tree growth slows and stops over winter) and early wood (of spring growth) is sharply differentiated, at least on the side closest to the bark. In contrast, false rings tend to be less sharply defined, with only a gradual change from darker bands to lighter early wood. Cessation of tree growth may occur during the normal growing season due to drought, out-of-season frost or defoliation by browsing animals such as insects or possums. Although this cessation of growth will be temporary, a growth ring, termed a false ring, will be formed.

In New Zealand, there have been numerous studies that involve determining age of trees using ring counting techniques. Dendrochronology, the study of sequences of annual growth rings in trees, has been reviewed by Norton and Ogden (1987) with an emphasis on New Zealand studies and applications. Norton and Ogden distinguish between strict dendrochronological techniques such as cross-dating and those involving ring counts to determine tree age. This chapter focuses on the latter, comparing the known age of planted totara stands with ring counts taken from cross-sectional increment cores.

Like all temperate gymnosperms, cross-sections of the trunk of totara exhibit growth rings (Meylan and Butterfield 1978). Examination of the growth rings of totara has led to a range of descriptions. Garratt (1924) described the growth rings as distinct to the unaided eye, tending to be close and uniform, and comprising very narrow bands of latewood with a gradual transition from early wood. Hinds and Reid (1957) state that the growth rings are poorly defined with latewood having slightly darker bands. Meylan and Butterfield (1978) indicate that the growth rings of totara are moderately distinct to distinct while Patel (1967) rates them as indistinct to distinct.

Previous studies using ring counting to age totara reflect the difficulties encountered in the reading of growth rings and indicate uncertainties as to whether they are annual in nature. In limited collections of cores taken from mature totara at approximately breast height, Dunwiddie (1979) found severe problems with ring wedging and lobate growth in both totara and Hall's totara. Lloyd (1963) noted apparently false rings in five species of podocarps including totara. In a preliminary investigation of several New Zealand timber tree species, Bell (1958) found the ring records difficult to read for totara, suggesting that there may be up to three rings in one year. Cameron (1959) acknowledged the possibilities of false rings having been counted as annual rings, and that more than one ring could have been produced in one year when he undertook measurement of growth ring widths of totara and other indigenous softwoods in North Auckland.

On the other hand, Wells (1972), in a study of Hall's totara in Central Otago, which has severe winters, reported annual rings. McSweeney (1982) used basal discs from windthrown or logged trees in South Westland for counting rings. He did not use increment cores from living trees because of the difficulties with compressed ring sequences as well as possible risks of damage. After drying and sanding the discs, he found very distinct growth rings with no evidence of discontinuous or false rings.

In addition to recognising and counting growth rings, other issues influencing age estimates include determining ring counts along missing sections of cores, extrapolating age estimates to non-cored stems of stands and estimating time taken to core sample height. Ogden (1985) has discussed some of these issues. The problem of increment cores that fail to reach the chronological centre or pith of the tree has been highlighted by Norton *et al.* (1987) with several studies evaluating various techniques to improve age estimates from cores for totara and other indigenous conifers (e.g., Matsui 2000; Duncan 1989).

Small stands and shelterbelts of totara have been planted in many regions throughout the country for over a century, and many were located in a Forest Research Institute survey undertaken in the mid-1980s (Pardy *et al.* 1992). In this study, increment cores were taken from many of these stands. Unlike many previous studies that have focussed on ring counts of mostly older trees from old-growth forest, this investigation provided an opportunity to determine the reliability of using rings for aging of relatively young totara stands. The aim was to use increment cores from plantations of known age less than 100-years-old to verify reliability of ring counts for estimating age. This would assist in the aging of young natural stands of totara regenerating on farmland of unknown age to determine growth rates and time taken for such stands to develop into a potential future timber resource that has been addressed in Chapter 6.

4.2 OBJECTIVES

The objectives are:

- to determine the reliability of using growth rings for recording annual growth of totara using trees of known age;

- to provide a description of a distinct growth ring that will improve age estimation of young totara stands using increment cores;
- to refine existing techniques for using growth rings where cores have missed the chronological centre of the tree and to allow for time taken for trees to reach coring height;
- to determine if selected site and stand factors influence reliability of ring counts as measures of age; and,
- to examine the applicability of these methods to determining the age of young naturally regenerating stands of totara of unknown age growing on farmland.

4.3 METHODS

4.3.1 Planted stands used for sampling

Increment cores were taken from 11 stands of totara, 10 located in the North Island and one in the South Island (Figure 4.1). All stands had been assessed as part of a survey of indigenous trees undertaken in 1985-86 (Pardy *et al.* 1992). The stands were revisited 10-12 years later for remeasurement of growth plots and for collection of increment cores for growth ring studies where permission from landowners or managers had been granted. Permanent Sample Plots (Ellis and Hayes 1997) were also established in each stand to determine stand density and growth. The stands ranged in age from 9-90 years at time of sampling. Stand details are given in Table 4.1, while brief descriptions of the site and climatic information are given in Appendix 4.1. Eight stands could be described as well-stocked with densities ranging from 1000 to 2500 stems ha^{-1}. Two stands were relatively open-growing and one planted as a shelterbelt.

4.3.2 Extracting cores

Cores were taken from stands at different times of the year, depending on when stands were being visited for assessment. Although the aim was to collect cores from a minimum of 10 trees, this was not achieved for all stands. There were only a limited number of suitable trees for coring on some sites, and the owners or managers of other sites would not allow more than a few cores to be taken. The number of cores used for reading growth rings, therefore, varied from 4-32 trees per stand (Table 4.2). Stems representing the range of diameters of canopy trees within each stand were selected for increment coring. Heights and diameters of sampled trees were recorded.

Table 4.1: Stand characteristics of each plantation for well-stocked stands and low-density stands.

Location	Stand type	Age (years)	Stocking (stems ha^{-1})	Mean DBH* (cm)	MAI DBH (mm)	Mean height (m)
Well-stocked stands						
Tapapkanga	Plantation	9	2500	8.0	8.9	4.4
Holt's Forest	Plantation	33	1975	15.4	4.7	9.3
TeKaraka	Plantation	50	1100	19.6	3.9	12.0
Pukekura (Area 1)	Plantation	62	1078	35.6	5.7	18.6
Purau	Plantation	86	1100	27.7	3.2	11.2
Prior	Plantation	88	1000	36.5	4.1	17.2
Puhipuhi (1925sph)	Plantation	90	1925	25.9	2.9	20.0
Puhipuhi (1275sph)	Plantation	91	1275	35.0	3.9	22.9
Shelterbelt or low-density stands						
Kamo	Shelterbelt	44	-	39.9	9.1	17.0
Pukekura (Area 6)	Low density	72	-	52.9	7.3	17.7
Pukekura (Area 7)	Low density	83	-	54.4	6.6	21.0

* Diameter at breast height (1.4 m).

Techniques used to sample cores were similar to those described by Norton (1998). Depending on the diameter of the bole, a 20, 30 or 35 cm long increment borer was used to extract a 5 mm diameter core from each tree. With the exception of one stand, all cores were taken at breast height (1.4 m above ground). At Tapapakanga, the youngest stand sampled, trees had small diameters with branches to below breast height and cores were, therefore, taken at 50 cm above ground where boles were relatively branch-free.

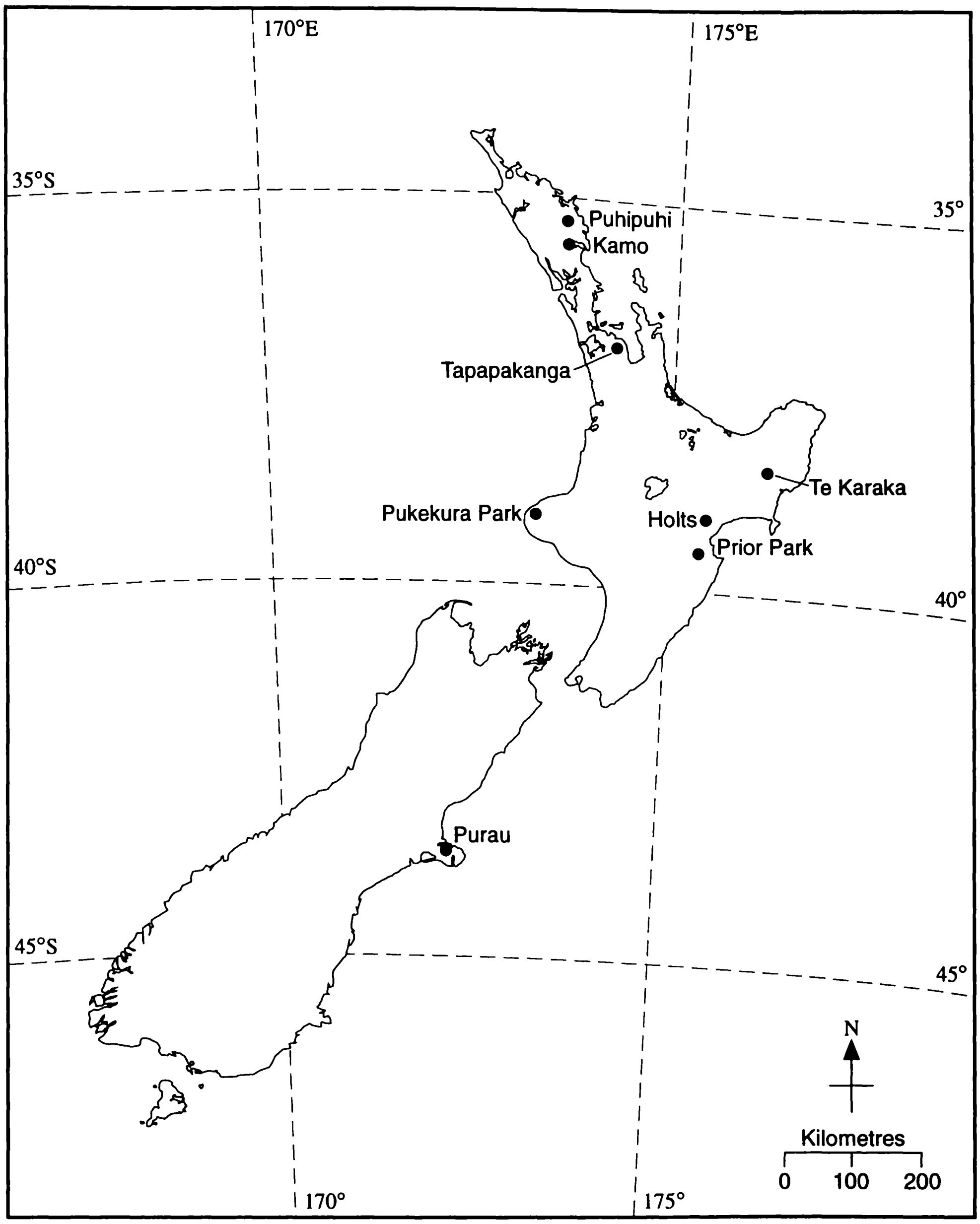


Figure 4.1: Location of the 11 planted stands of totara where increment cores were sampled. Two stands were located at Puhipuhi and three stands were located at Pukekura Park.

Cores were taken from the uphill side of trees when stands were on slopes. Irregularly shaped trunks such as those with asymmetric boles or forking at breast height were avoided. Cores were placed to avoid obvious irregularities in the bark such as branch scars.

Table 4.2: Increment cores sampled and growth ring visibility scores for each planted stand of totara based on those cores categorised as having distinct growth rings.

Location	Total number of cores sampled	Total number of cores read	Mean growth ring visibility score (1-5)*	Number of distinct† cores read	Percentage number of distinct† cores per stand
Well-stocked stands					
Tapapkanga	12	12	1.0	0	0
Holt's Forest	6	6	4.8	6	100
TeKaraka	18	16	4.1	12	67
Pukekura (Area 1)	10	10	3.4	5	50
Purau	14	11	3.2	4	29
Prior	6	5	3.0	2	33
Puhipuhi (1925sph)	32	24	3.5	12	38
Puhipuhi (1275sph)	31	22	2.7	6	19
Shelterbelt or low density stands					
Kamo	8	7	2.6	1	13
Pukekura (Area 6)	4	4	2.0	0	0
Pukekura (Area 7)	6	5	2.4	1	17

* Growth ring distinctness score: 1 = indistinct, 2 = slightly distinct, 3 = moderately distinct, 4 = distinct, 5 = very distinct.

† Growth ring clarity based on distinctness score: Indistinct = scores 1, 2 & 3; Distinct = scores 4 & 5.

The pith did not always occur in the geometric centre of the bole and it often proved difficult on larger stems over 15 cm diameter to locate the pith or chronological centre, as described by Norton *et al.* (1987). In a few cases, a second core was taken when the initial core missed the pith by a large margin. After cores were extracted, holes were filled with petroleum jelly to prevent entry of water and insects, although this practice was discontinued in later sampling as recommended by Norton (1998). Cores were temporarily stored in taped-up plastic drinking straws and identified by stand and tree number.

4.3.3 Preparing increment cores

Cores, including the bark, were extracted from the straws and glued into shallow-grooved wooden blocks using PVA resin glue. The grain of each core was orientated vertically to allow a transverse view of the growth rings. Cores became increasingly brittle as they dried out in storage and hence required the stable block-mounting for sanding and ring counting. The exposed upper section of the core was sanded, firstly with a motorised belt sander to obtain a 4-5 mm wide flat surface, and secondly by hand using progressively finer grades of sandpaper, ending with a 320 grit paper to gave a smooth surface for reading of growth rings. A light covering of wood polishing oil was rubbed into the core to enhance early and latewood bands.

Of the total 147 cores sampled from the 11 stands, 82% were used for the counting of growth rings (Table 4.2). Cores were discarded for a range of reasons. These included cores where the pith of the tree was estimated to be greater than 40 mm from the core, where the outermost part of the core with bark had been lost or where the cores had knots or other irregularities that made ring counting difficult.

4.3.4 Identifying and counting growth rings

The use of a low-powered stereo-microscope with a magnification power of 5x and 10x proved most effective in counting growth rings on most cores. The higher magnification was required where growth rings were less distinct or were very narrow. Incident light from one direction provided greatest contrast of rings. Ring counting by the observer was done without knowledge of the true age of the trees sampled. Considerable effort was involved in determining a consistent approach to recognising and counting of growth rings. Poorly briefed observers gave inconsistent results during initial ring counting sessions. Ultimately, all cores were read by the author using guidelines for identifying rings described below.

The descriptions of normal ring boundaries and false rings of Norton and Ogden (1987) were used to assist in identifying ring types. In the current study, a growth ring using the totara cores was defined as a sharply defined thin line of latewood (Figure 4.2). Although the colour of this line varied considerably both within cores and between cores, only clear lines that traversed the width of the core were counted as growth rings. Under magnification, the lines comprised 2-3 rows of tracheids that were compressed and had thickened walls compared with the early wood which tended to have circular tracheids and paler-coloured thin walls. One margin of the growth ring tended to be more defined than the other. The abrupt change in cell size and colour of growth rings was particularly evident on the edge of the band closest to the outer part of the stem where favourable conditions in spring and subsequent flush of growth is reflected in an immediate change to the lighter-coloured early wood.

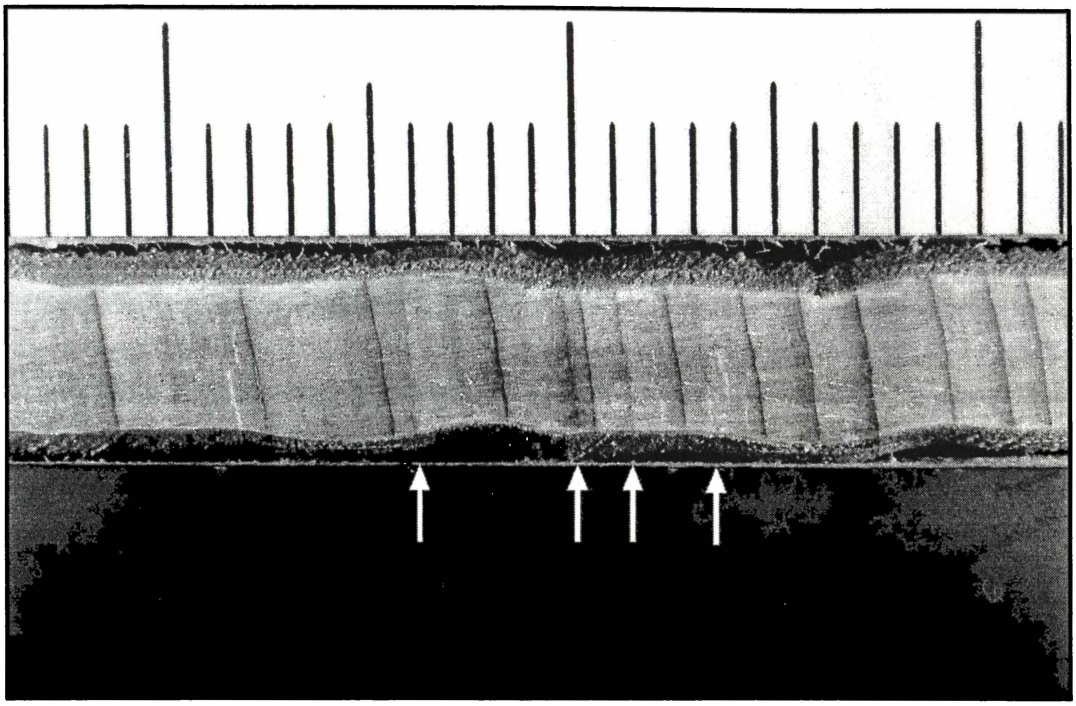


Figure 4.2: Growth rings as defined in this study on an increment core of a planted totara showing the thin clearly defined dark lines of latewood (scale: 1 mm between lines). Four less distinct lines marked with arrows are considered to be false rings. Outermost part of the section (bark) is on the right hand side.

All other features including poorly differentiated rings, areas of gradual colour change or amorphous areas of a single colour and texture were not counted as growth rings. False rings tended to have gradual changes in cell size and wall thickening and hence colour on both margins of the band in contrast to a normal growth ring where there is a pronounced change in cell size and width of cell wall towards the outermost end of the core. Examples of increment cores illustrating growth rings and false rings are shown in Figures 4.2 and 4.3, fusing of two rings into one (wedging) in Figure 4.4 and vague sections of indistinct rings in Figure 4.5.

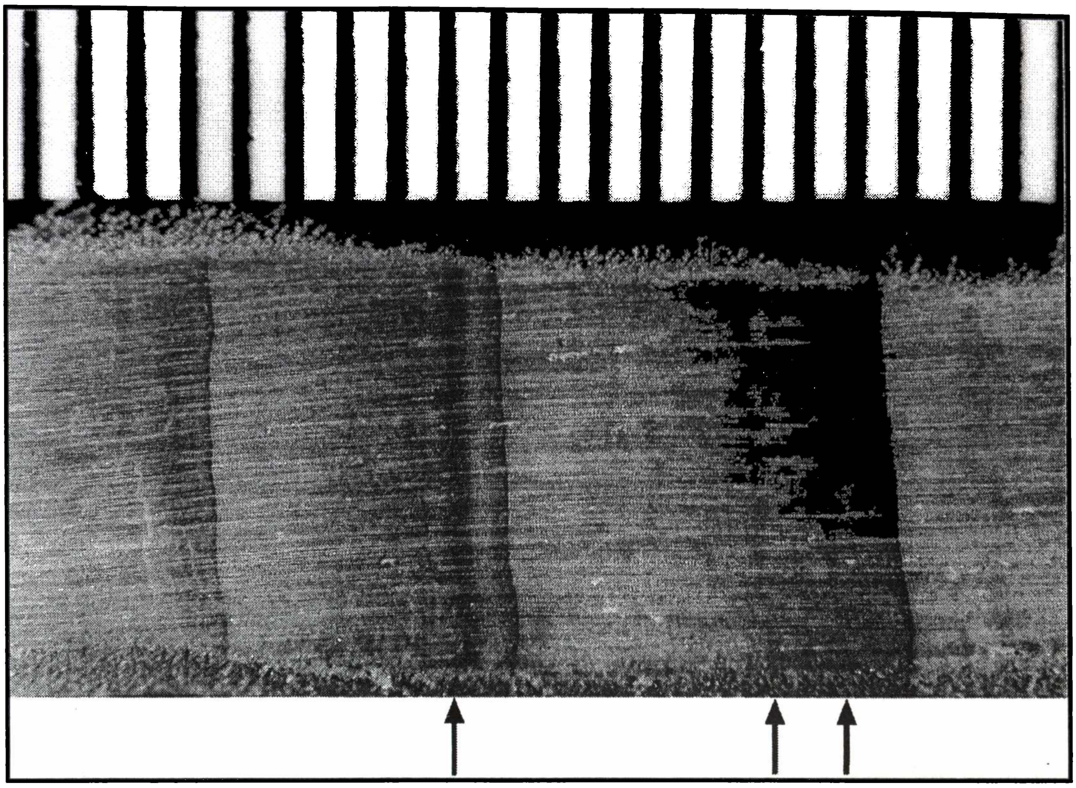


Figure 4.3: At least three false rings showing less distinct margins on either side on a section of an increment core from a planted totara stand that has undergone a period of fast-growth (scale: 1 mm between lines). Three distinct growth rings with an abrupt boundary closest to the bark of the tree (right hand side).

All cores were placed into one of five categories depending on visibility of late and early wood bands. These categories where based on taxonomic descriptions for classifying growth ring boundaries for gymnosperm woods described by Meylan and Butterfield (1978) as follows:

1 = indistinct,

2 = slightly distinct,

3 = moderately distinct,

4 = distinct, or

5 = very distinct.

Often rings were variable in clarity along the length of the core. In such cases, the dominant category was used to classify the whole core, although where indistinct sections were considered to compromise a realistic ring count, cores were classified toward the indistinct end of the continuum. Some subjective judgement in classifying cores was unavoidable.

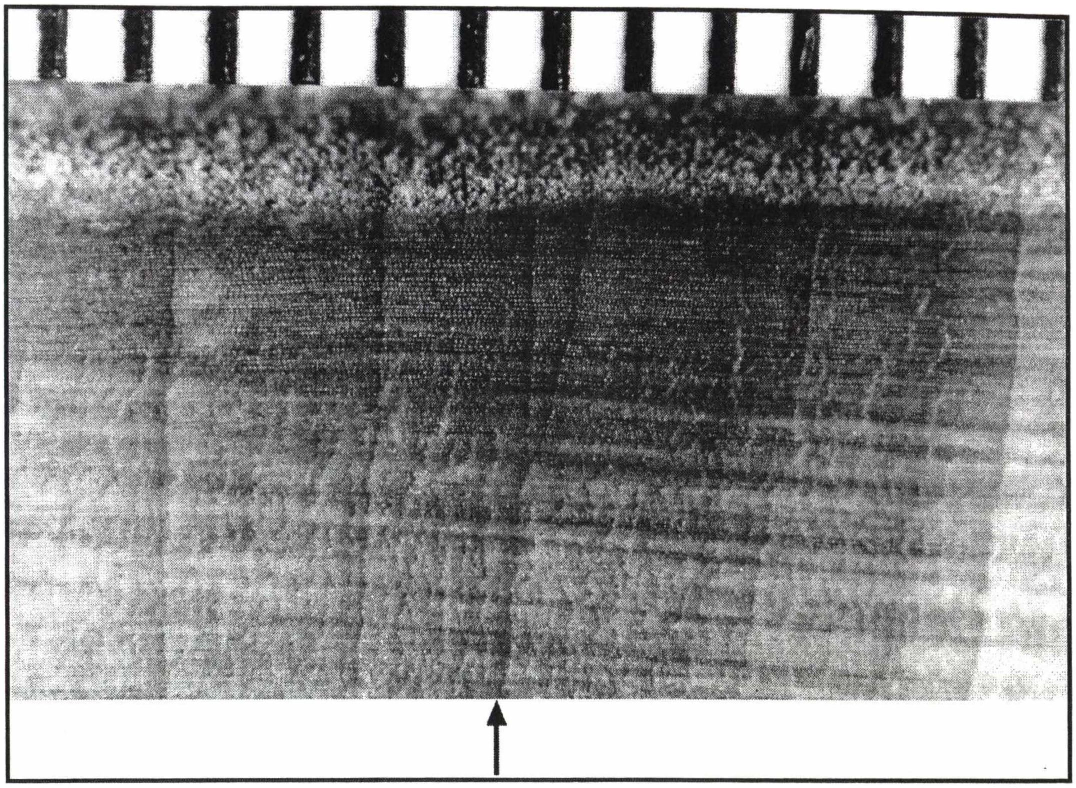


Figure 4.4: Wedging, or where two rings fuse into one (see arrow), are visible on an increment core taken from a relatively fast growing tree in a planted totara stand (scale: 1 mm between lines).

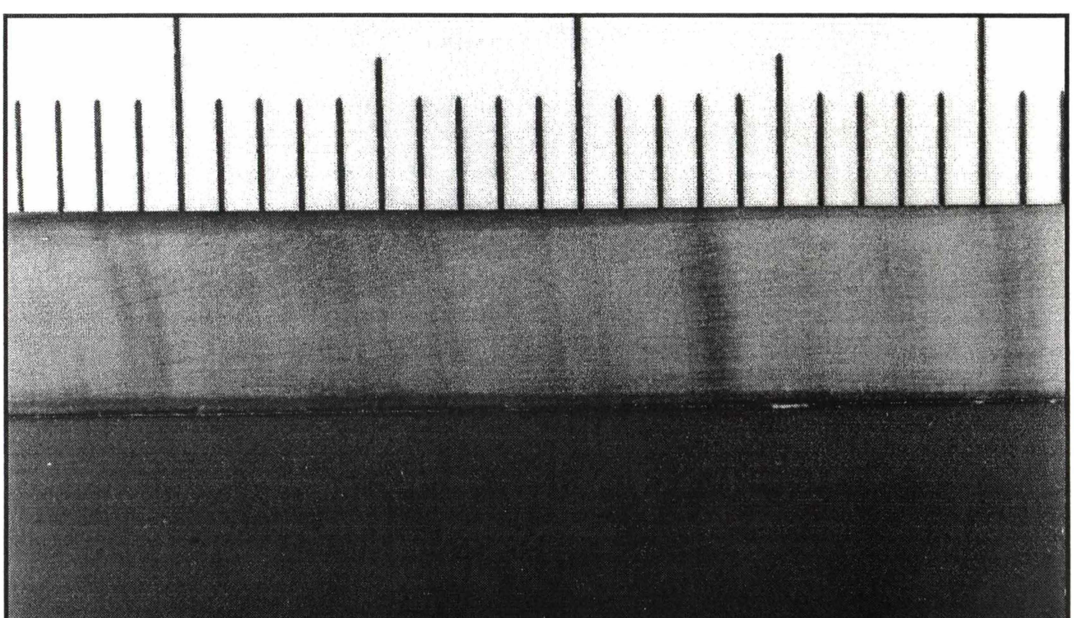


Figure 4.5: Sections of areas along an increment core of a planted totara where no clear growth rings could be detected (scale: 1 mm between lines).

4.3.5 Adjustment for cores missing the pith

Techniques for making adjustments to the growth record when cores missed the chronological centre of the tree first involved estimating the location of the pith. Using a method modified from Lui (1986), a line was drawn tangential to the last ring arc on the innermost part of core. The pith or chronological centre of the tree was assumed to be located along a line drawn perpendicular to the tangential line. A method described by Applequist (1958), involving the overlaying of a clear cellulose acetate with a pattern of concentric circles that best matched the arcs of growth rings on the innermost part of the core, was then used to locate the tree centre. This is similar to a method described by Norton *et al.* (1987) who used a compass to trace the arcs of inner rings to indicate the location of the chronological centre. The length of the missing core was then measured from the edge of the core nearest the pith to the estimated chronological centre (*a* in Figure 4.6). As Norton *et al.* (1987) cautioned, this method may only be relatively accurate when the core passes very close to the chronological centre. Therefore, cores taken from larger trees within older stands, which had missed the pith by greater than about 40 mm, were discarded. Cores taken from smaller trees generally passed within 30 mm of the pith.

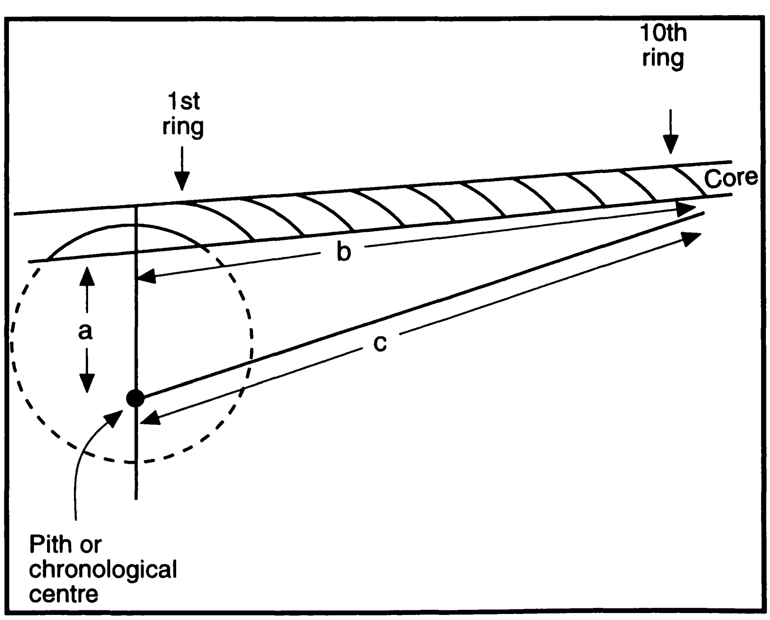


Figure 4.6: A geometric method was used to estimate the number of growth rings along the missing length of each core.

A simple geometric method was used to estimate the number of growth rings along the missing length of each core. The method requires the length of the missing core a, and the width of the innermost 10 rings b (Figure 4.6). If the number of rings in the missing length a is n, then the number of rings in the radius c must be n+10. Assuming a constant growth rate over the period covered by the radius c, the ratio of the lengths a to c must equal the ratio of the numbers of rings n to n+10. From this, the value of n can be readily obtained:

$$\frac{a}{c} = \frac{n}{n+10}$$

$$n = \frac{10a}{c-a}$$

$$n = \frac{10a}{\sqrt{a^2+b^2}-a}$$

This was added to the total ring count from the core.

This method is similar to the geometric model of Liu (1986) for estimating the pith position and number of missing rings. However, Liu's method requires very accurate measurements of growth ring angles on the core to establish the pith position. Transparent overlays were found to give far greater precision than Lui's method.

The method refined in this study is also similar to that of Duncan (1989) where a geometric model was used based on theoretical increment cores drawn on sanded discs of kahikatea trees estimated to be 400-500 years old. The method also involved accurate measurements for estimating the distance to the missed chronological centre based on the largest growth ring arc visible in the 5 mm core section.

4.3.6 Age to breast height

An allowance for the time taken for trees to reach the height at which the increment core was taken (1.4 m for all stands except Tapapakanga) was incorporated into age calculations. Seedling height at planting of about 50 cm was assumed. A growth rate of 10 cm in the first year after planting and 20 cm per annum for subsequent years was also assumed. In podocarp tree species on upland sites on the central North Island, growth rate in the first year after planting is slow, but then increases to about 20 cm per year (Beveridge *et al.* 1985). Although recommendations since c.1980 advocate the planting of taller seedlings 60-80 cm high (e.g., Forest Research Institute 1980a), planting heights for many early plantings tended to be less so a planting height of 50 cm is a reasonable assumption. Many of the plantations used in this study are on lowland sites where faster height growth rates of 40-50 cm are expected. However, most planting of indigenous tree species have often been poorly managed soon after planting (Pardy *et al.* 1992). Poor growth rates in early years due to competing weed growth where seedlings have not been adequately released for 3-5 years after planting and impacts of browsing by animals on young seedlings are often a feature of planted podocarps. Given the above assumptions, trees would reach 1.4 m five years after planting and, therefore, was added to the increment core ring count to provide an estimate of age since planting.

An alternative method for estimating growth to coring height that used ring counts from cores with distinct rings and which had passed through the pith was tested. This method assumes one ring equates to one year of growth. However, samples from six stands that had a small number of cores that passed through or within 1 mm of the pith, produced underestimates of stand age ranging from an average of 6 years for three stands and 9, 13 and 22 years for the other three stands. Although some stand underestimates were close to the five years used in this study for time taken to coring height, this method was somewhat variable and was not used here to improve age estimates.

4.4 RESULTS

4.4.1 Visibility of growth rings

The mean growth ring visibility score indicated there is considerable variation in the clarity of growth rings between stands (Table 4.2). However, most stands had at least some cores with easily identifiable growth rings along the length of the core as defined for this study. The best stands were Holt's Forest near Napier and Te Karaka near Gisborne with mean visibility scores exceeding four. The stands where growth ring clarity was poor with a mean score of less than three were Tapapakanga, Kamo, Pukekura (Area 6) and Pukekura (Area 7), and the lower density stand at Puhipuhi. All three low-density stands had poor ring clarity. These relatively open-grown plantings had formed large-crowned bushy trees compared with slower growing and relatively small-crowned trees in most of the other stands established as plantations. The three low-density stands had mean annual diameter increments exceeding 6 mm per year as did the Tapapakanga stand (Table 4.1). Some cores taken from fast-growing large diameter trees showed wedging of rings and lobate growth, similar to that reported for totara by Dunwiddie (1979).

For simplicity, cores in classes 4 and 5 were classified as 'distinct' and those in classes 1, 2 and 3 were classified as 'indistinct'. The percentage of distinct cores varied widely from 0-100% across all well-stocked stands. The small sample of shelterbelt and lower density stands had 0-17% of cores classed as distinct. Ring visibility was often less distinct in the outermost sections of the core compared with darker sections closer to the tree centre. Consequently many cores were categorised as indistinct due to identification difficulties over only a small outer section.

The cores taken at 50 cm height from the youngest stand at Tapapakanga (aged nine years) were particularly difficult to read (Table 4.2). All 12 cores sampled from widely dispersed trees over the 1 ha planting site displayed a consistent pattern of growth rings. The first 5-6 rings from the pith were clear, but there were no clear growth rings discernable over the outermost section of the cores (Figure 4.7). The cores from this stand were therefore not included in further analyses.

In contrast to faster growing stands, the slower growing ones such as Purau on Banks Peninsula and the more densely stocked Puhipuhi stand, had generally well defined rings (Table 4.2). However, some sections of these cores had growth rings that were very close together requiring higher magnification to count the rings.

The mean percentage age underestimate or overestimate is shown for each visibility score for both well-stocked and low-density stands in Table 4.3. For well-stocked stands, there was a tendency for underestimating age, but the mean error decreased with increasing ring visibility as did the standard deviation indicating reduced variability in age estimates. In contrast, for the low-density stands, stand age was increasingly overestimated with improved ring visibility, presumably due to the inclusion of false rings in the counts. Conversely, the lower error in poor visibility cores are presumably a consequence of difficulties in identifying rings where non-counted, less distinct rings cancel out the occurrence of false rings. The standard deviation was much larger in these more open-grown, faster-growing stands compared with the well-stocked stands reflecting lower sample sizes and probable greater variation in ring counts.

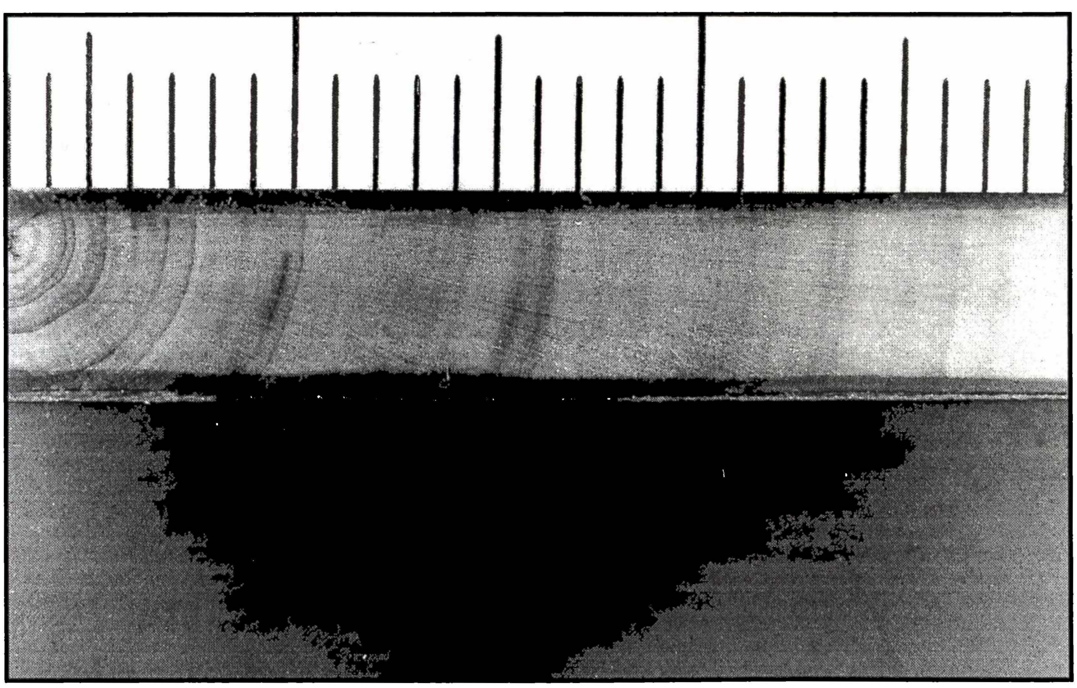


Figure 4.7: A core taken at 50 cm above ground from a totara at Tapapakanga, near Auckland, planted 9 years ago. The first five rings from the pith are well-defined representing the time seedlings were in the nursery at Rotorua including the first 1-2 years of growth after planting when growth was checked by transplanting shock and vigorous early weed growth. No clear growth rings are identifiable over the outermost section of core representing a period of fast growth on this fertile, lowland site (scale: 1 mm between lines).

4.4.2 Adjustments for missing centre

Of the 110 cores read from the 10 stands, 16% had passed through the chronological centre or pith of the tree. A further 44% of the cores had passed within a distance (core to pith length *a*) that was less than 5% of the estimated bark-to-pith radius (core length *b*) (Figure 4.6). Only 12% of the cores sampled less than 90% of the estimated growth record.

Table 4.3: Mean percentage error in estimating stand age for each growth ring distinctness score across all cores used for ring counting from seven plantations (excluding Tapapakanga stand) and three low-density stands.

	Growth ring visibility score (1-5)*	Number of cores	Percentage underestimated (-) or overestimated (+) age	
			Mean	Standard deviation
Well-stocked stands	1	5	-13.7	14.1
	2	25	-14.5	12.0
	3	17	-10.8	9.0
	4	20	-10.1	8.5
	5	27	-10.3	9.5
Shelterbelt or low-density stands	1	3	-1.3	32.1
	2	6	+10.9	17.1
	3	5	+18.6	22.7
	4	2	+20.2	13.2

* Growth ring distinctness score: 1 = indistinct, 2 = slightly distinct, 3 = moderately distinct, 4 = distinct, 5 = very distinct.

Compared with other aging studies in natural stands (e.g., Duncan 1989), the average diameter of stands sampled in this study were relatively small, varying from 8-36.5 cm for plantations and from 40-55 cm for the shelterbelt and low-density stands. Consequently, it was easier to hit tree centres when coring or to get within 10-20 mm of the chronological centre. Overall, adjustments made to ring counts in this study were relatively small.

4.4.3 Growth rings and stand age

Because of the difficulty in using cores with indistinct rings, only those cores classified as having 'distinct' rings with a visibility score of four or greater were used for estimating stand age. The estimated mean stand ages of the nine stands containing at least one tree with a distinct core, are given in Table 4.4. The growth ring counts were adjusted to account for the time taken for the tree to reach breast height and for the number of missing rings where cores had missed the tree centre. When compared with the known stand age, ages based on cores were underestimated by up to 19% for the well-stocked stands, although five of the seven stands were within 8% of the correct age (Table 4.4). This suggests that in well-stocked stands, clear growth rings may not be formed in all years. In contrast, in the open growing stands at Kamo and Pukekura (Area 7) age was overestimated, indicating that false rings were included in the ring count in these stands, although this is only based on one core in each stand that was classed as distinct.

Table 4.4: Average adjusted growth ring counts for each planted stand of totara based on increment cores categorised as having distinct† growth rings.

Location	Stand age (years)	Adjusted growth ring count#		Mean underestimate percentage error	Standard deviation of percentage underestimate
		Mean	Standard error		
Well-stocked stands					
Holt's Forest	33	30.7	1.0	7.1	7.6
TeKaraka	50	40.7	1.3	18.7	9.0
Pukekura (Area 1)	62	58.8	1.3	5.2	4.8
Purau	86	74.3	4.6	13.7	10.6
Prior	88	86.5	0.5	1.7	0.8
Puhipuhi (1925sph)	90	83.1	2.0	7.7	7.7
Puhipuhi (1275sph)	91	84.5	1.2	6.1	3.4
Shelterbelt or low density stands					
Kamo	44	57.0	-	-29.5	-
Pukekura (Area 7)	83	92.0	-	-10.8	-

† Growth ring clarity based on distinctness score: Indistinct = scores 1, 2 & 3; Distinct = scores 4 & 5.
# Adjusted growth ring count has been corrected for height that cores was taken and for estimated number of rings along the missing length of cores that did not go through pith.

A comparison of estimated age based on ring counts versus stand age is shown in Figure 4.8 for both distinct and indistinct core classes. It is clear that ring counts, even when adjusted for growth to core sampling height and missed rings in the centre of the core, tend to underestimate stand age. In most cases, however, by using only cores with distinct growth rings, the estimate of stand age has been improved.

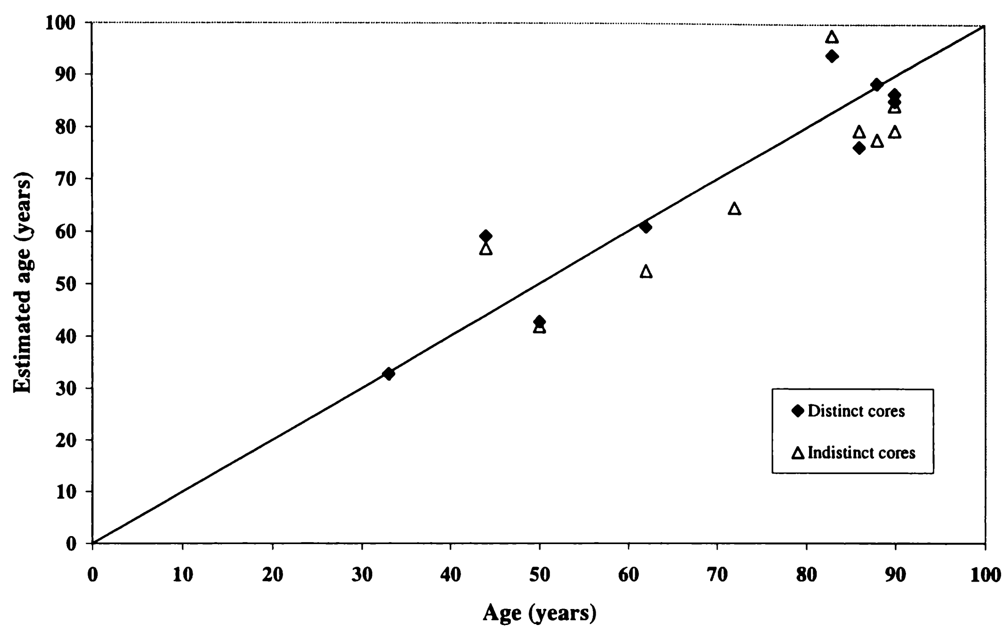


Figure 4.8: Comparison of estimated age with true age for ten planted stands of totara based on increment cores and for one stand based on cross-sectional discs.

4.5 DISCUSSION

The methods used in this study to identify growth rings were selected to give clear guidelines for the identification of growth rings on increment cores of relatively young, planted totara stands. The methods used to differentiate between latewood and early wood follows the description by Jane (1970) of seasonal rings formed annually and false rings. In this study, a growth ring has been defined as a band of gradually changing colour from light to dark as tree growth slows down in autumn and early winter, followed by an abrupt boundary with the sudden onset of spring growth. All other variations in banding including gradual changes in colour or texture were not considered to be true growth rings. While these criteria are rigid, the method proved to be relatively consistent when counting rings, even when cores were re-read several times.

The results of this study, based on young planted stands of known-age, have shown that ring counts can be used as reasonably reliable indicators of stand age. However, there are clearly some limitations. It is apparent that in slower growing trees there is a tendency to underestimate stand age (Figure 4.9). Analysis of individual trees in the seven well-stocked stands indicates that for average mean annual diameter increments of 2-4 mm, age determination based on ring counts can be underestimated by around 5-15%. This suggests that smaller suppressed trees do not always form clear growth rings every year. Norton and Ogden (1987), in a review of anomalous growth rings, indicate that tree growth which is severely reduced by environmental or biological conditions will result in partial or missing rings. They cite other studies suggesting this is either due to radial growth being confined to only the upper parts of the bole above the level of coring, or because of ring wedging, possibly as a result of development or death of major branches. In the current study, estimates of stand age improved where trees of moderate growth of around 5 mm mean annual diameter increment were used (Figure 4.9).

There are major difficulties in obtaining cores with a continuous series of distinct rings from trees growing in shelterbelts or in relatively open conditions. The small number of cores with distinct rings from these generally faster growing trees indicate that growth ring counts tend to over-estimate age. In these cases, trees are forming more than one growth ring in some years and it is difficult not to include these extra false rings in ring counts. Cores taken from both a slow growing and a fast growing tree in the same stand at Puhipuhi illustrate the contrast in growth ring clarity (Figure 4.10). Distinct rings are evident in the slow growing tree and indistinct rings in the faster growing tree.

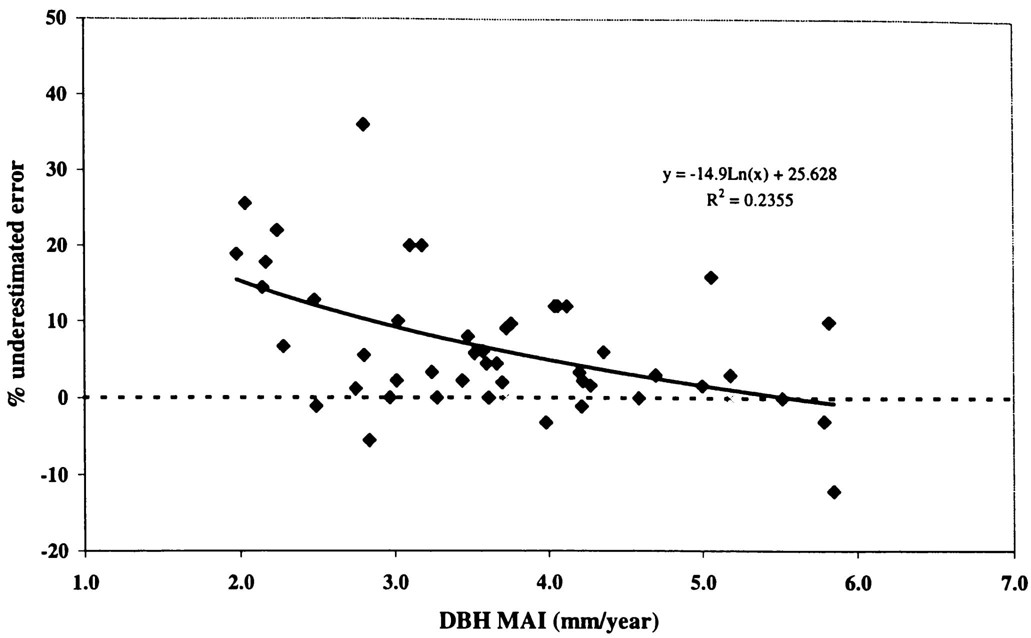


Figure 4.9: The percentage of error in underestimating age based on increment cores categorised as having very distinct or distinct growth rings taken from trees in seven planted stands of totara of known age versus the mean annual diameter increment of the stand.

Others have found similar problems with using growth rings of totara. Bell (1958) found ring records difficult to read for totara due to the presence of false rings with up to three rings formed in one year. Bell also found totara was prone to lack of uniformity and circularity where perfectly normal rings on one side of a cross-section would disappear completely on the other side. He used entire cross-sections for ring studies as cores from different radii are likely to give different ring counts. Matsui (2000) found wedging and missing rings caused difficulty in aging of totara in remnants of coastal dune forest dominated by totara and Hall's totara at Sandy Point, near Invercargill, in southern South Island. Others have highlighted difficulties in determining age of other indigenous conifers where wedging associated with lobate growth. Stewart and White (1995) found extreme wedging and lobate growth making age and growth rate difficult to estimate for rimu. Because of the problems with wedging often associated with irregular or lobate diameter growth, Norton and Ogden (1987) indicate that errors in age estimates are likely to be accentuated if based on increment cores. They suggested that missing rings on single radii could be as high as 10% of the total number of rings present.

In warmer lowland regions, multiple flushes of totara in one growing season are common. An in-depth study is required to determine what effect multiple growth flushes within one growing season, as well as what effect mild winters where there is no clear cessation of plant growth, may have on growth ring formation. Although Jane (1970) and Norton and Ogden (1987) discuss the effects of seasonal climate on ring formation, including the occurrence of droughts or sudden low temperatures during the growth period, the effect of mild winters that may result in diffuse bands on cores may be another factor making accurate ring counts difficult. Cores from the faster relatively open-grown trees of totara on warm, lowland sites in New Plymouth and in Northland proved difficult to age as indistinct rings often dominated sections of cores. However, stands at higher densities at both these sites tended to have a greater number of cores with distinct rings. A complex of stand characteristics as well as climatic factors is, therefore, likely to be influencing the formation of clear growth rings.

In cores taken from the youngest stand at Tapapakanga, the contrast between the distinct rings on the innermost section and the indistinct rings of the outermost section of the core may be related to pre- and post-planting phases of the seedlings (Figure 4.7). As seedlings at the Tapapakanga site were planted at an average height of 85 cm, the innermost clear rings are representing the growth period during the later part of the nursery phase and during the first 1-2 years at the site when transplanting shock would have checked growth and when seedlings were temporarily checked by vigorous growth of kikuyu. The seedlings were bare-root when planted, and although they were well conditioned in the nursery prior to planting, growth is usually restricted in the first year compared with subsequent years (Beveridge *et al.* 1985). The indistinct outermost part of each core, characterised by diffuse areas of light and dark bands, represents the last 4-5 years of rapid growth.

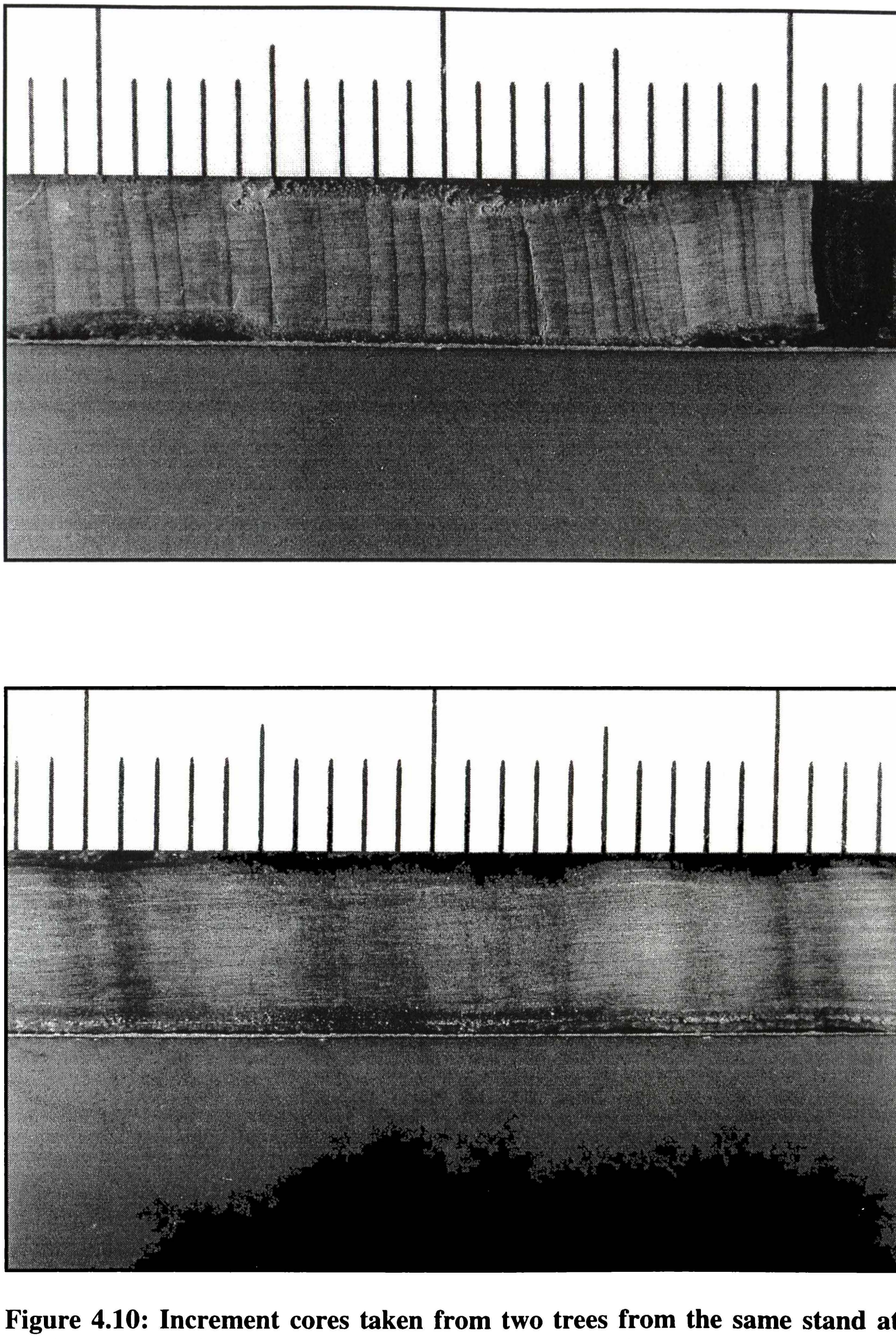


Figure 4.10: Increment cores taken from two trees from the same stand at Puhipuhi, Northland. Clear growth rings are formed by slower growing trees although counts indicate that rings may not be formed every year (top). Indistinct rings are a feature of faster growing trees, but indications are that more than one ring may be formed in some years as false rings are easily included in ring counts (bottom) (scale: 1 mm between lines).

The increasing difficulty in identifying rings along the outermost parts of the totara cores observed in this study across a range of stands has also been reported by Stewart and White (1985) in rimu. They found that rings along the outermost sapwood sections of cross-sectional discs were consistently the most difficult to measure. Visibility of rings in indigenous conifers appears to improve with age, with faint rings in outer sapwood sections becoming more visible as wood darkens during transition to heartwood. The reliability of using growth rings for aging stands is likely to be affected by difficulties in identifying clear rings in sapwood. This is particularly significant in young stands where stems are largely sapwood as has been found in the Tapapakanga stand.

Norton *et al.* (1987) list several problems when using growth rings. These include the tendency towards narrow rings with frequent wedging, increment cores failing to reach the chronological centre of the tree, sampling cores above ground level requiring an adjustment for the time taken by the young tree to reach sampling height, and extrapolating from a small subsample of trees to other trees in the stand. In the current study most of these problems were addressed. Rings in the moderately fast growing plantations tended to be wide, especially near the centre of the tree when they would have been growing in the open before canopy closure. Increment cores in most stands went through or close to the chronological centre, and adjustments for time taken to reach core sampling height and missed chronological centre also would have improved stand age estimates.

Natural stands of totara of unknown age regenerated amongst grass on hill slopes and along riparian areas since clearance of the original forest from the 1800s are a feature on farmland in many regions throughout New Zealand. Determining the reliability of rings for aging young totara stands is, therefore, necessary in any investigation into the regeneration and development of these natural stands. Implications from this study indicate that growth ring counts from increment cores especially from the slower-growing trees are likely to underestimate age by 5-15% (Figure 4.9). With natural stands that occupy sites at high densities, slow-growing suppressed trees so should be avoided. Obvious larger diameter trees which are possible outliers representing a much earlier cohort of scattered totara trees should also be avoided. Targeting trees within natural stands that represent the average stem size are likely to give reasonable estimates of stand age where it is considered that a relatively even-aged stand has developed. However, caution is required in relying on diameter as an indication of tree age (Ogden 1985; Ebbett 1998), especially where natural stands may have established over an extended period.

4.6 CONCLUSIONS

Growth rings in increment cores that consist of a clear line of latewood adjacent to lighter coloured early wood provide a reasonably consistent, repeatable method for estimating the age of totara in planted stands. Best mean estimates for most plantations between 1000-2000 stems ha^{-1} were within 10% of actual age where cores with distinct rings were used. Up to 20% of cores will need to be discarded initially due to irregularities, knots, rot, lost bark or core sections. Consistent with previous studies, cores that go through or very near the chronological centre will greatly improve accuracy of aging of stands using ring counts. The use of a simple geometric formula to estimate the number of rings along the missed core section, based on the length of the innermost 10 rings, has proved effective in adjusting stand age estimates where cores missed the chronological centre of the tree. Knowledge of the history of stand management and early growth will help determine pre-core height growth rate so that appropriate adjustments to growth ring counts can also be made. As found in trees from old growth stands, false rings and wedging are a feature of totara in relatively young planted stands. Selecting trees with regular, circular boles is likely to decrease the inaccuracies due to wedging.

This study indicates that the best estimates of stand age can be obtained by using increment cores from trees of moderate growth with around 4-5 mm mean annual diameter increment. Slow growing trees tend to produce less than one ring per year and so underestimate stand age while fast-growing trees, particularly from open or low density stands, tend to have indistinct sections of rings including the occurrence of false rings, leading to overestimates of age. In estimating stand age of planted stands using ring counts from increment cores, the largest and smallest or suppressed trees should be avoided.

The study showed that on average, only about one-third of the increment cores sampled were useful for giving good estimates of stand age. Clear criteria are required for observers to ensure that there is a consistent approach to the identification and counting of growth rings, classifying distinct and indistinct cores, adjusting stand age for the height of core sampling and correcting for cores missing the chronological centre. Increment cores that had distinct rings over the entire length of the core clearly gave better results and high rejection rates of cores with indistinct rings may be necessary to ensure improved estimates of stand age.

In dense natural stands where growth is slow, avoiding the suppressed trees, where narrow rings will be difficult to read and complete rings may not form every year, are likely to improve age estimates. However, a spread of ages that may be present in natural stands due to recruitment over several years until canopy closure is achieved is a further consideration in estimating age of natural stands. Cores should be taken from a reasonable sample of trees to allow for a spread of ages. As with planted stands, aging of trees is likely to be more precise where only cores that have distinct rings are used.

CHAPTER 5

ESTABLISHMENT OF TOTARA BY NATURAL REGENERATION ON HILL COUNTRY PASTURE

5.1 INTRODUCTION

Naturally regenerated stands of totara are found in many pastoral areas throughout New Zealand (Wardle 1974). Totara occurs as scattered trees or in groves, along fencelines and roadsides (Esler 1978), or in more extensive regenerating stands on hill country, and along riparian areas and on river flats, sometimes mixed with kahikatea (e.g., Duguid 1990). Regeneration occurs within grass to form pure stands of totara or can be in varying mixtures with other species including gorse (*Ulex europaeus*), manuka and kanuka.

Observations of the regeneration patterns of totara on farmland in one region, Northland, indicate that it readily regenerates on steep hill slopes in pasture where some grazing pressure exists. It is relatively unpalatable to farming stock and, therefore, becomes a problem for landowners keen to retain land in pasture. Establishment strategies for totara appear to vary, depending on site and existing vegetation cover. On steep hill slopes where there is a nearby seed source, totara can develop into small stands of saplings within 20 years where they are not heavily grazed or cleared regularly by landowners. However, the mechanisms and patterns of establishment of totara on farmland have not been previously studied. This chapter focuses on the early establishment phase of totara on a typical, grazed Northland hill country site.

5.2 OBJECTIVES

The major aim is to describe and quantify the pattern of regeneration of totara and other woody species on a pastoral hill country site. Specific objectives are:

- to determine whether recruitment of totara seedlings is influenced by degree of slope;
- to determine any correlation between pasture composition and density with presence and abundance of totara regeneration;
- to describe the effect of grazing animals on regeneration of woody species; and,
- to compare the regeneration strategies of totara with the other major woody species manuka, kanuka, gorse and kahikatea found on the site.

5.3 SITE DESCRIPTION

The selected study site is located on the property of Mr Doug Lane, south of Kaeo on the northeastern side of Northland (Figure 5.1). It comprises part of a large paddock dominated by exotic pasture species, predominantly a south-east facing side of a small, flat topped ridge ranging from flat areas to slopes over 50°. The altitude of the site is 25 m a.s.l. Cattle graze the paddock on a regular basis as part of a beef-raising regime. Management consists of annual topdressing of the site with superphosphate and lime applied by truck, covering all but the steepest hill country as part of standard farm practice. Regular maintenance includes spot spraying of gorse and kikuyu with selective herbicides using a knapsack. The study site is typical of hill country on this and neighbouring farms where, without regular hand clearing, totara readily regenerates on slopes where there is a local seed source. Although the landowner normally clears such sites of regenerating totara, this particular site has not be cleared for the last 10 years since it was established entirely in pasture.

The soils of the rolling and hill land are Otangaroa clay and sandy clay loams (Sutherland *et al.* 1980) taxonomically described as 'wet soils' of podzolised yellow-brown earths (Hewitt 1998). The soils of the flood plains at the base of the ridge are Whakapara silt loam and clay loam which are well to moderately well-drained 'recent soils' (Sutherland *et al.* 1980) now classed as Mottled Fluvial Recent soils which have been derived from river alluvium (Hewitt 1998). The nearest weather station to Kaeo located at Kerikeri has an average annual rainfall of 1682 mm, a daily mean temperature of 15.2°C, 25 ground frosts per year and an average of 2000 sunshine hours per year (New Zealand Meteorological Service 1983).

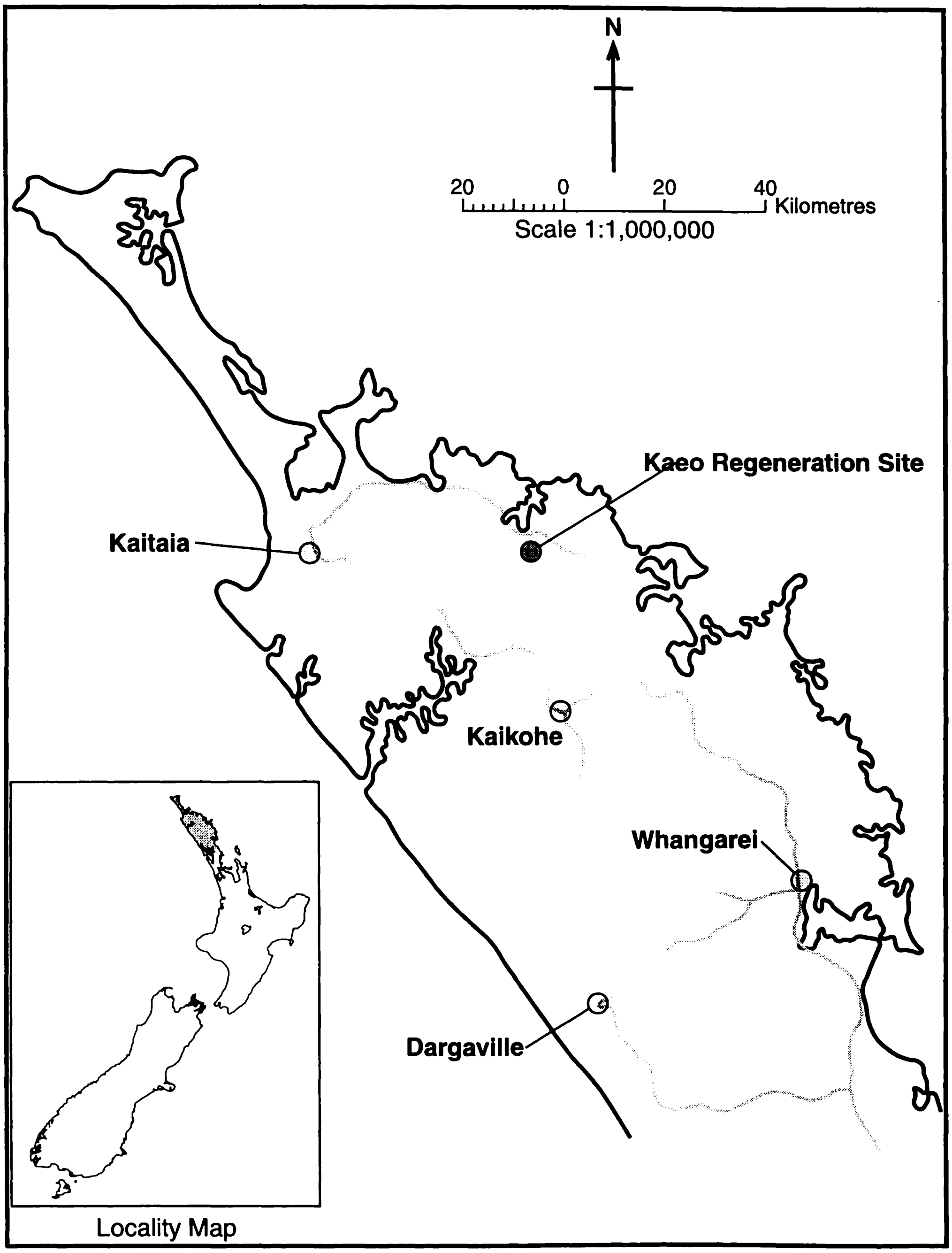


Figure 5.1: Location of totara regeneration site near Kaeo, Northland.

The surrounding area comprises ridges and hill slopes dominated by exotic pasture grasses and mostly fenced-off riparian areas along valley bottoms, comprising a mixture of naturally regenerating indigenous forest species and small stands of planted exotic trees. Totara and kahikatea are dominant in the indigenous forest areas as well as occurring as scattered trees in paddocks around the farm (Figure 5.2). Patches of mostly regenerating totara are found on steep slopes in paddocks along with scattered occasional trees of both totara and kahikatea that occur within the trial site, some of which were observed to be seeding in autumn (Figure 5.3).

Figure 5.2: Natural regeneration of totara occurs on steep hill slopes of farmland in many regions where there is a local seed source such as scattered trees in paddocks or along forested riparian zones. This site in Kaeo, Northland was in pasture about 10 years ago. Saplings and seedlings of totara are now invading the site in the presence of grazing cattle.

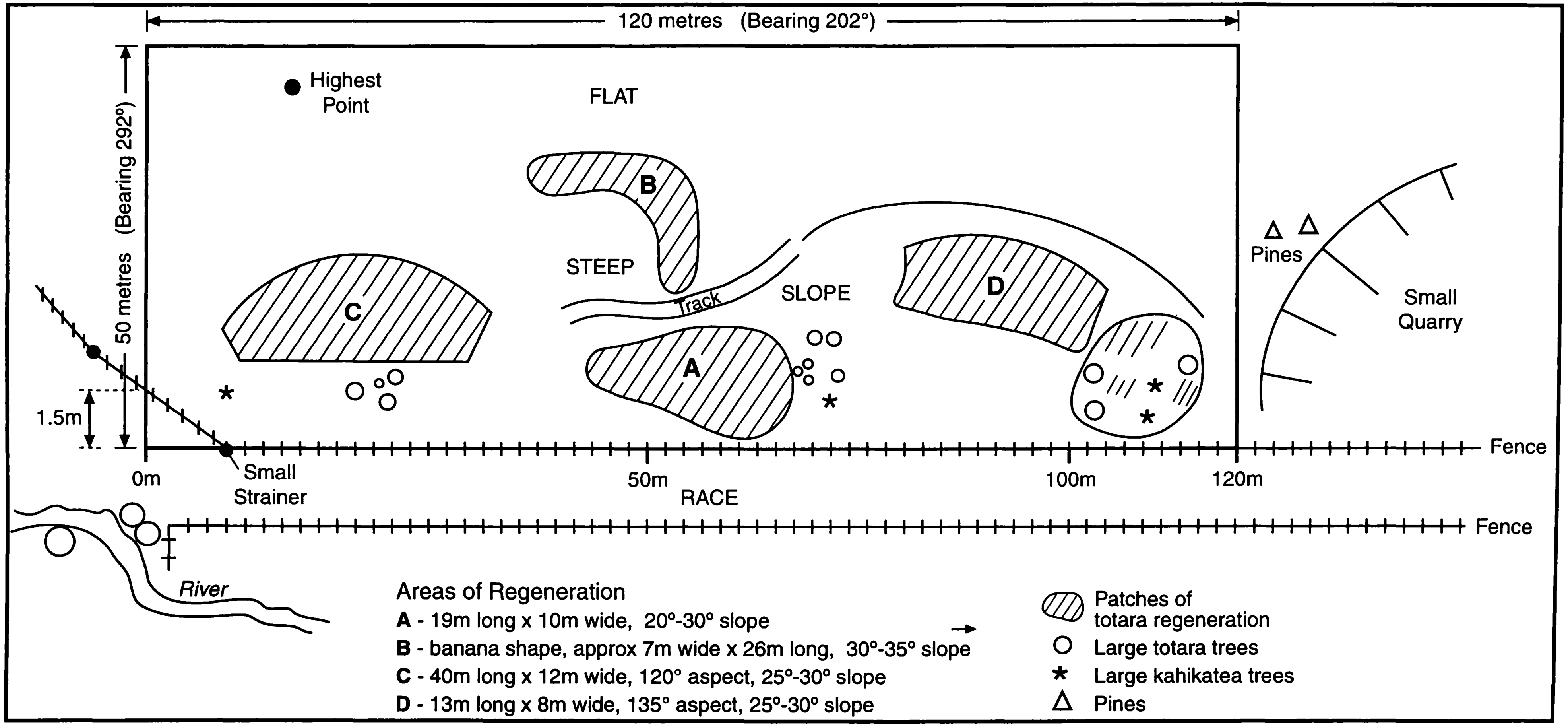


Figure 5.3: Diagram of totara regeneration survey area, Doug Lane's property, Kaeo, Northland.

5.4 METHODS

5.4.1 Field sampling

A rectangular 120 m x 50 m area was demarcated to encompass a hill slope from base to ridge crest (Figure 5.4). Transects were placed at 4 m intervals across the slope. Along each transect temporary pegs were also placed at 4 m intervals each forming the centre of a 2 m diameter plot. The edge of each circular plot was marked and vegetation cover assessed. A total of 348 circular plots was required to cover the area on a 4 m x 4 m grid.

Seedlings and saplings within six height categories were recorded for woody species which included mainly totara, kahikatea, gorse and manuka/kanuka (not distinguished apart) and small quantities of a few indigenous tree and shrub species. Height categories used for the woody species were 0-10 cm, 11-30 cm, 31-100 cm, 1-2 m, 2-5 m and > 5 m.

For ferns and herbaceous species (including grasses) percentage cover scores were based on a modified Braun-Blanquet cover scale (Mueller-Dombois and Ellenberg 1974). Vegetation cover classes recorded separately for each species were: 1, < 1%; 2, 1-5%; 3, 6-25%; 4, 26-50%; 5, 51-75%; 6, 76-95%; 7, > 95%. The overall vegetation cover and area in bare ground was also determined for each plot using the same seven point scale.

Site factors recorded for each plot included aspect, slope angle using hypsometer, degree of disturbance of the soil profile by cattle and any recent browsing and trampling damage to woody vegetation. The area was mapped in relation to nearby semi-mature totara and other tree species and evidence of seeding of totara within and in the vicinity of the survey site during autumn and winter was noted. The landowner was interviewed to ascertain the history of site management and current farming practices that were relevant to the vegetation cover over the survey site.

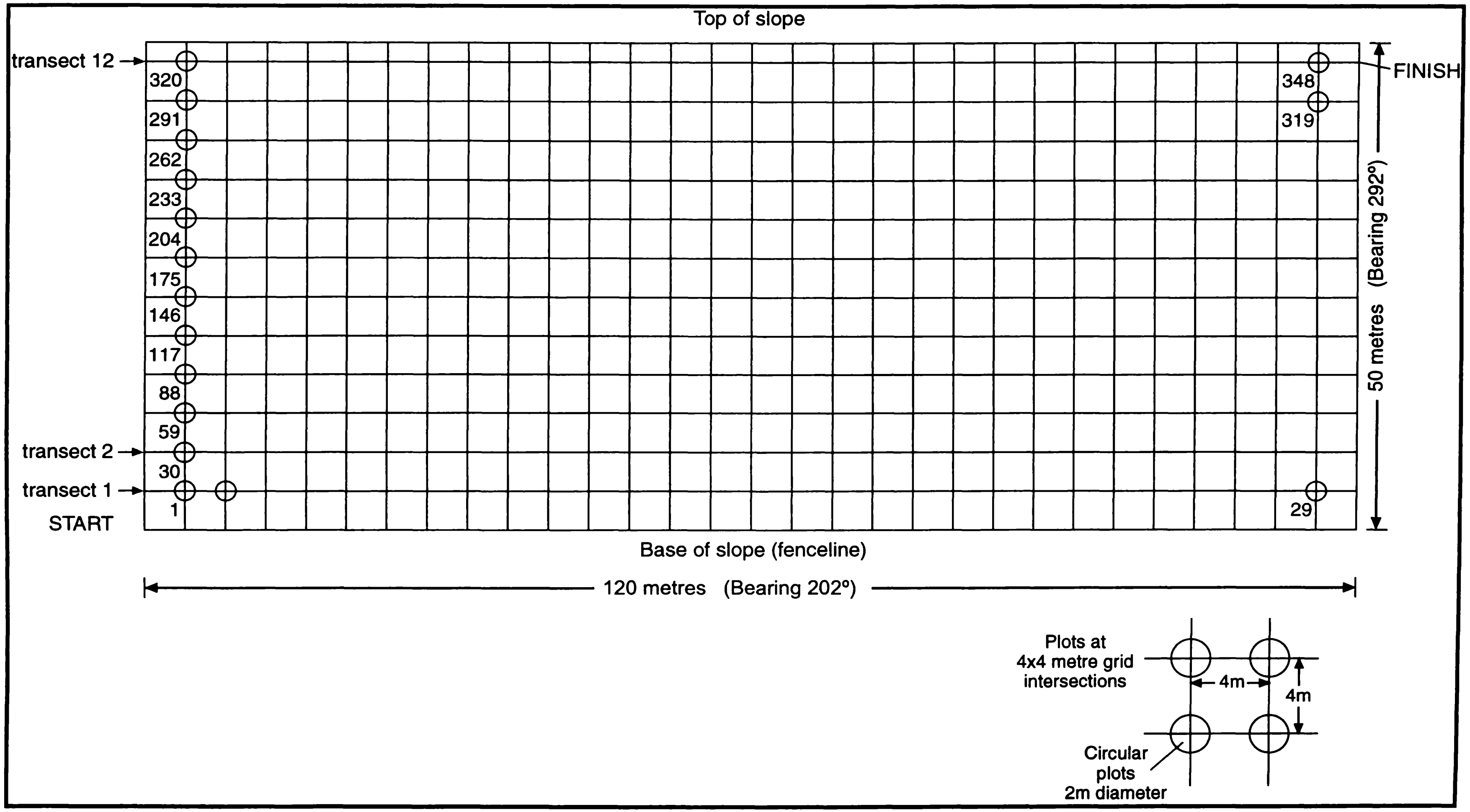


Figure 5.4: Plot layout of totara regeneration survey area.

5.4.2 Data analysis

An ordination using detrended correspondence analysis (DCA) (Hill and Gauch 1980) of the Braun-Blanquet cover values for pasture species was performed using DECORANA (Hill 1979a). The DCA default options of rescaled axes and 26 segments were used. Two-dimensional ordinations were constructed summarising floristic change that could be related to environmental gradients. Classification of plots based on the polythetic divisive technique of indicator species analysis (ISA) (Hill *et al.* 1975) was carried out using TWINSPAN (Hill 1979b). The default options used for presence/absence data included a maximum number of five indicator species, maximum level of six divisions and a minimum group size of five. However, TWINSPAN divisions were only taken to the second level for interpretation of results.

The relationship between presence/absence of each major woody species (totara, gorse, manuka/kanuka, kahikatea), the number of species present (representing a species richness score), percentage of bare ground, and the mean number and size class of totara in each plot, was tested against site factors (slope and aspect) using analysis of variance (ANOVA) and the least significant difference (LSD) test. For this analysis, slope was classified as 1, < 13°; 2, 13-23°; 3, 23-32°; 4, > 32°. Aspect was classified as N (north), 315°-45°; E (east), 45°-135°; S (south), 135°-225°; W (west), 225°-315°.

For the same variables together with slope, the TWINSPAN classifications were compared, also using ANOVA and LSD. These analyses were performed using SAS (SAS 1990). Because plots were systematically placed on a grid within the study area and were not spatially independent, general inferences made from statistical tests need to be treated with some caution. In addition, as only one site was sampled, all statistical tests undertaken in this study can only be applied to this specific site. Limited resources precluded similar assessments across a number of sites.

The position of field-plots on the first two ordination axes were graphed using different symbols for plots with and without the presence of totara. Eighty-percent confidence ellipses, based on bivariate normal distributions, were obtained for plots with and without the presence of totara and superimposed on this ordination graph. Similar graphs were obtained for the other major woody species. Comparison of mean ordination scores for plots with and without each of the major woody species was carried out using t-tests. DECORANA was used to plot the more common grass and herbaceous cover species against the first two ordination axes to aid interpretation of the axes in terms of environmental gradients and the relationships between these and the major species. Species codes for grass, herbaceous and fern species are the first three letters of generic and specific name for each species as listed in Appendix 5.1.

5.5 RESULTS

5.5.1 Woody species

The equivalent of over 7000 stems ha^{-1} of woody species were found regenerating in grass on this Northland site (Table 5.1). Totara and gorse made up nearly all woody regeneration with each species found in over half of the plots surveyed. There was a high proportion of plants in the smaller size classes less than 1 m high for both species, indicating that recruitment is continuing. Manuka/kanuka and kahikatea were present in only 5-7% of plots amounting to less than 400 stems ha^{-1} for each species. Mingimingi (*Leucopogon fasciculatus*), mahoe (*Melicytus ramiflorus*) and towai (*Weinmannia sylvicola*) amounted to less than 18 stems ha^{-1}. The few hardwood species that were found in the study area were within dense clusters of totara saplings and hence were protected from browsing.

Regeneration of woody species was greatest on steep slopes where there was more bare ground present compared with less steep slopes (Table 5.2). Bare ground increased from 3% to nearly 24% as mean slope increased from 9° for the gentle slope category to over 37° for the steepest slope class. Regeneration of the four most numerous woody species was highest on the two steeper slope classes where average slopes were over 28°. The average number of totara plants per plot increased from none on the shallowest slope class to over five plants per plot on the steepest slope class. There was no significant difference in size classes of totara with slope steepness. The number of species per plot (species richness) increased significantly from gentle slopes to steep slopes and a similarly significant trend was also reflected in the TWINSPAN groups (Table 5.2).

Table 5.1: Abundance and size class of the woody species regenerating amongst grass, Kaeo, Northland.

Species	Number of stems ha^{-1}	Plots with at least one plant present (%)	Proportion of plants in each size class (%)					
			0-10 cm	11-30 cm	31-100 cm	1-2 m	2-5 m	>5 m
Totara	3420	53	19	20	34	18	7	1
Gorse	3026	55	12	37	46	5	0	0
Kahikatea	366	7	40	28	28	3	3	0
Manuka/kanuka	384	5	64	33	2	0	0	0
Mingimingi	9	0.3	0	100	0	0	0	0
Mahoe	18	0.6	0	0	0	100	0	0
Towai	9	0.3	0	100	0	0	0	0
TOTAL	**7232**							

In contrast to totara, gorse was present in significant quantities on all four slope classes (Table 5.2). Routine management of this site involving selective spot spraying of gorse has probably reduced the proportion of this species, particularly for the conspicuous larger plants. The only significant trends in the three aspect classes were probably influenced by slope where the relatively smaller sample of north-facing plots were on the flat sites reflecting limitations in survey design.

DCA graphs plotting Axis 1 against Axis 2 for the four main woody species indicate that there is some separation of plots with and without species present along Axis 1 for totara (Figure 5.5), manuka/kanuka (Figure 5.6), kahikatea (Figure 5.7) and gorse (Figure 5.8). Confidence ellipses embracing 80% of plots indicate plots with woody species present have higher ordination values along Axis 1 whereas plots with no woody species present are distributed along the axis. t-tests of mean axis values indicate that separation along Axis 1 is only significant for totara and gorse (Table 5.3) and probably reflect increasing steepness with increasing axis value. Along Axis 2, confidence ellipses show that plots with kahikatea, and to a lesser extent manuka/kanuka, tend to have high values, gorse plots tend to be distributed at the lower end and plots with totara are spread throughout the range. t-tests indicate significant differences between mean axis values for plots with and without gorse, kahikatea and manuka/kanuka but not for totara (Table 5.3). Kahikatea present in plots with higher ordination values along Axis 2 may indicate an increasing moisture gradient along this axis.

5.5.2 Pasture cover

A total of 48 grass, herbaceous and fern species are present in the survey site (Appendix 5.1). These ranged from improved pasture species, grass species of secondary importance to farming, herbaceous plants often considered to be weeds in pasture, rushes, ferns and numerous other herbaceous species. All the grasses and dicotyledons were adventive and the ferns, rushes and sedge indigenous.

Table 5.3: t-tests for mean axis values for detrended correspondence analysis (DCA) graphs for the four main woody species.

Species	Axis	t-test	P value
Totara	1	8.0	<0.001
	2	1.9	0.054
Gorse	1	11.0	<0.001
	2	6.6	<0.001
Kahikatea	1	2.1	0.041
	2	7.5	<0.001
Manuka/	1	2.1	0.032
kanuka	2	3.8	0.0002

A DCA graph of the 29 most common grass, herbaceous and fern species indicates a trend along axis 1 from improved pasture species on flat sites and gentle slopes to pasture weed species and ferns that dominate steeper slopes (Figure 5.9). The correlation coefficient between axis 1 and slope was $r = 0.67$ ($p < 0.0001$). In contrast, there was no correlation between axis 2 and slope ($r = -0.06$; $p = 0.26$) and there appears to be no clear environmental interpretation for this axis.

Table 5.2: Site characteristics, regeneration of woody species and species richness of pasture species for each slope class, aspect class and TWINSPAN group. Within each group, values followed by the same letter are not significantly different (p = 0.05). P and F values are given in Appendix 5.2.

		No. of plots	Mean slope of each plot (°)	Bare ground (%)	Proportion of major woody species (%)				Mean size class of totara*	Mean number of totara per plot	Pasture species richness (No. of species per plot)
					Totara	Gorse	Manuka/ kanuka	Kahikatea			
Slope class	**1**	114	8.9 a	3.1 a	0 a	14 a	0 a	0 a	-	0 a	6.01 a
	2	111	18.2 b	11.6 b	7 a	31 b	3 ab	4 a	3.21 a	0.14 a	6.76 b
	3	82	27.8 c	20.3 c	49 b	60 c	7 bc	5 a	2.93 a	1.72 b	7.61 c
	4	41	37.5 d	23.6 c	83 c	56 c	10 c	22 b	2.93 a	5.32 c	9.37 d
Aspect class	**E**	80	19.9 a	15.2 a	21 a	46 a	9 a	5 a	2.64 a	0.79 a	6.30 a
	N	22	8.3 b	0.5 b	0 b	0 b	0 ab	0 a	-	0 a	5.64 a
	S	246	20.6 a	12.4 a	26 a	35 a	2 b	5 a	3.04 a	1.26 a	7.38 b
TWINSPAN Group	**1**	47	28.9 a	16.5 a	69 a	47 a	19 a	28 a	2.74 a	3.77 a	10.04 a
	2	126	24.7 b	19.7 a	34 b	62 b	2 b	0 b	3.00 a	1.40 b	6.72 b
	3	119	15.6 c	6.7 b	8 b	18 c	2 b	3 b	3.37 a	0.16 c	7.04 b
	4	55	8.6 d	3.8 b	0 c	0 d	0 b	0 b	-	0 c	5.18 c

* Size class categories – 1 = 0-10 cm; 2 = 11-30 cm; 3 = 31-100 cm; 4 = 1-2 m; 5 = 2-5 m; 6 > 5 m.

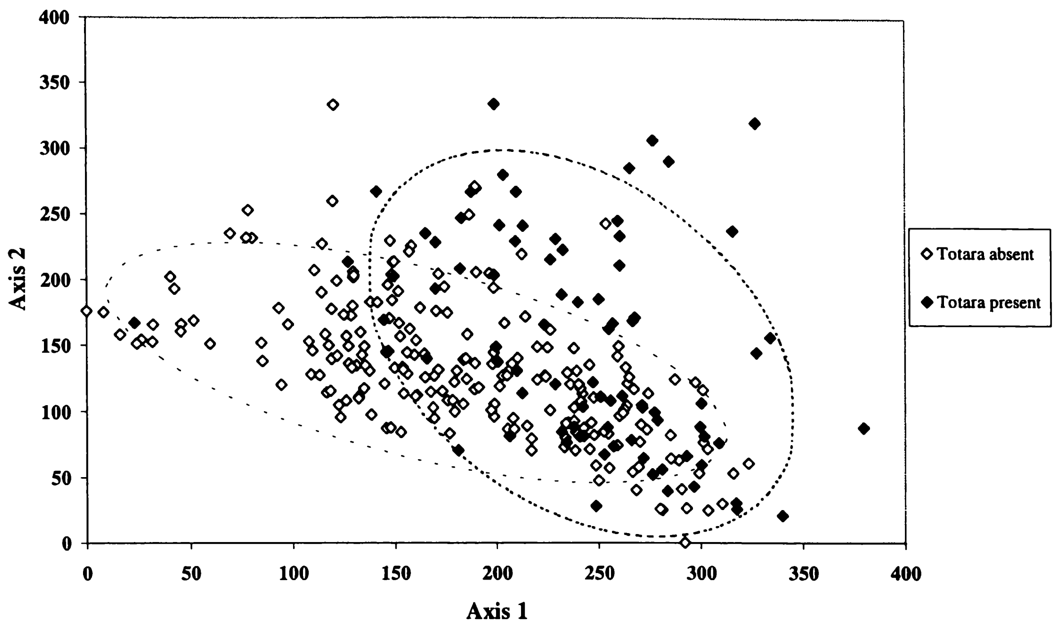


Figure 5.5: DCA scatter diagram on ordination axes 1 and 2 with and without totara present.

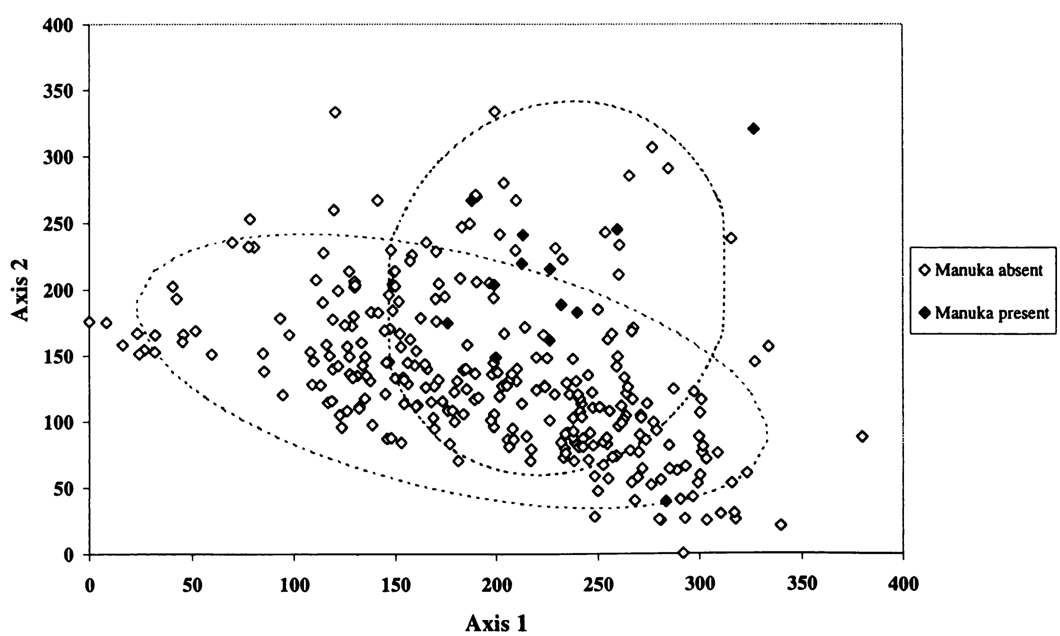


Figure 5.6: DCA scatter diagram on ordination axes 1 and 2 with and without manuka/kanuka present.

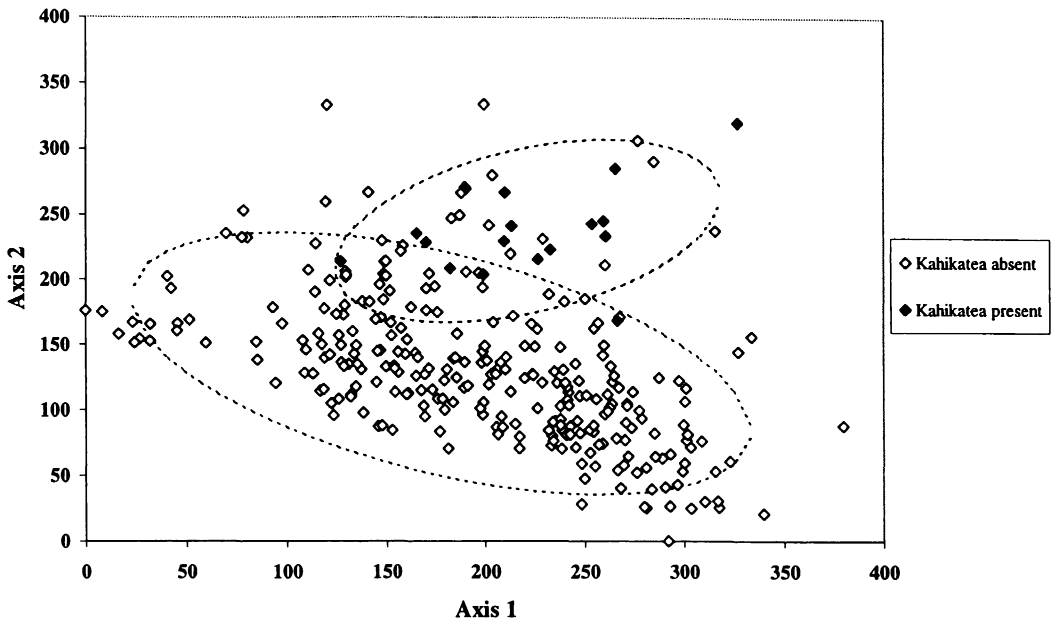


Figure 5.7: DCA scatter diagram on ordination axes 1 and 2 with and without kahikatea present.

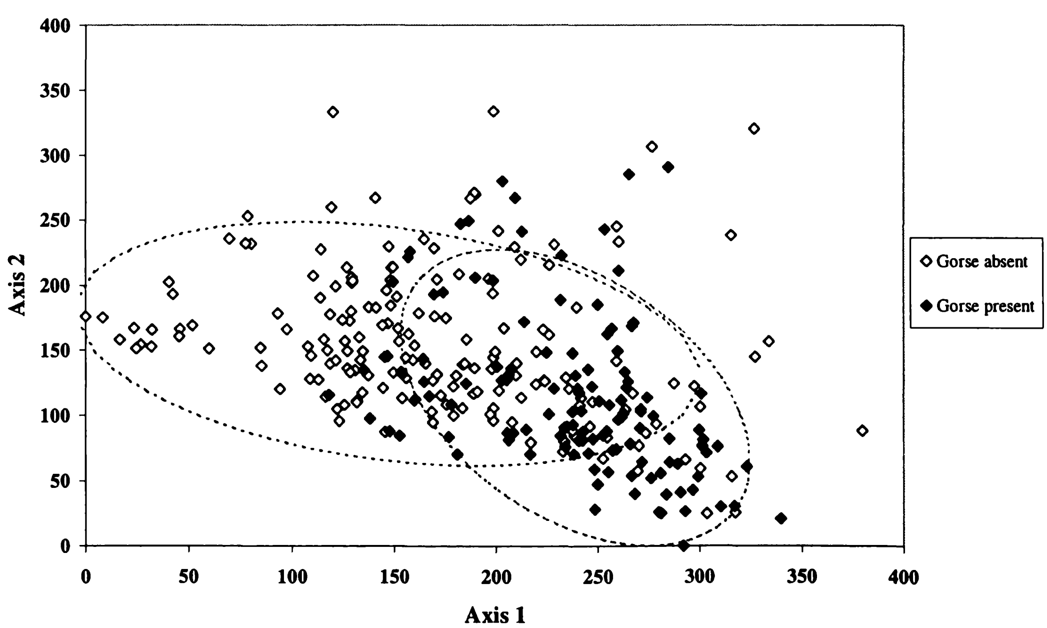


Figure 5.8: DCA scatter diagram on ordination axes 1 and 2 with and without gorse present.

A two-way ordered TWINSPAN table of the 48 cover species plotted against the 348 plots is given in Appendix 5.3. TWINSPAN groups classified to the second level show there are clear trends in grass and herbaceous species composition and abundance with site and woody vegetation variables (Table 5.2). There were significant differences between TWINSPAN groups in nearly all categories of slope, degree of bare ground, density of totara stems and proportion of major woody species. From left to right in the table in Appendix 5.3 the features of each TWINSPAN group are:

- ***Group 1*** – comprises plots with a wide range of species present. These include ground ferns such as scented fern (*Paesia scaberula*) and *Doodia media* and the tree fern wheki (*Dicksonia squarrosa*); pasture weeds Scotch thistle (*Cirsium vulgare*), foxglove (*Digitalis purpurea*), and dandelion (*Taraxacum officinale*); a wide variety of other herbaceous species such as hairy lotus (*Lotus sauveolens*), selfheal (*Prunella vulgaris*) and creeping buttercup (*Ranunculus repens*); the rush *Juncus gregifolius*; and the major pasture species sweet vernal (*Anthoxanthum odoratum*), cocksfoot (*Dactylis glomerata*) and perennial ryegrass (*Lolium perenne*). This group represents plots on the steepest slopes (average slope 29°) with totara in 69% of plots, gorse in 47%, manuka/kanuka in 19% and kahikatea in 28%. This group also had a significantly higher density of totara stems (nearly four stems per plot) compared to the other groups where totara was present. Estimated area in bare ground was 16.5%.

- ***Group 2*** – comprises the largest number of plots dominated by dandelion and sweet vernal in particular, as well as other pasture species such as paspalum (*Paspalum dilatatum*) and Yorkshire fog (*Holcus lanatus*). Some pasture weed species are still present in small quantities. Average slope was significantly different from Group 1 at 25° with the highest estimated area in bare ground at 19.7% reflecting observations that cattle trampling on slopes other than the less traversed steepest slopes has resulted in churning up of slippery slope faces, particularly during and after wet weather. Totara is present on 34% of plots with a density of 1.4 plants per plot. This group has the highest incidence of gorse occurring in 62% of plots compared to other groups.

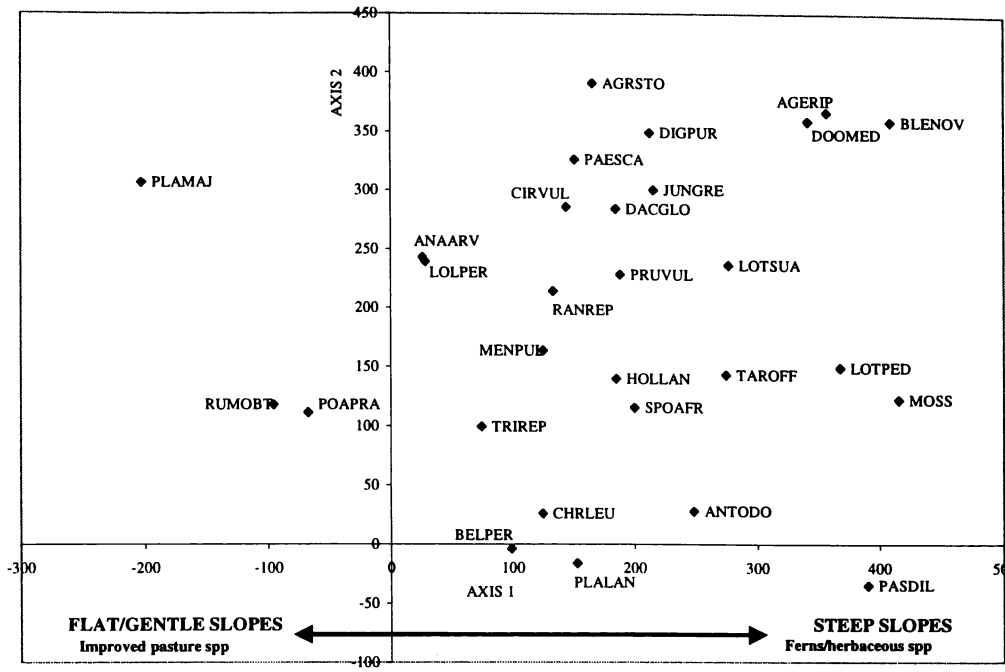


Figure 5.9: Scatter of pasture, herbaceous and fern species on a farmland site, Kaeo, Northland on the two ordination axes 1 and 2 from species ordination using detrended correspondence analysis. Species codes are listed in Appendix 5.1. The arrow shows the trend from improved pasture species on flat/gentle slopes to fern/herbaceous species on steep slopes.

- *Group 3* – comprises an increasing cover of major pasture species including sweet vernal, Yorkshire fog, perennial ryegrass, creeping buttercup and white clover (*Trifolium repens*). The moisture dependent pennyroyal (*Mentha pulegium*) has its highest concentrations in this group. The presence of many of these species on these slopes that average 16° reflects an improved moisture gradient, deeper topsoils and less damage to ground cover by trampling with a lower average bare ground area, estimated at 6.7% compared to significantly larger bare areas for TWINSPAN divisions with steeper slopes. Totara is present in only 8% of plots with gorse present in 18% of plots.

- *Group 4* – comprises the smallest group of plots that are dominated by improved pasture species including perennial ryegrass, clover and Kentucky bluegrass (*Poa pratensis*) at cover values often exceeding 3 (> 25% cover) on the Braun-Blanquet scale. Many plots have up to 95% cover of perennial ryegrass. The average slope of these plots is less than 9° with the lowest bare ground area of 3.8% compared to the other TWINSPAN groups, although only significantly different from Groups 1 and 2. No woody species are present in these plots.

5.6 DISCUSSION

5.6.1 Regeneration of totara

The regeneration study in Northland confirms earlier observations that totara can successfully regenerate in pasture. Results indicate a significant correlation between steep slope, weedy open grass cover, and significant areas of bare ground with good regeneration of totara and the other, relatively non-palatable woody species found. Although research is required to determine which factors are the most influential in promoting natural regeneration, that presence of bare ground and the effects of grazing appear to be important in establishment of totara. Inevitably there is less machine movement on steep slopes from agricultural operations compared with flat or gently rolling country which is also contributing to recruitment of totara. Regeneration of woody species on the Northland site is still at an early stage as overall density is little more than 7000 stems ha^{-1}. Considerable areas of steep slopes are not yet occupied by woody species so further infilling of pasture is likely to continue on slopes over about 20° (Figure 5.2).

The ability of totara to colonise pasture has been observed by others, including Beveridge (1977) and Wardle (1974). Regeneration of totara has also been described in open seral vegetation, such as under a light canopy of manuka and kanuka (Wardle 1991). These and other studies indicate that totara is light-demanding, tolerant of dry exposed sites and is not very palatable to livestock.

Totara, and to a lesser extent kahikatea, were the only podocarp species found regenerating in pasture on this Northland site. Differences in site requirements between the two species may explain the lesser abundance of kahikatea in this study, kahikatea favouring moister sites than totara (e.g., Wardle 1991). Esler

(1978), in a description of the distribution of totara and kahikatea on flood plains of the Manawatu, suggested that totara occurred mostly on high ground on the coarser alluvium while kahikatea grew on the finer sediments which remained moist throughout the year. Although not covered in this study, totara along with kahikatea, is common on floodplains throughout Northland. However, subtle differences between these two species in availability of seed and seed dispersal characteristics, as well as relative palatability to stock, may also be contributing factors.

The pattern of regeneration of totara on farmland in Northland is consistent with the 'catastrophic' regeneration mode described by Veblen (1992) where an even-aged stand develops after a massive disturbance such as fire, mass movement, flooding, large-scale windthrow or volcanic eruption. Seedlings of species that adopt this mode are typically shade-intolerant. Ebbett and Ogden (1998) showed that totara and kahikatea display the greatest height growth responses to increased light compared with the other major podocarps matai, rimu and miro. They suggested that these light-demanding species have the greatest ability to respond to large canopy openings and that catastrophic disturbance would, therefore, be the likely disturbance regime present at totara and kahikatea-dominated sites. Clearance of forest cover for farming has resulted in similarly catastrophic disturbance and consequently, shade-intolerant species such as totara and kahikatea which can establish in early years on exposed sites, are successful colonisers on farm sites (Burns 2000).

5.6.2 Cluster regeneration pattern

A feature of the regeneration pattern at this Northland site is that totara is establishing in clumps or small clusters over the hill slope. These clusters tend to form around one or more established saplings that afford protection and mutual support for further recruitment of seedlings leading to expansion of these groups (Figure 5.10). Birds dispersing seed may be attracted to clusters of 2-4 m high saplings as temporary refugia or resting points acting much like fencelines where birds perch and defecate or drop seed. Regeneration of totara along fencelines is common due to bird perching and lack of disturbance by farm machinery immediately either side of fences. The proximity of seeding trees of totara at the

Northland site is also an important factor in ensuring that seed is available for bird dispersal over relatively short distances.

Figure 5.10: Small clusters of seedlings develop around one or two established saplings which attract perching birds similar to birds on fences. Seed defecated or dropped by birds around these saplings germinates and with the added protection of adjacent saplings develop and thus expand the size of clusters.

This cluster regeneration pattern is a feature in other successional communities colonising open ground or low-stature seral vegetation (Wardle 1991). Seedlings of shrubs and trees with succulent fruit are concentrated near isolated trees and shrubs that are taller than surrounding seral vegetation which have attracted perching birds. Silvester (1964) found that wheki played this role in forest succession of dense scented fern and grass. Like scented fern, wheki is able to establish in open conditions, but with time, wheki form tall isolated groves smothering and shading scented fern and grass ground cover. Birds roosting in the wheki fronds effectively dispersed seed of hardwood species beneath the tree ferns, ideal sites for seedling growth, forming islands of vegetation that eventually fuse to form a canopy. Allen *et al.* (1992) found clustering related to site suitability where kanuka establishment was confined to gaps between plants of ungrazed herbaceous species before the site became fully occupied. The high variability in kanuka stem density in young stands arose from clustering, probably related to the distribution pattern of suitable establishment sites. Clustering observed with totara may also be related to patchy ground disturbance by cattle producing bare sites for successful establishment.

5.6.3 Pasture composition

The composition of grass and dicotyledon species, occurrence of more bare amongst a relatively open grass cover and shallow, less well-developed skeletal soils characteristic of steep slopes are factors that are likely to be influencing establishment of totara on hillsides compared to flatter sites. Improved pasture species forming dense swards on gentle slopes and flat sites with good soil development along the base of slopes and on flat topped ridges provide vigorous competition for regeneration of woody species.

In New Zealand, the aim of pastoral farmers is to achieve high productivity throughout the year. This is often achieved to a large extent by encouraging a limited mixture of pasture species that grow in different seasons and together tolerate a range of seasonal constraints such as drought or cold temperatures (Levy 1970). In the northern latitudes of Northland, cool-temperate grasses grow from late autumn through to early summer, but are inhibited by summer drought and possibly heat stress, especially on shallow soils (M. Dodd pers. comm.). Warm-temperate grasses such as paspalum found in the study site on the moderate slopes averaging 25° (TWINSPAN group 2) produce maximum growth in summer and early autumn. Kikuyu is also a warm-temperate species that is particularly drought resistant but of lower nutritional value and is common throughout Northland pastures and wastelands. It has been kept to low levels in the study site by intensive selective herbicide spraying by the landowner.

A subjective assessment of the fertility tolerances of the grass and herbaceous species (Table 5.4) compiled from species fertility and site preferences from several sources (Daly 1973; Lambrechtsen 1975; Levy 1970; Parham and Healy 1976) indicate a gradient from species with high-medium fertility requirements (e.g., perennial ryegrass, clover, Kentucky blue grass) on flatter sites (TWINSPAN group 4) to increasing proportions of medium fertility species (e.g., sweet vernal, Yorkshire fog) as slopes become steeper (TWINSPAN groups 2 and 3) and low-fertility-tolerant species (e.g., dandelion, hairy lotus) on the steepest slopes (TWINSPAN group 1). The permanent, highly productive grass swards dominated by perennial ryegrass and clover are common on fertile soils throughout the country and are effective in preventing reversion to woody vegetation, while weedy poor quality pastures are prone to reversion by ferns and manuka (Levy 1970).

Table 5.4: Subjective fertility-tolerance categories for selected grass and herbaceous species found in the regeneration study site, Kaeo, Northland. This has been compiled from species fertility and site preferences from Daly (1973), Levy (1970), Lambrechtsen (1975) and Parham and Healy (1976).

	Fertility tolerance categories		
	High	**Medium**	**Low**
Grasses	perennial ryegrass paspalum tall fescue kikuyu	cocksfoot Yorkshire fog sweet vernal Kentucky blue grass	ratstail
Legumes	white clover	*Lotus pedunculatus*	hairy lotus
Herbaceous species	field daisy Scotch thistle	narrow-leaved plantain foxglove scarlet pimpernel oxeye daisey *Cotula australis* chickweed	sheep's sorrel fleabane scrambling fumitory dandelion
Species tolerant of damp conditions	creeping buttercup	broad-leaved plantain selfheal broad-leaved dock mist flower	

The fertility-tolerance categories in Table 5.4 are largely consistent with species found in improved pasture and unimproved pasture categories defined by Newsome (1987). Improved pasture species defined as exotic sward grassland of good pastoral quality reflecting relatively high soil fertility and good grazing management comprise perennial ryegrass, white clover, cocksfoot, Yorkshire fog and paspalum. Unimproved pastures defined as exotic grassland of poor pastoral quality reflecting low soil fertility levels and less intensive grazing management comprise amongst other species sweet vernal, Yorkshire fog and ratstail (*Sporobolus africanus*).

A schematic diagram of a transect through the survey site is given in Figure 5.11. Along the broad flat tops of hill slopes (Group 4), improved pasture species of perennial ryegrass, clover and Kentucky blue grass dominate to the exclusion of virtually all weed and herbaceous species that are more common on hill slopes. Sweet vernal, which is present on all slopes, is also out-competed on the flat or near flat sites, as are all woody species. Abrupt changes from broad level expanses to steep slopes are not uncommon. The preponderance of pasture weed species dominated by dandelion that are present on the steepest slopes in excess of 25° are indicative of sites which are prone to drying out and where shallow soils are subject to continual small-scale erosion and disturbance (Group 1). It is this combination of less grass competition and highly disturbed microsites prone to drought which favours establishment of totara and other woody pioneer species. The ferns scented fern, *Doodia media*, kiokio (*Blechnum novae-zelandiae*) and wheki are most often confined to the steepest slopes. This is consistent with regeneration patterns of grassland in the Hunua Range (Silvester 1964) where scented fern and wheki were effective in establishing from spreading rhizomes in the broken moist clay slips common on steep slopes. As slope angle decreases, hardy grass species such as paspalum become prevalent, and sweet vernal becomes even more dominant than on the steepest slopes. Weed abundance slowly decreases as grass species become more dominant and bare ground is at its greatest as it is not too steep for cattle which churn up ground cover by trampling, particularly in wet weather (Group 2). Towards the base of the hillside, slopes decrease to less than 20°. With the increasing moisture gradient, increased soil development and buildup of colluvium, species less tolerant of drought including pennyroyal and Yorkshire fog, become significant with an increase in clover to the exclusion of many pasture weed species (Group 3). Suitable microsites for establishment of woody plants decrease significantly.

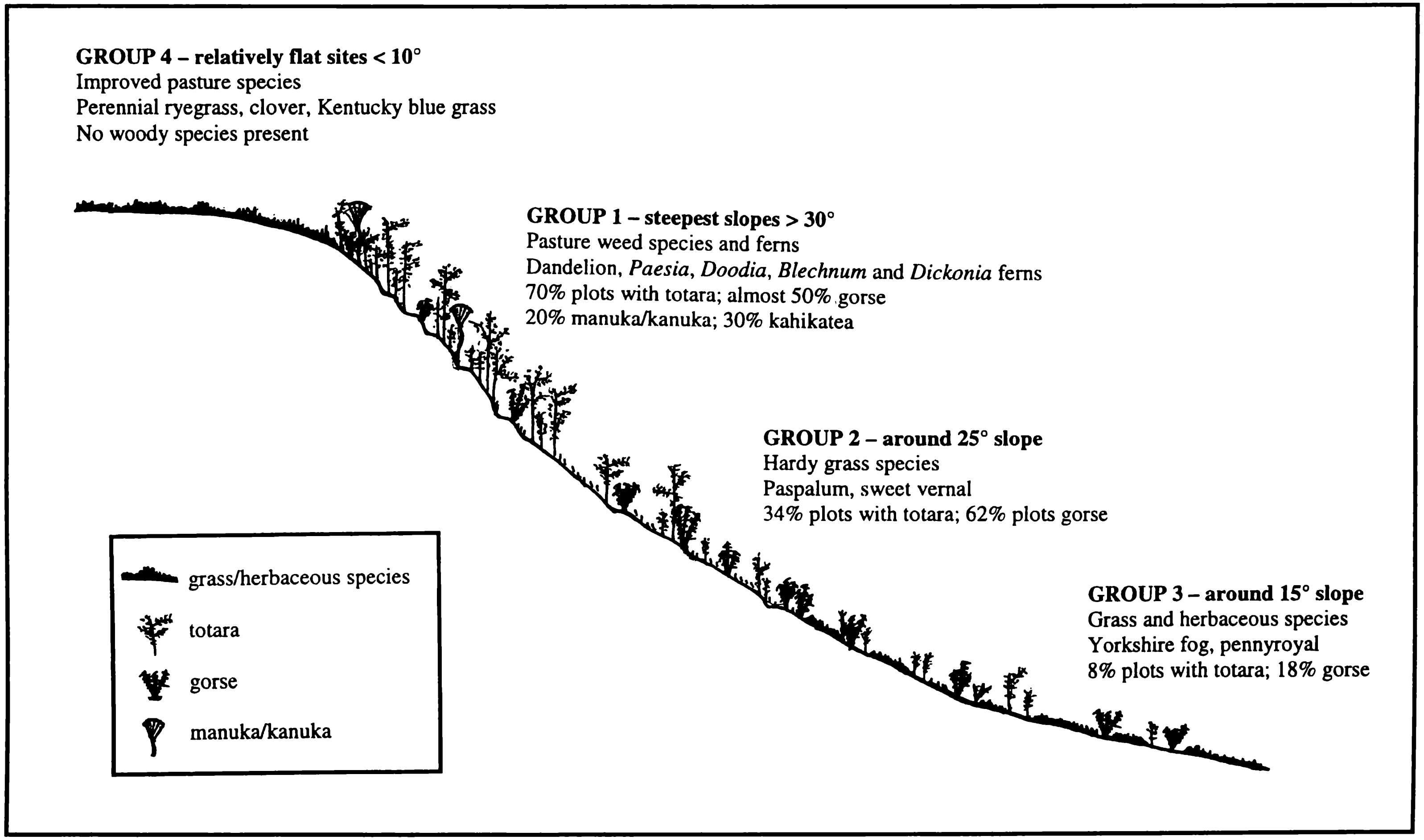


Figure 5.11: Diagrammatic representation of the totara regeneration site at Kaeo, Northland, showing the four TWINSPAN groups and major cover species and woody vegetation. Slope angle is exaggerated.

5.6.4 Influence of grazing

Grazing plays a significant role in creating establishment sites that allow regeneration of totara and the other woody species. Keeping grass cover short increases light levels to near ground level for newly germinated seedlings. On sloping ground particularly when wet, footfalls of cattle churn up the soil profile and prevent development of dense ground cover of grass. In an experiment on impact of cattle treading on hill country during winter, damage to the soil surface was greatest on animal tracks and camps on moderate slopes, with high levels of disturbance to the soil surface due to skid damage on steep inter-tracks (Sheath and Carlson 1998). Although not quantified directly on the Northland site, considerable skid damage was evident on steep faces between animal tracks in the greater proportion of bare ground on steep slopes compared with flat sites. Suitable sites for germination and development of totara are, therefore, created with many seedlings establishing on bare ground and less densely vegetated steep faces between formed animal tracks. Although trampling by livestock can severely damage young totara (Bergin and Pardy 1987), many seedlings are able to survive and eventually develop on the steeper hill faces.

Grazing not only maintains a light cover of grass, but also eliminates regeneration of palatable species such as hardwood trees and shrubs, some of which would regenerate quickly on these sites, that are likely to compete with totara and slow down establishment. Wardle (1991) indicates that seral shrubs and trees can form self-perpetuating communities where grazing eliminates tree seedlings of more palatable species. The unpalatable shrubs manuka and gorse, and the trees kanuka and totara clearly have an advantage on these grazed pasture sites in Northland. As grazing is continuing in most stands, no other forest tree species have a chance to regenerate.

Esler (1967) regards the effects of grazing in the conversion of grassland to shrubland on Kapiti Island as diverse. Grazing either accelerates or retards succession of woody species depending on certain other site factors and can also determine which species are likely to succeed. Esler (1967) found that small areas of grassland remained on parts of Kapiti Island where heavy grazing occurred or where there was no grazing at all. Intensive grazing of pasture on fertile soils retards the appearance of woody species but on other sites the invasion of manuka and kanuka ceased when sheep and goats were removed due the development of a dense deep turf. In management of hill country for pasture, Levy (1970) indicates that the intensity of grazing is a major factor in succession of woody species. There are also differences between sheep and cattle grazing which can influence reversion of hill country to woody species. Intense close grazing by sheep leads to invasion of manuka, hard fern and rushes whereas controlled grazing with cattle will maintain a permanent sward provided that clovers are kept growing strongly by applications of phosphate. In the Northland regeneration study site, the current farm management practices of cattle grazing and topdressing with fertilisers are effectively maintaining the clover-perennial ryegrass dominated pastures on the lower angle slopes and flats. The steeper slopes are, however, dominated by the less fertility-demanding grass species and with grazing, this open cover is allowing regeneration of totara and other non-palatable seral species such as manuka and gorse.

5.6.5 Comparison with gorse

It is not surprising that both totara and gorse were found to be the dominant species regenerating on grassland on this typical Northland farm site. They are both light-demanding pioneer species that readily establish in grass and are relatively unpalatable to grazing stock (e.g., Ebbett and Ogden 1998; Zabkiewicz 1976). Both species are still actively regenerating on the Northland site as most plants are in the lower size classes of less than 1 m high. Consequently, regeneration of woody species is at a young stage on this site where there was only pasture 10 years earlier.

In contrast to totara, gorse does not show a strong preference for establishing on steeper slopes in the Northland study, establishing on all but the flattest sites which were dominated by improved pasture species. Despite some selective spraying of gorse on this site, seedling densities of 3000 stems ha^{-1} were similar to those of totara. In a study of gorse-dominated communities near Dunedin, Lee *et al.* (1986) found high densities of gorse seedlings on recently cleared sites but lower densities of less than 15,000 stems ha^{-1} where it was establishing amongst rank pasture or a sward of herbaceous plants. Lee *et al.* (1986) found that gorse seedling establishment was not significantly influenced by altitude, aspect or slope. They found that gorse is able to establish in areas of low intensity pastoralism in pastures dominated by sweet vernal, cocksfoot, Yorkshire fog and browntop (*Agrostis capillaris*).

Gorse and totara differ markedly in seed longevity in seed banks and in seed dispersal. Storage of totara seed indicates that it can remain viable from 6-18 months (Forest Research Institute 1980b). In contrast, seed of gorse may continue to germinate after 30 years in the soil and consequently ongoing germination in pasture over decades is possible making it extremely difficult to eradicate from farmland (Zabkiewicz 1976). Although seed of totara is produced most years and viable seed can be formed on relatively young trees, distribution of that seed is dependent on bird dispersal. Given that totara seed banks are likely to be only temporary compared with gorse, local seed trees and a good bird population to disperse seed are crucial to ensuring effective regeneration of totara on suitable pasture sites. Natural regeneration of totara is, therefore, only taking place in Northland and other regions on pasture sites where seed trees are found nearby.

5.6.6 Comparison with manuka and kanuka

Observations of many farmland sites throughout Northland indicate that regeneration of totara can be in pure stands or in mixture with manuka and kanuka as well as with gorse. Manuka in particular has long been known to be effective in colonising a wide range of soils where sites have been subject to forest clearance, grazing animals and fires (Cockayne 1928). Although totara does not have a light seed like manuka or kanuka that are widely dispersed by wind (Molloy 1975), totara seed can be effectively spread by birds where there are seeding trees present (Beveridge 1964). Other studies of manuka and kanuka indicate that these light-demanding species readily establish in short, open, lightly grazed pasture (Grant 1967) similar to the regeneration of totara found on hill slopes in Northland. North of latitude 38°, the common associates of grazed manuka stands are the shrubs *Coprosma rhamnoides* and mingimingi, the grasses *Oplismenus imbecillus* and *Microlaena stipoides* and the fern *Doodia media* with *Ageratina* spp. growing in damp hollows (Wardle 1991). Most of these species were present in the Northland regeneration study site and supports Wardle's further comments that where there are local seed sources present, less palatable tree species including totara, mapou (*Myrsine australis*) and tanekaha invade.

Further similarities can be drawn between manuka and kanuka and that of totara in their roles in primary and secondary successions in the presence of grazing. Wardle (1991) indicates that both kanuka and manuka often invade fresh river flats and slip surfaces with manuka colonising stony surfaces and kanuka the finer deposits, and may be enhanced by the presence of grazing which has hindered development of other species. Large-scale pasture reversion to dense manuka and kanuka communities in hill county on the East Coast of the North Island has been occurring over several decades with the almost total absence of other species, attributable to grazing (Bergin *et al.*1995). Extensive regenerating manuka and kanuka stands following abandonment of previously farmed land in the Waitakere Range have also developed where there has been a long history of grazing and trampling by cattle (Esler and Astridge 1974). On Kapiti Island, Esler (1967) suggested that grazing had been a predetermining factor in the development of manuka and kanuka stands.

5.6.7 Development of totara stands

As in parts of Northland and other hill country regions where pastoral farming has become marginal, reversion of grazed hill country to woody vegetation is a major problem for farmers where insufficient resources have been available for control. Newsome (1987) estimates over 2 million ha of grassland and manuka/kanuka scrub and over 200,000 ha of grassland and gorse occur throughout the country particularly on hill country. Consequently, extensive stands of woody vegetation are developing depending on availability of seed source. Unlike along the East Coast, scattered groves or individual trees of semi-mature or mature totara are providing local seed sources for regeneration in many parts of Northland, and along with regeneration of manuka, kanuka and gorse, are resulting in a mosaic of single-species and mixed-species stands.

Wardle (1991) suggests that manuka and kanuka increase when graziers are unable to maintain pasture density on hilly and infertile land and that without intensive, phosphate-dependent pasture development, these species can become dominant over large areas. Although soil fertility was not assessed in this study, totara could also be taking similar advantage of reduced fertilising regimes by colonising pasture where there is a local seed source and bird populations to disperse the seed. Periods of downturn in the rural economy that have occurred from time to time throughout the last century and earlier may have provided opportunities for regeneration of totara. These range from the youngest stands that are currently establishing as a direct result of poor returns from sheep and cattle during the 1990s, to stands dating back to the economic depression of the early 1930s, the World Wars and the inevitable surges in reversion of scrub after natural fertility was exhausted on land cleared in late 19^{th} and early 20^{th} centuries (e.g., Guthrie-Smith 1921; Sinclair 1959). This has resulted in a mosaic of relatively even-aged stands of different ages in farmed landscapes throughout Northland and in other regions of New Zealand. The composition, structure and development of these stands over time are covered in the next chapter.

CHAPTER 6

DEVELOPMENT OF NATURAL STANDS OF TOTARA ON FARMLAND

6.1 INTRODUCTION

In many parts of New Zealand, totara is a prominent feature of the rural landscape. Scattered trees and groves of young totara are found dispersed through productive pastures in many regions including Northland, Waikato, King Country, Horowhenua, Wairarapa, Nelson, Kaikoura and the West Coast (Wardle 1974). Most stands range in age from 50-120 years and are the result of regeneration since original land clearing. Regeneration occurs in grass or within scrub comprising various proportions of kanuka, manuka and gorse. Totara also often occurs on river plains along riparian areas where it has regenerated on terraces after flooding (Esler 1978). Older stands can be almost pure totara or can be in mixture with other native conifers, particularly kahikatea (Esler 1978; Wardle 1991).

The abundance of totara in pastoral areas where reversion of marginal hill country is occurring indicates that there is a considerable resource of totara with the potential to be managed as a future long-term supply of specialty timber (Figure 6.1). An investigation of the development of naturally regenerating totara-dominant stands of indigenous scrub and forest on farmland was therefore undertaken. For logistical reasons, a single region, Northland, was chosen. The development of such stands was studied by sampling them across a wide range of ages. This chapter describes the results of this study and implications for management of such stands as a long-term timber resource.

Figure 6.1: There is an abundance of totara in pastoral areas where reversion of marginal hill country is occurring. Rounded brighter green crowns are those of totara emerging through a canopy of manuka and some kanuka. The considerable resource of totara developing in these landscapes has the potential to be managed as a future long-term supply of specialty timber.

6.2 OBJECTIVES

The aim is to describe the development of naturally regenerated totara-dominant stands in hill country farmland, quantifying growth in terms of stem density and tree size over time. Specific objectives are:

- to determine the characteristics of sites and canopy species composition;
- to determine the effects of ongoing farming practices, including grazing on stand development;
- to describe successional development of totara in pure stands and in mixture with the seral species manuka, kanuka and gorse;
- to consider effects of possums on growth; and,

- to compare growth rates and other stand characteristics with planted totara stands.

The implications on the potential for management of naturally regenerating stands of totara as a long-term wood resource are then considered.

6.3 METHODS

6.3.1 Study sites

Several reconnaissance trips throughout Northland were undertaken to determine the extent and nature of regenerating indigenous forest dominated by totara on farmland. Many stands were inspected and estimates of stand ages using ring counts from increment cores were made. In addition, anecdotal evidence was sought from landowners to give further insights into the range of ages of these stands and their development over the last few decades. The three districts selected, Glenbervie, Kaeo and Herekino (Figure 6.2), contained stands that ranged in age from newly-established areas of totara to groves over 100 years old. In each district, a range of different-aged stands were located for sampling. Due to lack of uniformity in stand structure at all sites and the difficulty in determining boundaries of homogeneous forest cover, all plots were regarded as sampling separate stands. In total, 33 plots were established.

Stands ranged from almost pure totara to mixtures of species including kanuka, manuka and gorse in younger stands, and scattered indigenous hardwood trees and occasional kanuka in dense semi-mature stands. All stands occurred on hill country that had previously been cleared for farming. The area of stands varied from 0.05 ha to extensive tracts of forest that were part of large-scale reversion of hill country to indigenous forest. Brief descriptions including stand management history and soil types for each study area are given below. Climatic and geographic data for each study area are given in Appendix 6.1. Overall, Northland has a mild climate with an average of 1800 mm of rainfall with occasional summer droughts, daily mean temperature of 14°C and an average of 2000 sunshine hours per year (New Zealand Meteorological Service 1983). Descriptions of the type of stand and site information by plot are given in Appendix 6.2.

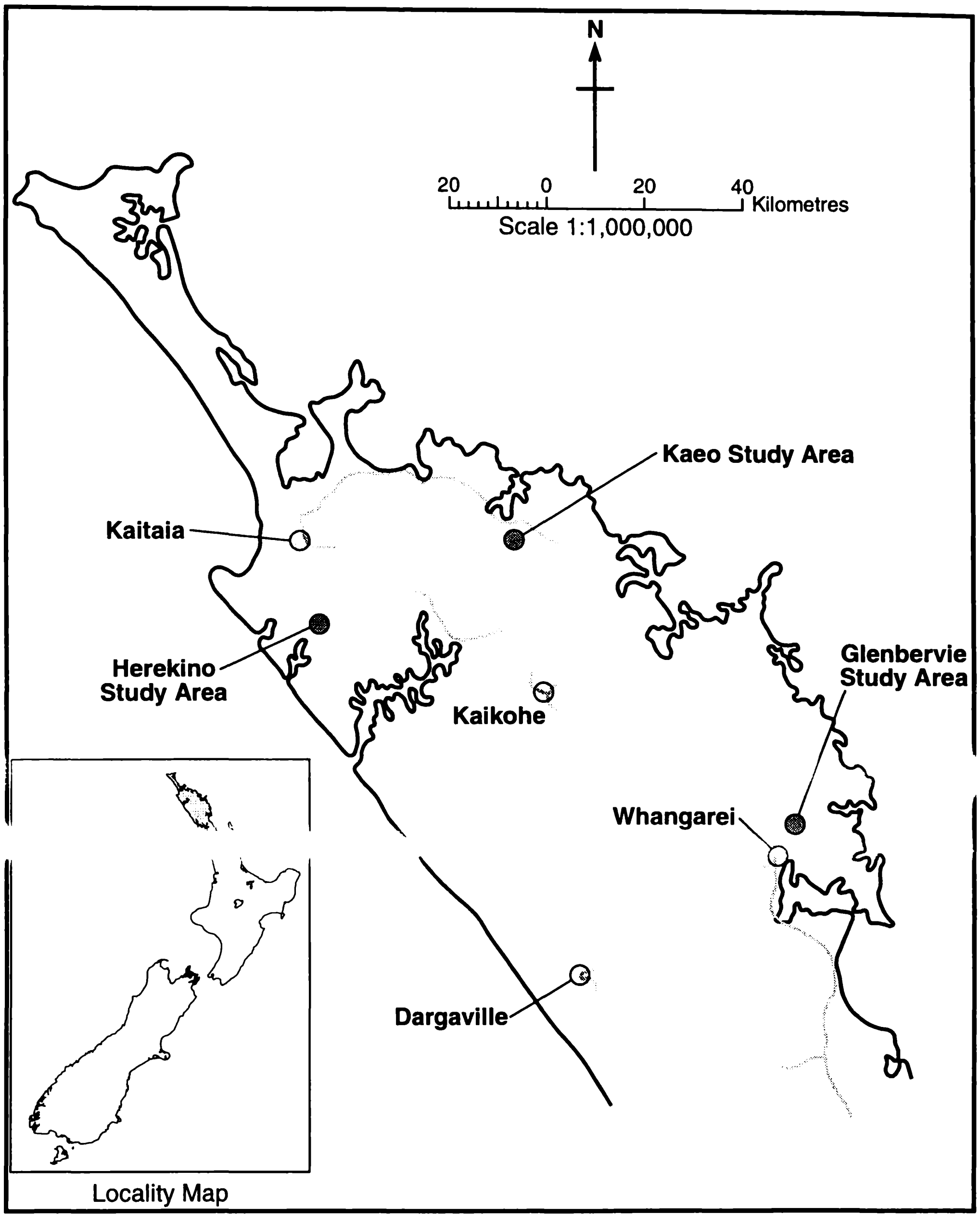


Figure 6.2: Location of the three study areas in Northland, New Zealand.

Glenbervie - Three separate study sites were located within 15 km northeast of Whangarei (Figure 6.3). These sites are identified by the codes DONE, BRID and REED. DONE and BRID occur on private land in the Glenbervie area. REED is located on the outskirts of Whangarei City within the Reed Memorial Reserve. The BRID site was grazed at the time of sampling and the DONE site had been fenced to exclude grazing within the last five years. As REED was in a public reserve it has been fenced for many decades. Eight stands were identified and a total of 11 plots established. Soils are Marua clay loam which are well to moderately well-drained yellow-brown earths (Sutherland *et al.* 1981) recently classified as Humic Orthic Podzols (Hewitt 1998).

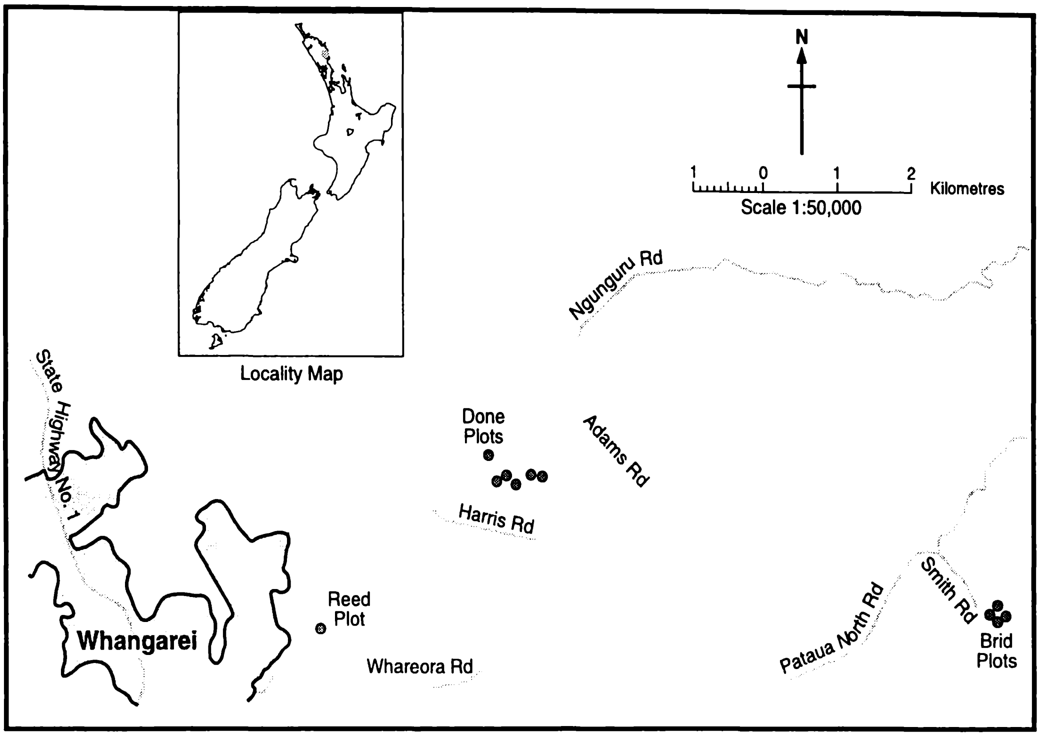


Figure 6.3: Location of the three sampling sites in Glenbervie, Northland, New Zealand.

Kaeo - Two sites were located within 5 km of Kaeo on the northeastern side of Northland (Figure 6.4). The two sites are identified as QUIN which was located on a small lifestyle block and recently fenced to exclude grazing and LANE which was located on private farmland. Five totara-dominant stands were identified and six plots were established. Soils for the QUIN plots are Waiotira clay, moderate to strongly leached yellow-brown earths (Sutherland *et al.* 1980) now classified as Typic Acid Brown Soil (Hewitt 1998). Soils at the LANE site are Otangaroa clay and sandy clay loam of the podzolised yellow-brown earths ('wet soils') group (Sutherland *et al.* 1980) now classified as Perch-gleyed Albic Ultic Soils (Hewitt 1998).

Herekino - Three sites were located on farmland along the Broadwood-Herekino road on the northwestern side of Northland (Figure 6.5). The sites are identified as

COOP, OWEN and MACK. Both COOP and MACK were grazed with animals controlled recently at the OWEN site. A total of eight different-aged stands of naturally regenerating totara were sampled at these sites with 16 plots established. Soils at COOP and OWEN are Waiotira clay (Sutherland *et al.* 1979) of the moderately to strongly leached yellow-brown earth group now classified as Typic Acid Brown Soils (Hewitt 1998). Most plots located at MACK were Waiotira clay but some on lower slopes near the flats were likely to be Waiotira clay loam. Weather stations on the western side of Northland in the vicinity of the Herekino stands record significantly lower ground frost per year than the Kaeo and Glenbervie areas (New Zealand Meteorological Service 1983).

6.3.2 Field sampling

Two sampling techniques were used to characterise plots depending on size of stems. Temporary reconnaissance plots were used for sampling young stands comprised of seedlings and saplings, and Permanent Sample Plots (PSPs) were used in pole and semi-mature stands. In this study, seedlings are defined as < 1 cm DBH, saplings 1-10 cm DBH, poles 10-25 cm DBH and semi-mature trees > 25 cm DBH. Plots were placed within forest cover that was as homogeneous as possible and representative of surrounding cover although stands were often small in extent. Stand edges and canopy gaps were avoided. Sampling technique and areas of each plot are given in Appendix 6.3.

For stands comprising saplings and seedlings where permanent identification of individual stems was impractical, plots based on the standardised reconnaissance plot methods of Allen (1992) were used with some modifications. A plot size of 5 m x 2 m was used for very dense stands and 10 m x 4 m for less dense stands. Basal diameters or root collar diameters (RCD) taken at or near ground level were measured for all stems. For plots where saplings and poles occurred, both basal diameters and breast height diameters were taken. Heights were measured for all saplings and seedlings using a height pole. Proportion of vegetation cover, including ground cover and lower tiers, were recorded along with aspect, slope, degree of disturbance from browsing stock and evidence of clearance of earlier scrub cover. Species composition and stand structure were described including other species such as kanuka or manuka that occurred within the canopy in some of these younger stands. To cover a range of ages, stands were selected across a range of stem sizes on the assumption that stands dominated by small diameter stems were generally younger than stands with larger diameter stems. Plots were subjectively located in areas of each stand where totara was dominant and where vegetation characteristics were typical of the stand.

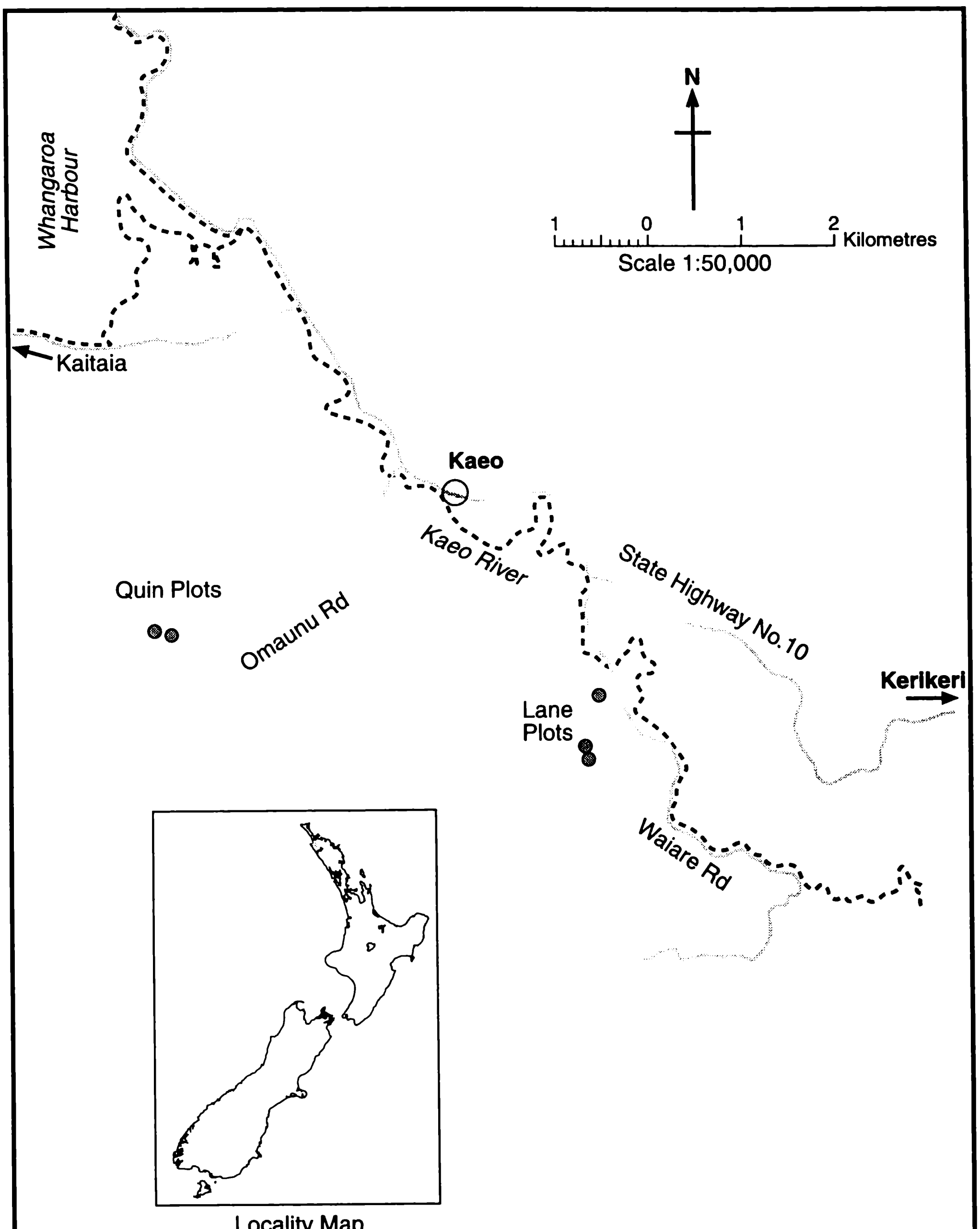


Figure 6.4: Location of the two sampling sites in Kaeo, Northland, New Zealand.

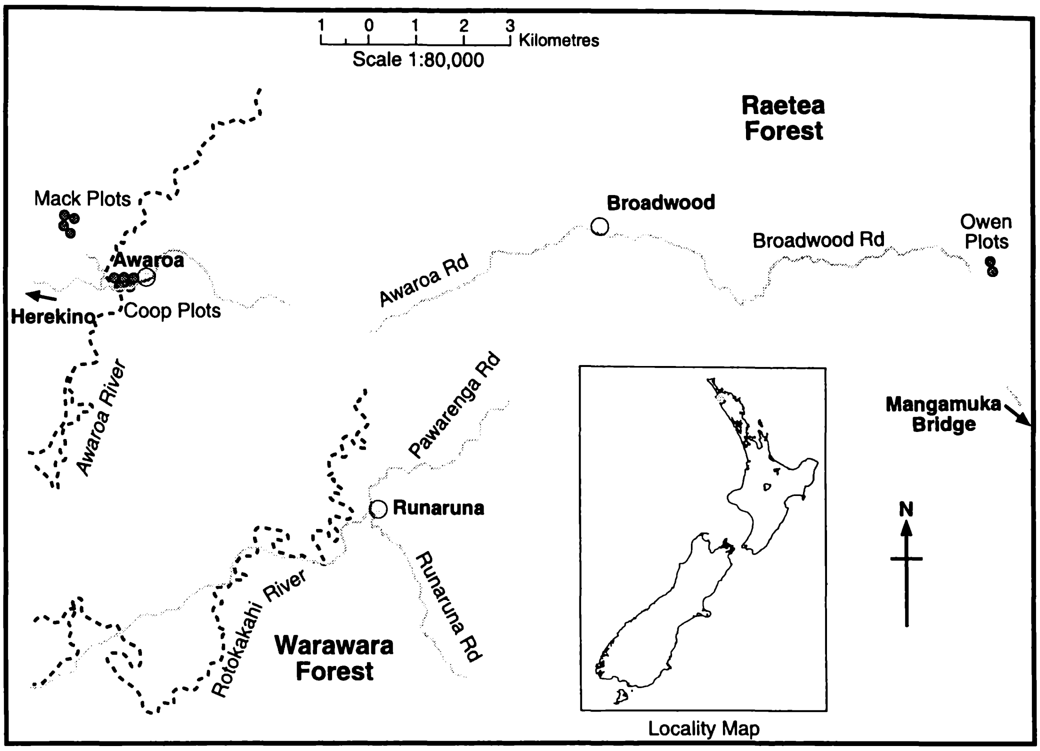


Figure 6.5: Location of the three sampling sites in Herekino, Northland, New Zealand.

Permanent Sample Plots were established using the methods of Ellis and Hayes (1997). Bounded circular plots ranging in diameter from 10-22.8 m were used so that stem densities could be determined. Plot size was chosen to give a minimum of 20 canopy trees within the plot. A treated wooden 50 mm x 50 mm peg was placed in the plot centre. All poles and trees within the plot were permanently identified using numbered aluminium tags nailed to the trunks with a 75 mm galvanised nail. Tags were placed at 1.4 m above ground level as measured from the uphill side but facing toward the plot centre. DBH was measured for all saplings, poles and trees, and a sample of a minimum of 12 canopy trees was measured for height using a hypsometer. Bearing and distance from the central plot peg were recorded for all numbered trees and poles to enable easier re-location in future measurements. Diameters were also taken for dead standing trees. All tree species were included in assessments. Average plot slope and aspect were recorded as well as other site characteristics such as recent evidence of disturbance from farm stock and other animals, number of fallen dead stems and any other disturbance. The presence of ground cover and lower tier vegetation was also noted for each plot. Any anecdotal information from landowners on stand history was also recorded.

6.3.3 Sampling cores and discs

Stand age information was estimated using increment cores and/or cross-sectional discs taken from a selection of trees from all but one stand after permission had been granted from landowners or managers. For practical reasons, including the desire by some landowners not to fell larger stems, increment cores were generally taken from the older, large diameter stems and discs were taken from smaller diameter stems. The sampling of cores was not permitted by managers of the older totara stand in the Reed Memorial Reserve (REED) so an age estimate for this stand was based on diameters and ring counts of similar stands in this study site. Five to twenty discs or cores were taken from each stand with trees selected to cover the diameter range. The total number of cores and discs sampled in each plot is given in Appendix 6.3.

Cores were taken at 1.4 m above ground using standard tree borers from 20-35 cm long depending on the size of the tree using techniques described by Norton (1998). Holes were immediately plugged with petroleum jelly to prevent entry of water and insects into core holes although Norton (1998) does not regard this practice as necessary. There was some difficulty in obtaining cores passing through or near the pith. For plots where only cores were taken, sampling covered the range of small, medium and large stem diameters in each stand.

One semi-mature stand (DONE5) that had just been felled prior to sampling had discs taken from stumps at approximately 30 cm above ground level. Other cross-sectional discs were taken for saplings and poles at approximately 5 cm above ground where no flaring was evident. Discs were stored under cover for several months before sanding.

6.3.4 Ring counting

Cores were mounted in blocks and sanded down using progressively finer grades of sandpaper from 80-280 grit, first with a belt sander and then by hand. The number of rings was counted using a low-powered binocular microscope. Cores were classified according to ring clarity using the descriptions of normal ring boundaries described by Norton and Ogden (1987) and refined in Chapter 4. Five categories were used depending on visibility of late and early wood bands, ranging from indistinct to very distinct. Growth rings were often variable in clarity along the core, and in such cases, the dominant category was used to classify the whole core. Where indistinct sections were considered to compromise a realistic ring count, cores were classified toward the indistinct end of the continuum. Some subjective judgement in classifying cores was, therefore, unavoidable. Only those cores with a distinct score of four or five were used for ring counts and for making adjustments to missing tree centres. The methods described in Chapter 4 for making adjustments to the growth record when cores missed the chronological centre were used.

An allowance was made for the time taken for trees to reach the height at which the increment core was taken. Firstly, this involved estimating the mean basal diameter of 1.4 m high seedlings from a height versus root collar diameter regression equation derived from all seedlings up to 2 m in height. Secondly, counts of the inner growth rings from the pith to a radius corresponding to this diameter was undertaken on a sample of 85 cross-sectional discs from the study.

Cross-sectional discs were sanded using a belt sander and progressively finer grades of sandpaper from 80-280 grit. Two transects were marked on each disc spaced at greater than an angle of 90°. Transects were located to avoid any fluting of the stem and along parts of the disc where rings appeared to be most easily read along the entire length from pith to bark. Two independent observers counted rings. Ring counts from both observers for both transects were averaged to give the final ring count for each disc. Adjustment for the heights at which discs were taken at 5 cm and 30 cm were two rings and five rings respectively based on expected growth rates.

6.3.5 Assessment of possum diet

Macroscopic analysis of gut contents was undertaken on 19 possums recovered from within and surrounding totara-dominant stands at the DONE study site at Glenbervie. Fresh possum carcasses were recovered by the landowner as part of a programme to reduce the local possum population in both exotic plantations and in indigenous forest. The type of forest in which possums were recovered from was recorded. Carcasses were frozen until analysis.

After thawing, stomachs were removed and gut contents rinsed over a 2 mm sieve to remove the fine, partially digested stomach contents from the undigested material. The smaller undigested material was examined using a microscope at 10x and 20x magnification while larger material was identified by unaided eye. Material was oven dried at 60°C for 72 hours and proportion of identifiable totara material and other material was recorded separately for each possum.

6.3.6 Data Analysis

As plots covered a wide range of stem sizes from young seedlings and saplings to poles and trees in older stands, RCD was not taken for stems in PSPs established in older stands and DBHs could not be taken from stems less than 1.4 m high in Reconnaissance Plots. Consequently, a regression equation relating RCD to DBH was derived from all trees where both had been measured. Any swelling of stem butts were regarded as negligible in the relatively young stands measured in this study. Using this equation, RCD was estimated for trees where only DBH had been measured. A regression equation was then derived for each plot between RCD and estimated age of trees from which cores with distinct rings or discs had been taken. This equation was then used to estimate age of all stems. As heights were only taken from a sample of trees in PSP plots, a height/RCD function was obtained for each plot to estimate heights for all stems within the plot.

Long-term performance of a stand is best represented by the largest stems rather than all stems. Therefore, stand parameters based on the largest 1000 stems ha^{-1} of each plot were calculated. The mean age of the largest 1000 stems ha^{-1} was considered to be a more accurate measure of mean stand age than the more commonly used oldest tree in the stand (e.g., Tyrell and Crow 1994) as there is some risk in the latter method that an older, single outlier may misrepresent the age of the majority of larger stems.

Mean height, DBH, BA, volume and age were calculated for the largest 1000 totara stems ha^{-1}. For comparison, stand parameters for all totara stems, and for all species were also calculated. Total stem volume was derived from BA and height using the kauri pole stands volume table of Ellis (1979).

$$V = 2.071\ln(D) + 0.8386\ln(H) - 3.14$$

where V = total stem volume under bark (dm^3), H = total tree height (m), D = DBH (cm). A volume table for totara does not yet exist. Of the available volume tables, the height and diameter ranges of the trees used in developing a kauri pole stand equation were most similar to the totara trees in this study and this equation was therefore used. DBH/age, height/age, BA/age and volume/age regression equations were then fitted for the largest 1000 stems ha^{-1}. A regression equation relating density of all stems including non-totara species to age was also fitted.

The relationship between total stem density and mean DBH was established using a linear regression equation between the logs of both variables. To approximate a mean tree biomass versus density relationship, BA x height was calculated for individual trees. BA was calculated using RCD, or predicted RCD. Height and RCDs of non-totara species were estimated using the totara equations (RCD vs DBH and Height vs RCD). This was justified on the basis that although they were invariably part of the canopy, they generally formed only a small component of the vegetation. A linear regression between the log (mean (height x BA)) and log (density) was then fitted. Analyses were carried out using SAS procedures (SAS 1990).

6.4 RESULTS

6.4.1 Species composition

The proportion of totara varied from 20-100% of the total species composition in each plot (Appendix 6.4). Most plots in the youngest stands, estimated to be less than 40-years-old had less than 40% of totara present, with manuka and kanuka a significant component. With increasing age, occasional plots had a small proportion of high forest species including kohekohe (*Dysoxylum spectabile*) and nikau palm (*Rhopalostylis sapida*). Persistent grazing by sheep and cattle at nearly all sites had prevented development of palatable hardwood species and resulted in an open understorey. Where totara regeneration was not too dense, unpalatable species such as manuka, the shrub *Coprosma rhamnoides* and gorse occurred in younger stands. *C. rhamnoides* was common in younger stands as an understorey. Kanuka persisted in a few older plots whereas early successional species including manuka and gorse had been ousted by totara.

6.4.2 Site characteristics and disturbance

Most stands sampled were located on moderate to steep slopes of up to 40° with a range of aspects represented (Appendix 6.2). Over two-thirds of the 32 plots were on slopes over 20°. All plots were on lowland sites at least 15 km inland of the coast at altitudes ranging from 40-150 m a.s.l.

Soil types were clay or clay loams of the yellow-brown earths group varying from well to moderately well-drained, moderate to strongly leached and podzolised. Although not inherently fertile, since original forest clearance and development of pastures, these soils are now regarded as relatively fertile due to regular topdressing with superphosphate as part of past, and on some sites, current farm management practices. Other than the oldest stand at REED which was a fenced public reserve, all sites are currently or were until recently lightly to moderately grazed by cattle and sheep. Evidence of stock was found in most stands, including the oldest stands dominated by totara.

Possum sign, including browsing of branch tips, droppings and bark scratching were present in most areas. Gut analysis confirmed that browsing of totara is occurring. Although sampling was limited from mid-winter to mid-summer and only a small proportion of the contents comprising recognisable material was analysable, of 19 possums sampled, four had between 13-72% of their stomach contents comprising totara foliage. These were in animals recovered in spring and early summer. On average, foliage and fruit from citrus trees in nearby gardens formed half of the recognisable stomach contents assessed, with grass, clover and other herbaceous species the remainder.

6.4.3 Determining age of plots

A linear regression relating RCD to DBH (D) was derived from trees where both were measured (Figure 6.6):

$$RCD = 0.543 + 1.16\,D, \qquad R^2 = 0.97 \quad n = 575$$

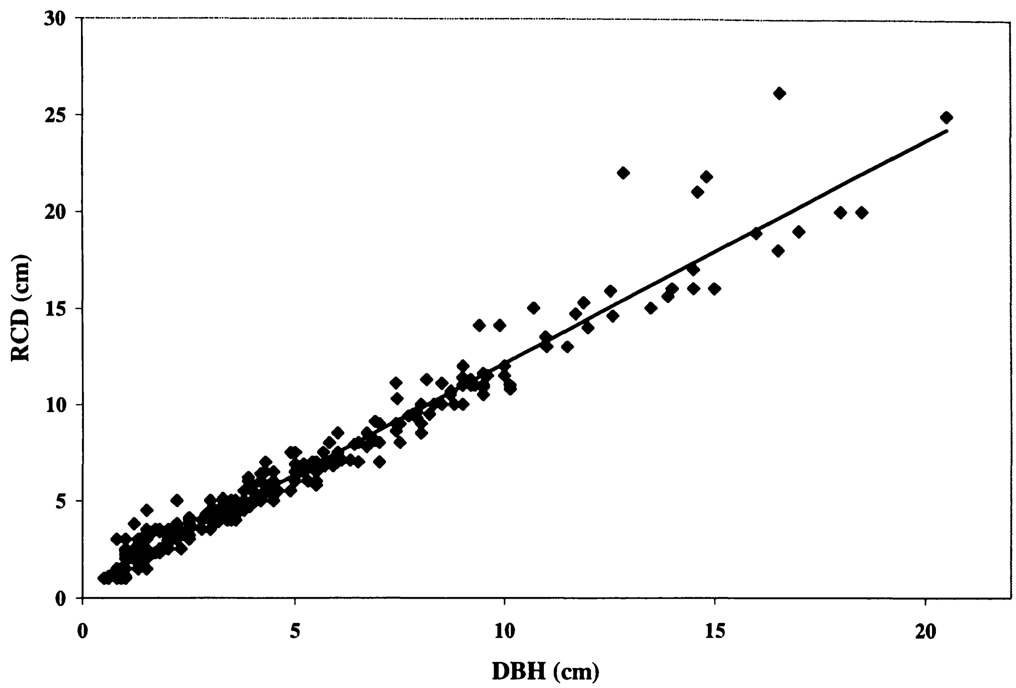


Figure 6.6: Relationship between RCD and DBH for natural totara trees (R^2 = 0.97).

To estimate the time taken for seedlings to reach 1.4 m high, the following non-linear regression equation between height (H) and RCD was derived (Figure 6.7):

$$H = 1.54 \times RCD^{0.913}, \quad R^2 = 0.62 \quad n = 504$$

From this, the mean RCD corresponding to a height of 1.4m (breast height) was calculated as:

$$RCD = (1.4/1.54)^{(1/0.913)} = 0.90 \text{ cm}$$

Based on this, the average RCD of a seedling at 1.4 m high was, therefore, about 1 cm diameter. The average number of rings from pith to a radius of 5 mm was then counted for a sample of 85 discs, and found to be 10.6 rings. With a further allowance of 1-2 years for seedlings to reach 5 cm (average height at which discs were taken), a value of 12 was, therefore, added to the ring count from cores taken at 1.4 m.

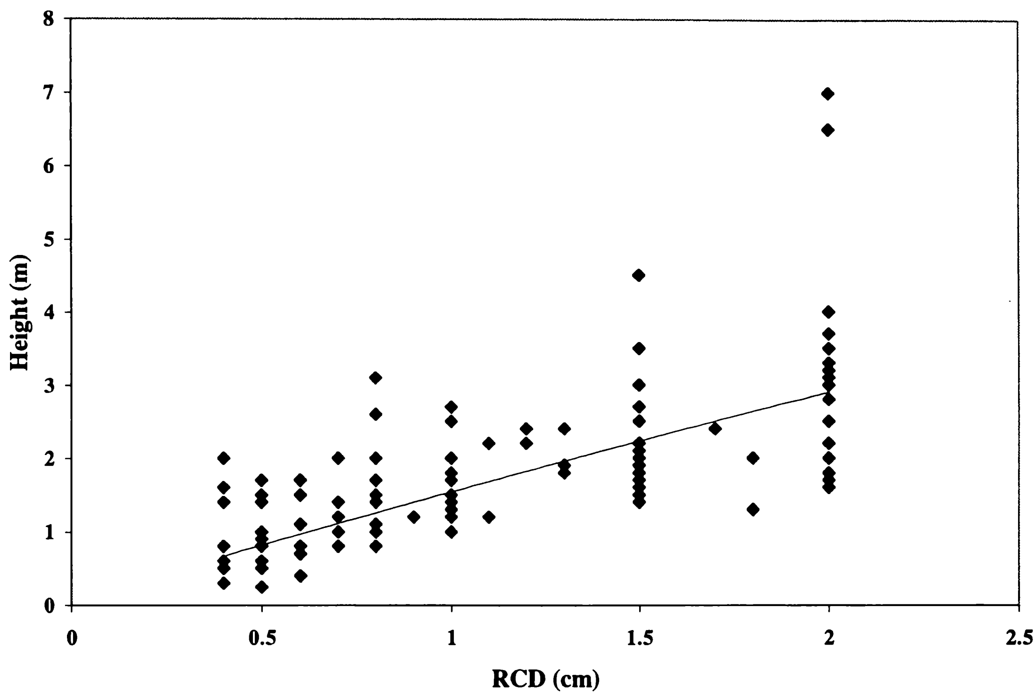


Figure 6.7: Relationship between height and RCD based on growth of seedlings in natural stands less than 2 m high (R^2 = 0.62). This was used to determine basal diameter for seedlings at 1.4 m high, the height at which increment cores were taken from larger trees.

Age estimates based on growth ring counts from increment cores are given in Table 6.1 and based on rings counts from cross-sectional discs in Table 6.2. Only those cores that had a ring distinctiveness score of 4 or 5 were used to estimate age. Hence the number of cores for some plots were significantly less than originally sampled as listed in Appendix 6.3. In contrast to difficulties in using cores for ring counting, easier reading of rings on discs meant that nearly all discs were used to give an estimate of age. A total of 94 cores and 161 discs was used to estimate stand ages.

Where both discs and cores were sampled from the one plot, there were generally large differences in estimated ages from cores and discs. The cores were taken from the larger, generally older stems and the discs were taken from the smaller, generally younger stems. For example, the increment cores from 18 stems used for estimating age for LANE3 had a mean DBH of 14.3 cm and an age estimate of 66.8 years (Table 6.1), whereas the six discs sampled from the same plot had a mean RCD of 6.3 cm and age estimate of 39.2 years (Table 6.2).

Table 6.1: Age estimates for plots based on increment cores.

Plot	Mean DBH (cm)	Mean age (years)	Age standard deviation (years)	Number of cores sampled	Number of cores used for ring counts*
QUIN1	9.2	25		2	1
DONE2	5.5	28		4	1
OWEN1	12.7	36		2	1
COOP3	10.2	36.5	2.1	5	4
COOP2	7.9	37.4	2	5	5
DONE3	8.5	38.6	5	7	5
COOP1	7.9	40.8	5	7	6
OWEN2	9	42	1.4	3	2
QUIN2	12	43.7	9	5	3
MACK8	13.8	53		4	1
DONE1	12.5	61.9	8.6	24	13
LANE3	14.3	66.8	7.5	25	18
DONE6	22.9	80.3	18.1	22	4
MACK2	22.6	84.7	15.8	19	9
BRID2	19.2	85.6	14.6	10	7
MACK1	26.4	90.7	16.1	20	7
BRID1	39.3	131.6	20.5	13	7

* Only cores classed as having distinct rings based on distinctness score of 4 or 5 (refer Chapter 4)

Using the RCD vs DBH regression equation to estimate RCD of trees where only DBH had been measured, the following regression equation was derived between age (T) and RCD for each plot using all cores and discs, with a common slope but separate intercepts for each plot:

$$\ln(T) = a + 0.239 \times \ln(RCD), \qquad R^2 = 0.93 \quad n = 255$$

where the intercept, a, differed for each plot. This equation was used to estimate ages of all totara stems. The mean age of each plot was then calculated, along with the mean age of the 1000 largest stems ha^{-1}.

Table 6.2: Age estimates for plots based on cross-sectional discs.

Plot	Mean RCD (cm)	Mean age (years)	Age standard deviation	No. of discs used for ring counts
OWEN2	3.3	18.8	0.5	4
MACK5	2.8	18.9	2.8	14
MACK6	2.7	19.1	4.3	13
LANE1	4.6	19.7	7.1	12
COOP2	2.8	20.4	4.4	5
LANE2	4.4	20.7	7.2	11
DONE3	4.1	22		1
COOP1	3.1	24.8	8.6	14
MACK4	5.8	24.8	10.7	9
MACK3	3	25.3	5.9	7
COOP3	4.6	25.4	4.2	3
MACK7	5.8	26.3	6.2	9
DONE2	6.6	27.5	10.6	2
BRID4	3.4	28.3	3.2	3
BRID3	3.7	31	6.9	3
MACK9	5.4	38.1	6.3	9
LANE3	6.3	39.2	10.1	6
MACK8	7.2	44.2	6	5
COOP4	19.5	47.3	8.2	4
COOP7	20.9	51.8	6.9	4
DONE1	10.2	55.9	5.8	4
DONE5	31.8	99.6	23.4	19

The age estimates for each plot for all totara stems and for the largest 1000 stems ha^{-1} based on merged ring count data from cores and discs are given in Table 6.3. Mean age of plots for all totara ranged from 16-140 years. The age range within plots was from 12 years for the younger stands to over a 100 years for the older stands. The mean age of the largest 1000 totara stems ha^{-1} was generally about 10 years greater than the mean age across all totara for the younger stands, but this difference increased for stands with a mean age over 40 years.

6.4.4 Diameter and height with age

Height and DBH for all species and for all totara are given in Table 6.4, and for the largest 1000 totara stems ha^{-1} in each plot in Table 6.5. Mean stand height ranged from 1.7 m for the youngest 16-year-old stand to over 23 m for the oldest stand estimated to be 140 years old. MAI for height ranged from 11-28 cm and for DBH ranged from 11-48 mm .However, in the younger stands, both mean height and DBH of the largest 1000 totara were up to three times greater than mean stand height and DBH for all stems. These differences between all stems and the largest 1000 totara stems ha^{-1} decrease with age as stand density decreases towards 1000 stems ha^{-1}.

Although there was a general increasing trend in all height and diameter parameters from youngest to oldest stands, there was some anomalies (Table 6.4). For example, QUIN1 with a estimated mean age of 24 years had a mean height (6.2 m) over one-third greater than similarly aged stands (3.1-3.7 m). Conversely, plots MACK8 and MACK9 with estimated ages of 44-45 years had heights only half that of similarly aged stands. Differences in diameters were even greater. The rapidly increasing range in DBH as stands became older reflects the large variation in sizes of stems in most stands. Both mean height and DBH of the largest 1000 stems ha^{-1} in each plot showed a more consistent trend with age (Table 6.5).

Table 6.3: Age estimates for plots based on merged data from increment cores and cross-sectional discs. Plots are in order from youngest to oldest based on mean age of all totara.

Plot	Mean age for all totara (years)	Minimum age (years)	Maximum age (years)	Range in age (years)	Mean age of largest 1000 stems ha^{-1} (years)
MACK6	16	10	24	14	23
LANE1	19	8	28	20	28
MACK5	19	12	24	12	24
LANE2	21	11	33	22	33
MACK3	24	12	38	26	35
QUIN1	24	15	33	18	32
MACK7	25	12	42	30	41
MACK4	26	10	38	28	35
OWEN2	26	17	34	17	33
OWEN1	27	13	35	22	35
COOP1	31	16	44	28	43
BRID3	34	25	42	17	41
BRID4	34	14	48	34	44
COOP2	34	19	45	26	45
DONE3	36	21	51	30	48
DONE4	36	21	51	30	48
DONE2	37	22	47	25	46
COOP3	39	24	47	43	47
QUIN2	40	25	55	30	53
COOP4	41	32	49	17	47
COOP7	43	21	56	35	56
MACK9	44	20	67	47	67
MACK8	45	16	71	55	68
LANE3	55	33	88	55	79
DONE1	60	33	81	48	78
BRID2	77	51	96	45	94
DONE6	82	52	101	69	91
MACK2	83	54	122	78	97
MACK1	94	48	112	64	104
DONE5	118	60	165	105	137
BRID1	129	70	155	85	137
REED1	140*				150*

* Estimated age based on DBH and similar aged stands in same locality as stand could not be sampled for cores or discs.

Table 6.4: Height and DBH for natural totara stands. Plots are arranged from youngest to oldest age estimates.

Plot	Mean age all totara (years)	Mean height all stems (m)	Mean height totara (m)	Mean DBH all stems (cm)	Mean DBH totara (cm)	Min DBH (cm)	Max DBH (cm)	Range in DBH (cm)
MACK6	16	1.7	1.6	3.9	1.4	0.5	3.5	3.0
LANE1	19	2.6	2.5	3.3	3.0	1.0	10.1	9.1
MACK5	19	3.5	2.7	5.4	1.6	0.8	4.0	3.2
LANE2	21	3.1	3.2	3.3	3.3	0.5	11.0	10.5
MACK3	24	3.4	1.5	7.5	1.7	1.0	6.9	5.9
QUIN1	24	6.2	6.2	9.8	6.5	2.0	18.9	16.9
MACK7	25	3.7	3.6	4.3	4.1	0.8	14.5	13.3
MACK4	26	3.1	2.8	7.1	2.3	0.8	9.0	8.2
OWEN2	26	5.7	4.7	5.3	2.2	1.5	9.5	8.0
OWEN1	27	6.0	5.1	5.6	3.3	1.0	12.6	11.6
COOP1	31	3.9	3.9	5.9	5.4	2.3	11.5	9.2
BRID3	34	6.0	3.6	6.5	2.2	1.0	6.7	5.7
BRID4	34	4.6	2.9	5.7	2.4	0.6	9.3	8.7
COOP2	34	4.2	4.4	7.5	6.1	1.3	14.8	13.5
DONE3	36	5.4	5.4	6.9	6.9	1.0	14.8	15.8
DONE4	36	10.1	10.1	11.8	11.8	3.8	22.6	18.8
DONE2	37	5.8	5.8	10.6	10.6	2.5	16.5	14.0
COOP3	39	5.6	5.8	10.6	9.3	3.0	18.7	15.7
QUIN2	40	5.7	5.7	11.4	6.1	2.0	17.0	15.0
COOP4	41	9.2	9.2	11.9	11.9	5.8	18.9	13.1
COOP7	43	8.0	8.0	11.4	10.8	1.5	21.3	19.8
MACK9	44	3.8	3.6	6.6	5.7	0.8	18.0	17.2
MACK8	45	4.2	4.0	8.1	7.8	1.0	20.5	19.5
LANE3	55	13.4	13.4	9.3	8.3	2.1	30.2	28.1
DONE1	60	9.7	9.7	11.3	11.3	2.0	23.8	21.8
BRID2	77	11.8	11.8	14.5	13.3	5.0	25.5	20.5
DONE6	82	17.0	17.0	20.5	19.3	6.8	38.6	31.8
MACK2	83	16.4	16.4	21.4	20.9	7.0	57.1	50.1
MACK1	94	16.3	16.3	27.4	27.3	5.0	44.5	39.5
DONE5	118	17.0	17.0	37.2	37.2	6.4	87.0	80.6
BRID1	129	20.5	20.5	30.1	28.1	7.1	56.6	49.5
REED1	140	23.1	23.1	30.8	29.6	10.5	60.0	49.5

Table 6.5: Growth performance of the largest 1000 stems per ha of totara in each plot.

Plot	Mean age for totara (years)	Mean height (m)	Mean height growth rate (cm per year)	Mean DBH (cm)	Mean DBH growth rate (mm per year)	BA (m^2ha^{-1})	Total stem volume (m^3ha^{-1})
MACK6	23	4.0	17	3.1	13	0.8	1.5
LANE1	28	5.1	18	10.1	36	8.1	20.6
MACK5	24	4.3	18	3.6	15	1.0	2.1
LANE2	33	6.9	21	11.0	33	9.5	31.4
MACK3	32	3.8	11	3.8	11	1.1	3.6
QUIN1	30	8.9	28	15.4	48	16.6	69.4
MACK7	39	9.0	22	12.0	29	11.3	47.8
MACK4	32	4.6	13	5.7	16	2.5	7.1
OWEN2	31	6.3	19	7.3	22	4.2	13.9
OWEN1	33	8.0	23	10.5	30	8.6	33.0
COOP1	42	7.9	18	10.1	23	8.0	29.5
BRID3	39	5.0	12	5.2	13	2.1	5.3
BRID4	42	4.8	11	6.8	15	3.7	9.0
COOP2	45	8.0	18	14.8	32	17.1	65.3
DONE3	45	7.4	15	11.5	24	10.4	37.2
DONE4	45	11.6	24	19.6	41	30.2	158.9
DONE2	44	6.9	15	15.1	33	17.8	61.0
COOP3	47	8.5	18	18.7	40	27.4	112.1
QUIN2	52	7.5	14	14.6	28	14.9	53.6
COOP4	45	10.0	21	15.0	32	15.7	73.4
COOP7	56	10.2	18	21.2	38	24.9	119.3
MACK9	66	9.6	14	18.0	27	24.1	108.6
MACK8	65	9.4	14	17.5	26	24.2	107.2
LANE3	73	13.6	17	18.7	24	24.6	143.9
DONE1	75	11.4	15	19.6	25	30.2	159.0
BRID2	90	13.0	14	22.0	23	33.9	201.0
DONE6	84	17.2	19	23.8	26	43.8	345.7
MACK2	90	17.9	18	26.3	27	53.2	441.4
MACK1	99	16.3	16	32.4	31	80.8	588.5
DONE5	126	17.0	12	44.2	32	150.5	1177.9
BRID1	125	20.1	15	35.5	23	73.0	685.5
REED1	130	22.9	15	32.7	21	74.2	788.8

There was a linear trend between mean DBH (Figure 6.8) and mean root collar diameter (Figure 6.9) with age across all naturally regenerating totara stands. The following linear regression equations were, therefore, derived for DBH (D) and RCD for the largest 1000 stems ha^{-1} with their mean age (T):

$$D = 0.352\,(T-12), \qquad R^2 = 0.81 \quad n = 32$$

$$RCD = 0.359\,(T-2), \qquad R^2 = 0.85 \quad n = 32$$

The equation for DBH is formulated to intersect the age axis at age 12, while the RCD equation intersects at age 2, based on the mean age at which trees are expected to reach the sample heights.

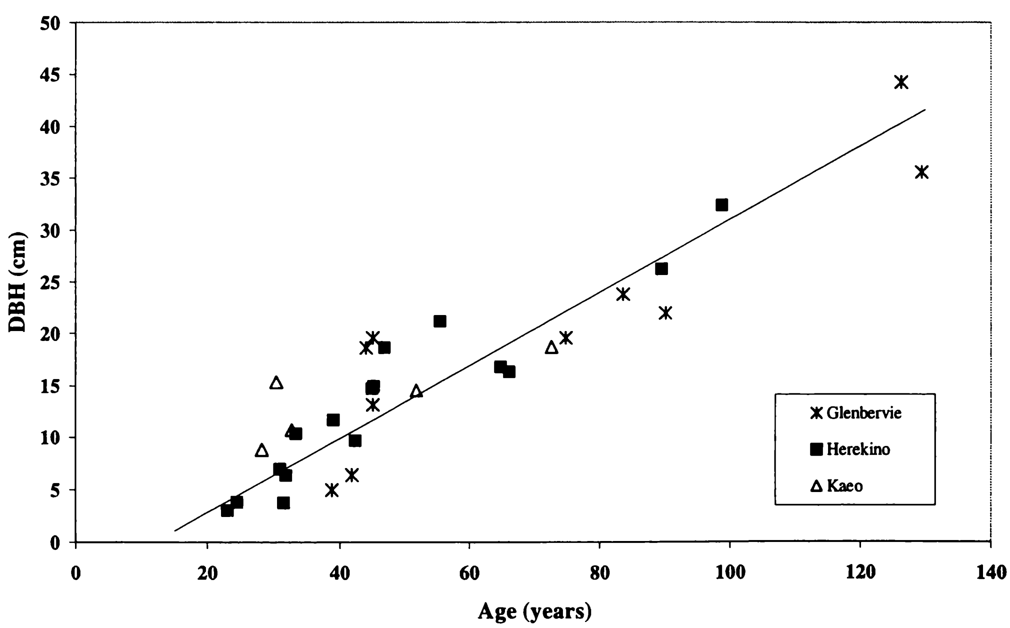


Figure 6.8: Relationship between mean DBH and age for the largest 1000 stems ha^{-1} for natural stands ($R^2 = 0.81$).

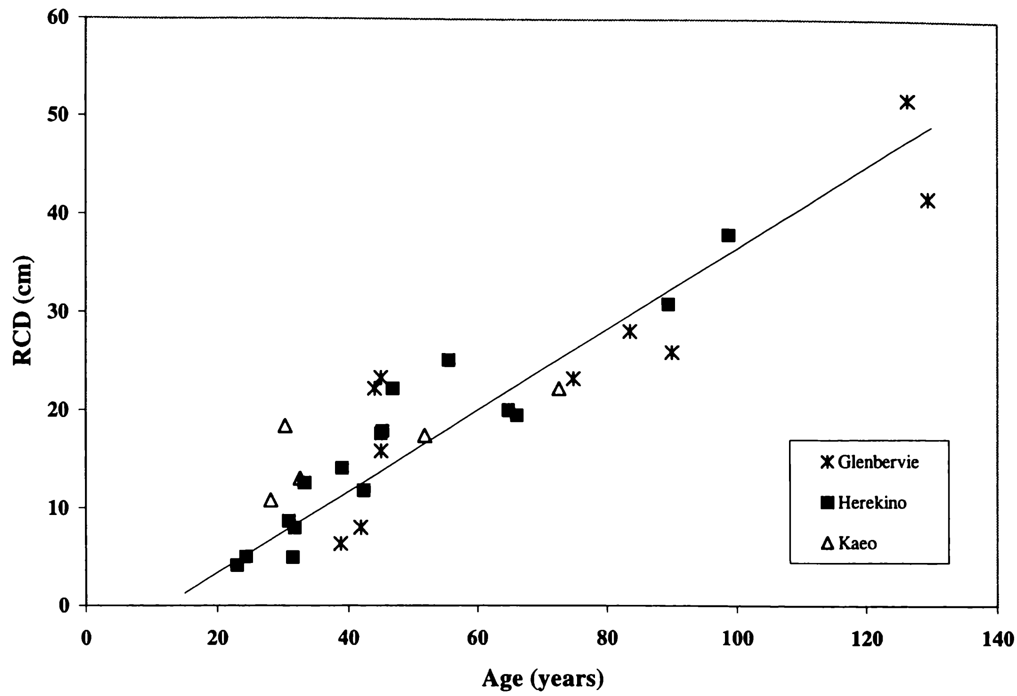


Figure 6.9: Relationship between mean RCD and age for the largest 1000 stems ha^{-1} for natural stands (R^2 = 0.80).

Separate regression equations were fitted to each of the three study areas and compared using F tests. Differences between sites were found to be non-significant, indicating that the above equations were appropriate across all three sites. Similar tests were carried out for the regression equations subsequently presented in this chapter, and in all cases, no significant differences between study areas were identified.

As only a sample of tree heights were taken in each plot, height/RCD equations from each plot (examples of two plots are shown in Figure 6.10) were used to estimate heights (H) of all totara within plots using the following non-linear height versus RCD regression:

$$H = a \times RCD^b$$

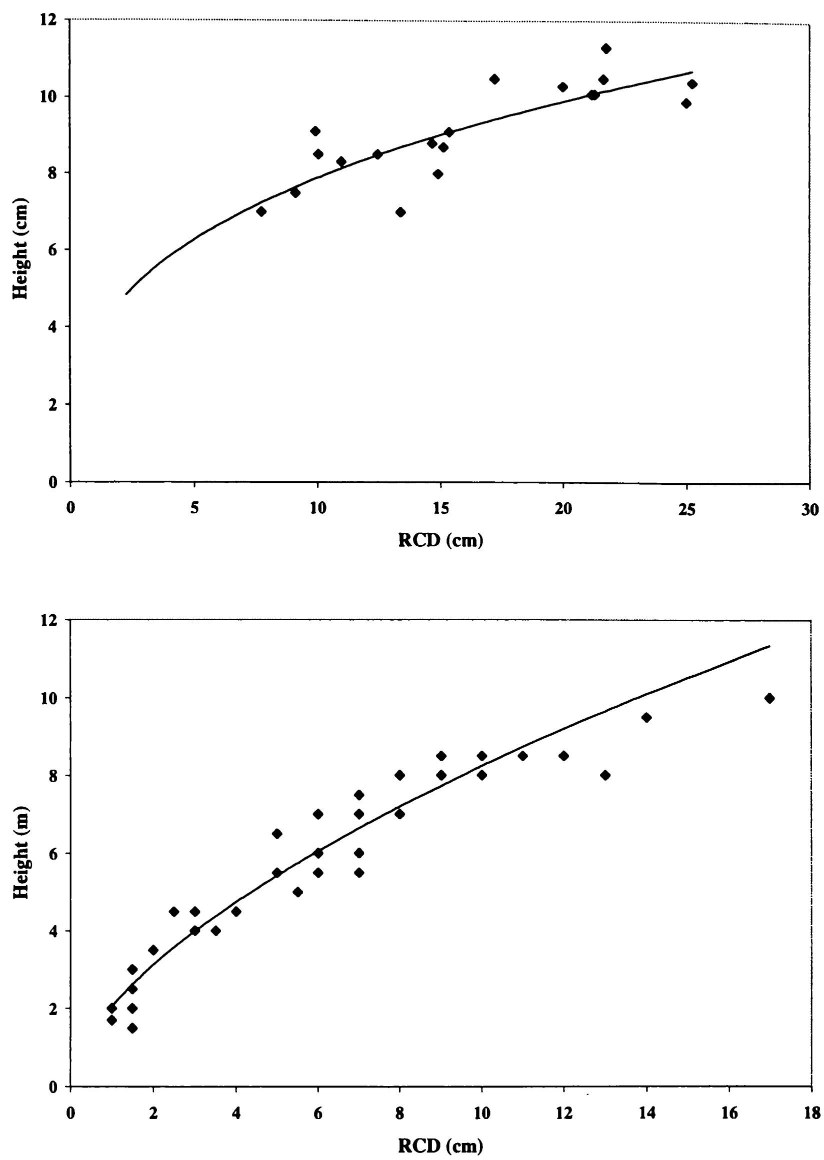


Figure 6.10: A non-linear height versus RCD regression equation was derived using the trees measured for height of totara in each plot. The relationship between height and RCD of trees for two selected stands is shown (top COOP7; bottom MACK7). These equations were then used to estimate heights of all totara stems in each plot.

Height growth of the largest 1000 stems ha^{-1} decreased as stands reached around 100 years (Figure 6.11). Therefore, the following regression equation which shows a decreasing rate of growth with age was derived for height (H) of the largest 1000 stems ha^{-1} with their mean age (T):

$$H = 32.25 \text{ x } (1 - \exp(-0.00761 \text{ T}))^{1.107}, \quad R^2 = 0.84 \quad n = 32$$

6.4.5 Basal area and volume with age

BA and total stem volume are given for the largest 1000 stems ha^{-1} in each plot in Table 6.5 and for all totara in Table 6.6. BA and volume of the largest 1000 stems ha^{-1} were 73-150 m^2ha^{-1} and 685-1177 m^3ha^{-1} respectively for stands over 100 years of age (Table 6.5). Both BA and volume show relatively slow growth over the first 60 years or so but an increasing growth rate beyond that with BA of close to 70 m^2ha^{-1} (Figure 6.12) and volume of 500 m^3ha^{-1} (Figure 6.13) by 100 years. The following nonlinear regression equations were derived for BA and volume (V) with age (T) of the largest 1000 stems ha^{-1}:

$$BA = 0.0145 \times (T-12)^{1.89}, \qquad R^2 = 0.86 \quad n = 32$$

$$V = 0.00649 \times (T-12)^{2.51}, \qquad R^2 = 0.90 \quad n = 32$$

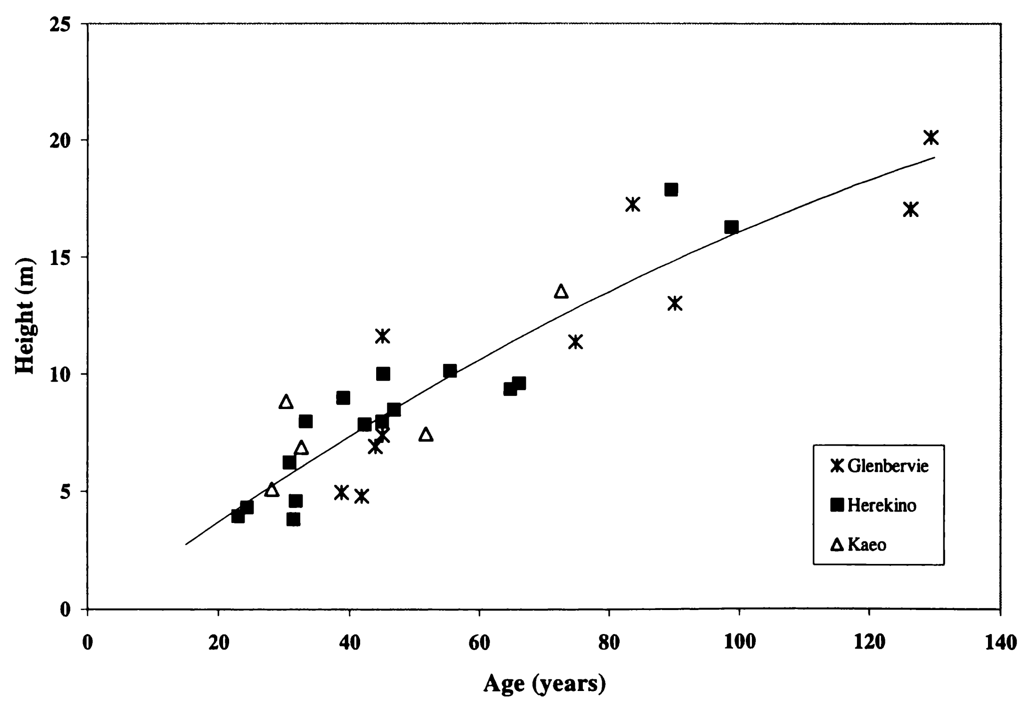


Figure 6.11: Relationship between mean height and age for the largest 1000 stems ha^{-1} for natural stands (R^2 = 0.84).

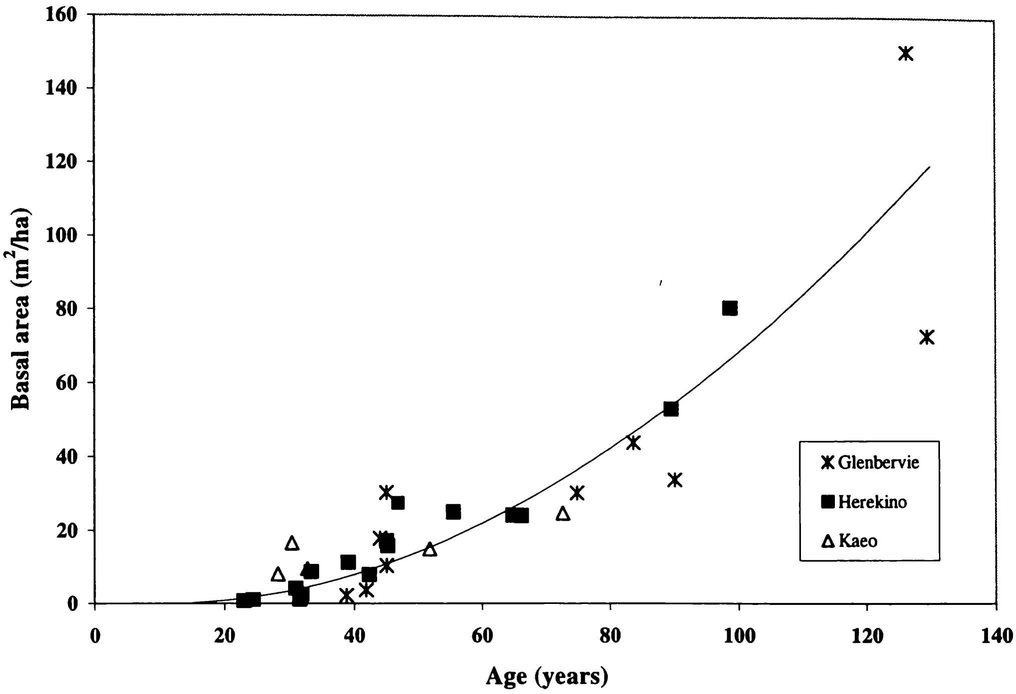


Figure 6.12: Relationship for BA and age for the largest 1000 stems ha^{-1} of totara for natural stands (R^2 = 0.86).

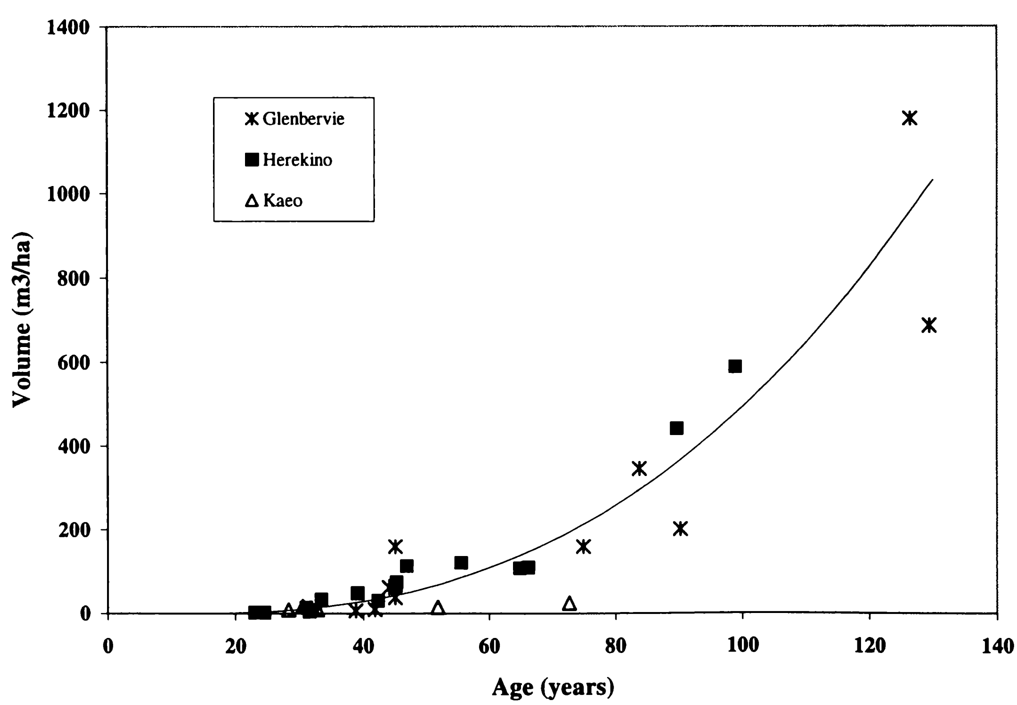


Figure 6.13: Volume/age curve for the largest 1000 totara stems ha^{-1} for natural stands (R^2 = 0.90). Volume is based on total tree height.

6.4.6 Stem density with age and growth

Stand densities in excess of 60,000 stems ha^{-1} at a mean age around 20 years rapidly decreased to less than 1000 stems ha^{-1} in stands over 100 years old (Table 6.6). The following regression equation representing this pattern was derived for stem density (N) with age (T) for all stems ha^{-1} (Figure 6.14):

$$N = \exp(17.84 - 2.36 \times \ln(T)), \qquad R^2 = 0.79 \quad n = 32$$

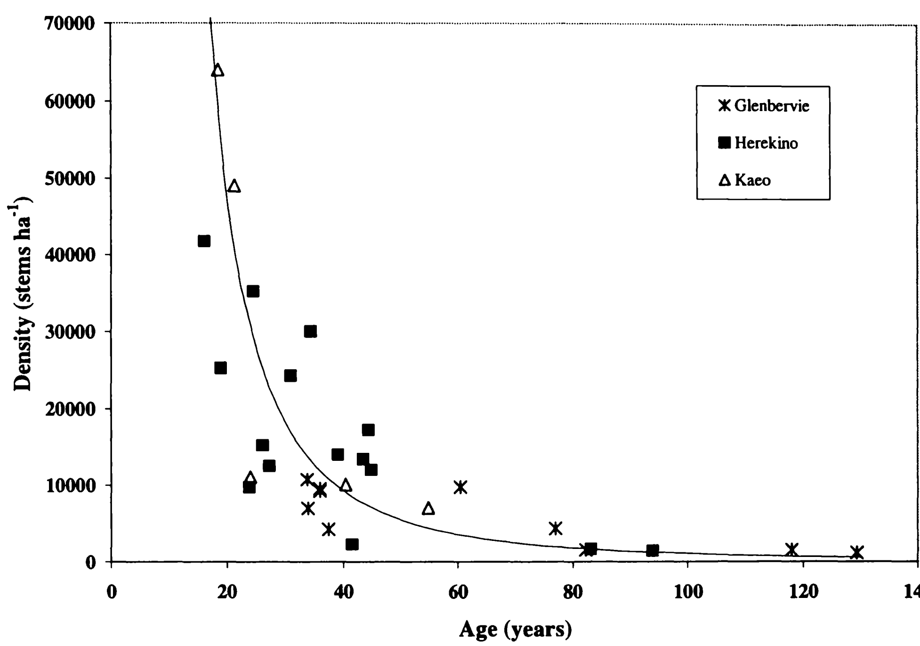


Figure 6.14: Relationship between stem density and age of natural stands of totara (R^2 = 0.79).

The following regression equations were derived for DBH (D) with density (N) for all stems ha^{-1} (Figure 6.15) and for BA x height (H) with density (Figure 6.16):

$$\ln(N) = 12.70 - 1.62 \ln(D), \qquad R^2 = 0.85 \quad n = 32$$

$$\ln(BA \times H) = 19.87 - 1.45 \ln(N), \quad R^2 = 0.86 \quad n = 32$$

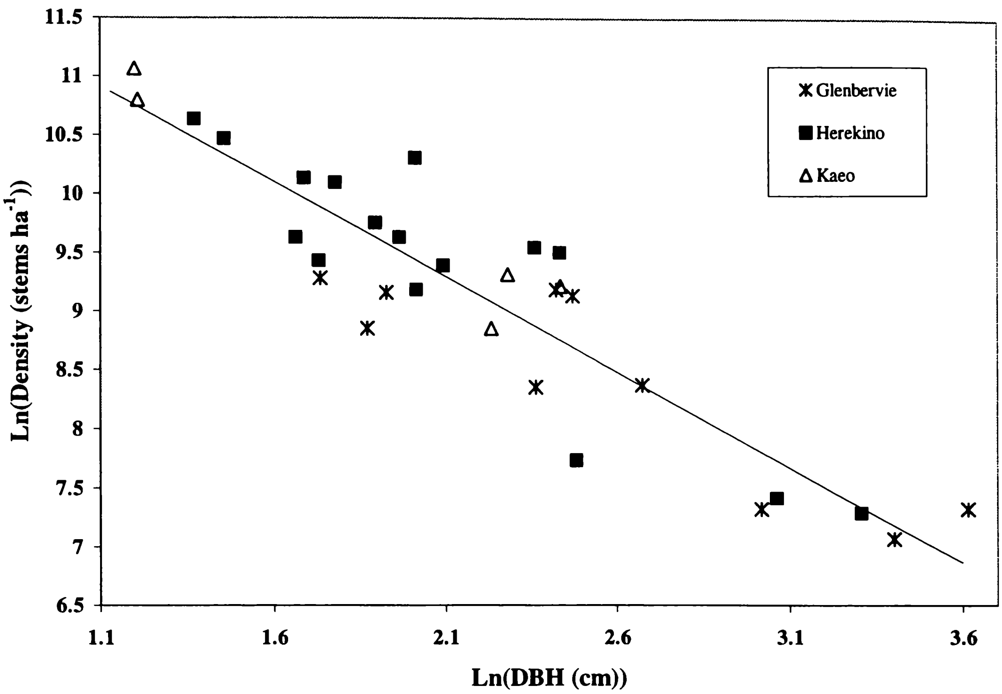


Figure 6.15: Relationship between stem density and mean DBH for all stems and all species in totara-dominated naturally regenerating stands (R^2 = 0.85).

Here BA is the mean individual basal area for each tree. The product of BA and mean canopy height is an estimate of plant biomass and decreased with increased stem density (Figure 6.16).

6.4.7 Population size structure

Examples of population size structures for stands representing three different estimated mean stand ages are given in Figure 6.17. The 21-year-old LANE2 stand shows the strongly positively skewed (skewness coefficient = 1.98), reverse-J distribution expected in a young stand dominated by small stems. A largely uni-modal diameter distribution is evident in the mid-aged DONE4 stand (skewness coefficient = 0.45). This suggests that the plot contains a single cohort of roughly even age. In contrast, the older MACK1, shows a multi-modal diameter distribution indicating that more than one cohort exists in this stand.

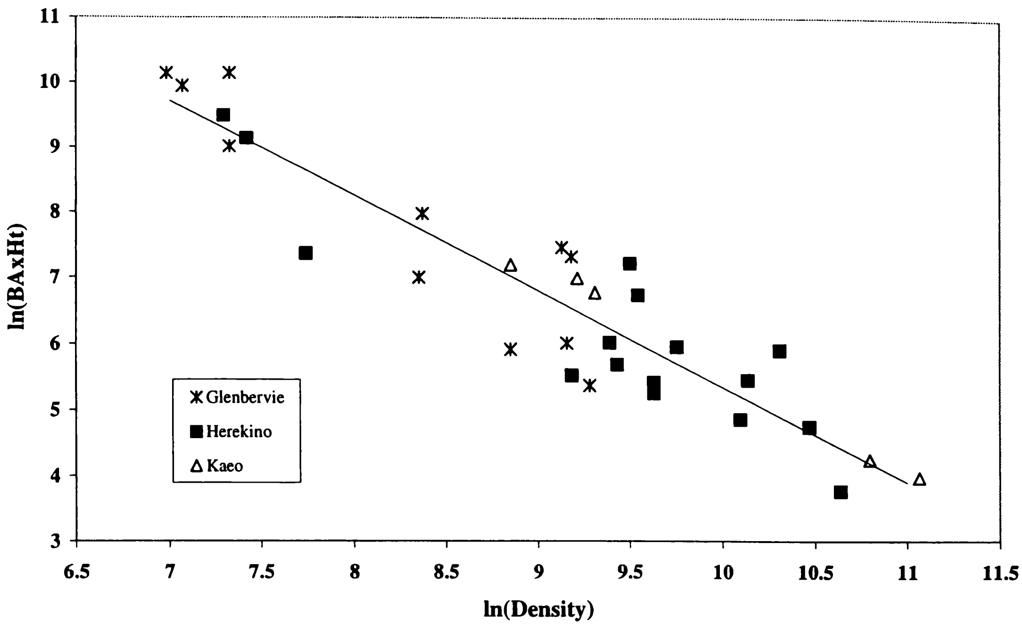


Figure 6.16: Relationship between stem density and mean BA x height for all stems and all species in naturally regenerating totara-dominated stands (R^2 = 0.86).

6.5 DISCUSSION

6.5.1 Aging of stands

Estimated ages within plots of naturally regenerated totara-dominant stands in Northland differ from as little as 12 years in younger stands and as much as 105 years in older stands (Table 6.3). This prompts the question as to whether these stands are in fact even-aged or whether they contain two or more cohorts of regeneration. Despite the wide range in ages, tree size (DBH and RCD) is significantly correlated with mean stand age (Figure 6.8 and Figure 6.9). Ogden (1985) cautions the use of an age:diameter relationship where a large error variance from a small sample of inaccurately aged trees may be masking different cohorts of regeneration. He cites several examples of relatively even-aged stands where tree ages and diameter are not closely related (e.g., Herbert 1980; Ogden 1983), but these are from stands where trees are several centuries old. Ogden (1985) suggests that a stand can be regarded as even-aged if most of the individuals in it fall within an age range of less than ten percent of the normally attainable age, defined as the age at which the dominant trees in a stand tend to die. As the longevity of totara is at least 600 years (Ebbett 1992), the relatively young Northland stands can, therefore, be regarded as relatively even-aged. In comparison, kahikatea remnants on farmland in the Waikato were composed of two distinct cohorts: a majority of stems aged between 80-120 years old and a few larger stems much older at 200-500 years (Burns *et al.* 1999). Observations of other stands during the Northland study indicates that there are totara-dominant stands with large differences in stem diameter that are likely to have different cohorts, similar to the kahikatea remnants.

The pattern of regeneration described in Chapter 5 indicates that seedlings of totara germinate and advance into saplings in small clusters scattered over steep slopes between animal tracks. These clusters provide protection for further germinated seedlings as they increase in size until eventually the groups of saplings and seedlings coalesce to form a closed canopy as seen in the youngest stands here. Consequently, the range of ages found in the developing totara-dominant stands reflects this continuum of regeneration, and may be a decade or more in younger stands and several decades in older stands. The time taken for canopy closure will depend on a range of factors including a local seed source that is being effectively dispersed by birds, intensity of grazing and other farm management practices. Alternatively, gaps may have been created where a previous cover that included manuka and gorse has died out leaving gaps to allow in-filling by further recruitment of totara, thus also giving a wide range of ages.

6.5.2 Improving age estimates

Variability in ages could be due to inaccurate reading of growth rings as described in Chapter 4 which indicates that small, suppressed trees tend to produce underestimates of age, while better estimates are gained from trees growing at about the average growth rate. As a wide range of different sized trees was sampled for aging the natural stands, under-estimated ages from small trees are likely to be contributing to the large apparent variation in ages obtained, especially in older stands. Choice of the largest 1000 stems of totara ha^{-1} for most of the analysis of stands has eliminated many of these suppressed trees, thus decreasing age variability within plots and given a more accurate basis for comparison of stand ages. Using age of oldest trees to estimate stand age, as is often done in age studies (e.g., Tyrrell and Crow 1994), was considered to give less accurate stand age estimates as full site occupancy has usually taken several years or decades. Where older stands appear to have bimodal population structures such as for MACK1 (Figure 6.17), mean estimates of stand age based on the largest 1000 stems ha^{-1} would capture the larger stems, providing further evidence that this method of aging is likely to be more accurate than including all stems.

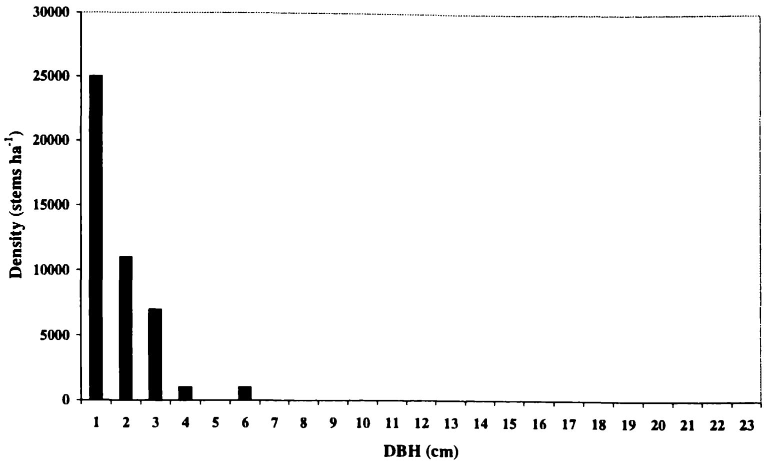
While Ogden (1985) accepts as reasonable the assumption that rings are annual, he reviews several problems in determining age of trees from growth rings. With regard to totara, most of the solutions to these problems were addressed in Chapter 4, and refinements to ring counting using increment cores were used to improve age estimates of natural stands in this chapter. This included selecting only cores with distinct rings, making adjustments to the growth record for cores missing tree centres and making allowances for time taken for seedlings to reach cored height.

6.5.3 Succession and population structure

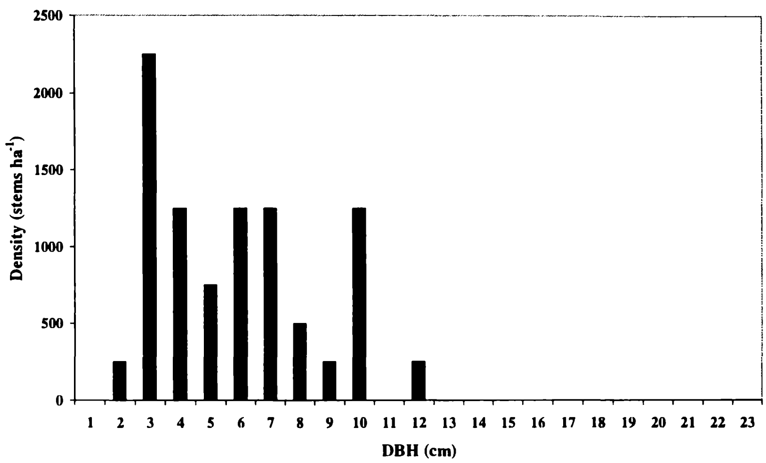
Although larger differences in the ages of stems within older stands indicate that some recruitment has occurred over several decades since the first trees established, it could only have happened where there were canopy gaps existed to allow effective development of the light-demanding totara seedlings. The occurrence of kanuka, manuka and gorse with totara on many sites in varying proportions is dependent on the successional process at each site determined by such factors as degree of grazing, farm management practices such as fertilising regimes and stocking of sheep and cattle, as well as seed source. This vegetation pattern is widespread in secondary successional vegetation in New Zealand where the diversity and pattern of indigenous and adventive species invading pasture is compounded by the varying success of attempts to destroy them through fire, herbicides and grazing (Wardle 1991).

Table 6.6: Stand density, basal area and volume for natural totara stands. Plots are arranged from youngest to oldest age estimates.

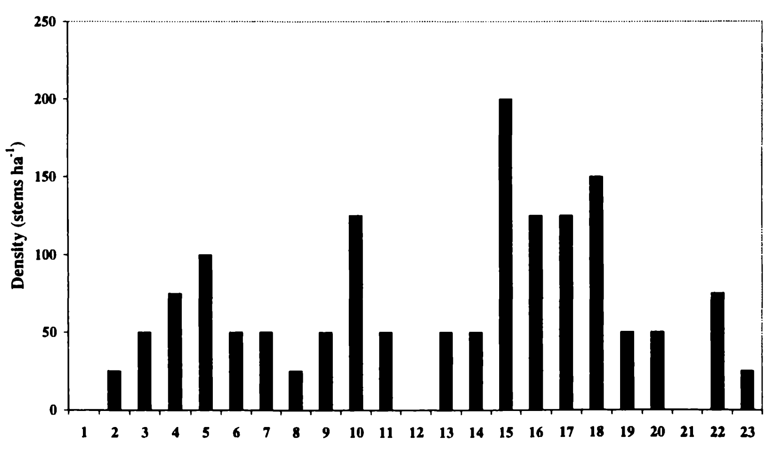
Plot	Mean age for all totara (years)	Stand density (stems ha^{-1})	Density of totara (stems ha^{-1})	BA of all stems (m^2ha^{-1})	BA of totara (m^2ha^{-1})	Total stem volume of totara (m^3ha^{-1})
MACK6	16	41750	33000	28.1	3.5	5.3
LANE1	19	64000	58000	44.8	36.8	77.1
MACK5	19	25250	21500	50.0	4.6	8.3
LANE2	21	49000	47000	39.5	39.3	98.8
MACK3	24	9750	4750	22.0	1.2	3.7
QUIN1	24	11082	6879	83.3	37.0	134.3
MACK7	25	35250	33750	38.7	35.8	125.1
MACK4	26	15250	3000	24.9	2.6	7.2
OWEN2	26	15250	3250	33.3	5.8	17.3
OWEN1	27	12500	3500	31.2	10.5	37.0
COOP1	31	24250	18250	31.6	26.5	79.9
BRID3	34	7000	2750	23.1	2.7	6.3
BRID4	34	10750	4000	25.2	4.7	11.0
COOP2	34	30000	21000	131.2	88.8	249.4
DONE3	36	9500	9500	35.1	35.1	109.9
DONE4	36	9250	9250	101.4	101.4	511.1
DONE2	37	4250	4250	37.6	37.6	120.0
COOP3	39	14000	9000	122.9	96.1	345.4
QUIN2	40	10064	6369	102.7	29.0	94.4
COOP4	41	2293	2293	25.7	25.7	114.7
COOP7	43	13428	12367	136.4	121.9	536.5
MACK9	44	17250	12250	51.9	38.6	167.0
MACK8	45	12000	11000	42.5	39.4	163.0
LANE3	55	7006	5860	47.8	38.1	217.7
DONE1	60	9750	9750	97.2	97.2	468.0
BRID2	77	4331	3566	71.5	60.2	337.4
DONE6	82	1520	1078	49.9	44.3	348.5
MACK2	83	1667	1544	59.8	57.4	466.5
MACK1	94	1471	1348	86.4	86.0	624.5
DONE5	118	1520	1520	165.0	165.0	1284.5
BRID1	129	1176	735	83.8	73.0	685.5
REED1	140	1078	882	80.2	74.2	788.8



LANE2 – 21-years-old



DONE4 – 36-years-old



MACK1 – 94-years-old.

Figure 6.17: Examples of population size structure showing density of stems in 1 cm DBH size classes for three totara-dominant natural stands representing different estimated mean stand ages.

In young stands, manuka, kanuka, gorse and totara have established together at several sites and are likely to be contributing to the range of ages and stem sizes of totara that is often apparent. Where totara has established in mixture with these species during the initial stages of pasture reversion, gaps created by short-lived manuka and gorse are likely to be in-filled by later recruitment of totara. Other studies have shown that manuka (Bergin *et al.* 1995) and gorse (Lee *et al.* 1986) will live for about 20-30 years before senescence leads to opening of the canopy allowing light levels to increase at lower tiers and giving opportunities for recruitment of other species. In the Northland stands, as manuka and gorse die out, totara seedlings which are often present in large numbers rapidly grow to fill canopy gaps. The continued presence of grazing prevents establishment of palatable indigenous hardwood trees and shrubs. Of the indigenous conifers, totara and kahikatea have the fastest height growth responses to increased light and, therefore, the greatest ability to respond to large canopy openings (Ebbett and Ogden 1998). As viable seed of totara can be produced within 10 years (Chapter 3), these earliest recruited trees have the potential to enhance the local seed supply after a about a decade.

With the totara-dominant stands in Northland, short-stature species such as manuka and gorse eventually become suppressed as totara increases in height and begins to dominate the canopy. Older plots show that the longer-lived and taller growing kanuka can remain a significant component of the canopy on some sites for several decades, consistent with other succession studies where both manuka and kanuka is present (e.g., Burrell 1965; Esler and Astridge 1974). In the oldest Northland stands around 100 years of age, there was often large kanuka present in the canopy but most were unthrifty. Occasional dead stems of kanuka in these stands indicated that this species was more prevalent in earlier years.

6.5.4 Influence of animals

As with the establishment phase covered in Chapter 5, the presence of grazing stock during the development of these stands appears to have little adverse effect on totara, and continued presence of grazing stock will prevent regeneration of palatable species. Unlike establishment of other native tree species and of exotic forestry on farmland, developing stands of totara on these sites do not need to be fenced.

The older Northland stands invariably become monocultures of totara where the continued presence of sheep and cattle prevent regeneration and development of palatable species. Esler and Astridge (1974) also found a lack of palatable species, particularly large-leaved shrubs, in regenerating manuka and kanuka stands in the Waitakere Ranges where cattle were present. Observations of permanently fenced stands indicated species diversity was considerably greater with a large number of broadleaved shrub and tree species are present in all tiers under a totara canopy, including hardwood trees such as puriri, taraire and kohekohe, species which are considered to be relatively shade-tolerant (Wardle 1991).

Gut analysis of the small sample of possums recovered from one of the study sites in Northland shows that totara foliage is being eaten by possums. However, more intensive study of the effect of possum browsing on growth and seed production of totara would be required to determine if impacts are significant. However, previous diet studies in podocarp forests indicate that possums could have major impacts on growth of totara including the closely related Hall's totara. In a study of deer (*Cervus* spp.) and possum diets and impacts in podocarp-hardwood forest at Pureora Forest Park, Nugent *et al.* (1997) found that possums relied heavily on fruits in good seasons but crops sometimes failed and Hall's totara foliage was their main food. Many large trees were reported to be dead or dying. Deer or possums did not eat Hall's totara regeneration. Rimu was also not eaten and there was little browsing of the other conifers, matai, miro and tanekaha. Mason (1958), in an intensive study of possum stomach contents and field observations of damage to plants in the Orongorongo Valley, Wellington, found that totara leaves were eaten by possums and trees were sometimes severely damaged. Possums also consumed the fruits and seed of totara.

6.5.5 Growth rates

The mean annual diameter increment of 3 mm across all natural stands assessed in this study was considerably less than many plantations assessed in Chapter 8 where MAI of DBH can be up to 10 mm, similarly to reported growth rates of planted totara stands by Pardy *et al.* (1992). Annual height increments of natural stands (15-25 cm per year) were also significantly less than planted totara stands of 24-38 cm per year (Pardy *et al.* 1992) and over 40 cm for plantations assessed in Chapter 8. BA (Figure 6.12) and volume (Figure 6.13) of natural stands were significantly less than similar-aged planted stands (Chapter 8). At 60 years of age, natural stands averaged a basal area of 22 m^2ha^{-1} compared with 70 m^2ha^{-1} for planted stands. At the same age, natural stands had only attained about a quarter of the 470 m^3ha^{-1} stem volume found in planted stands. The relatively slow growth of the naturally regenerating stands represents the poor site quality these stands establish on, as well as the effects of high densities.

Older natural kahikatea stands in the Waikato have generally faster diameter growth rates of 3-8 mm per year (Burns *et al.* 1999) compared with regenerating totara stands in Northland. However, BA of these kahikatea stands ranging from 50 to nearly 120 m^2ha^{-1} is similar to many of the older, naturally established totara stands in Northland (Table 6.6). The older stands on these Northland farm sites have densities in excess of 1000 stems ha^{-1} and are similar to stem densities found in kahikatea remnants in the Waikato ranging from 700-1600 stems ha^{-1} (Burns *et al.* 1999).

6.5.6 Stand density and natural thinning

The rapid decline in stem density with age for natural stands follows an expected trend of decreasing mean stem density with increasing age from over 60,000 stems at around age 20 years to less than 1000 stems by age 80 years (Figure 6.14). Intraspecific competition in early years causes death of the smallest individuals, reducing plant density. Stands from all three sample areas in Northland exhibit this trend of 'self-thinning'. The slow growth rates reported for these stands are largely due to the intense within-stand competition where, even at 50 years of age, plant density is still around 5000 stems ha^{-1}. The variability around the regression line, particularly for stands less than 40 years, is probably due to the wide variation in tree age and size that is evident in most plots where regeneration has occurred over several years or decades.

The relationship between logs of stocking and average plant mass (BA x height) given in Figure 6.16 for the totara-dominant stands has a slope close to the theoretical -3/2 thinning line widely reported for many tree species (White 1985). Yoda *et al.* (1963) observed a general relationship between plant mass and stand density with successive measurements of a stand undergoing self-thinning. They found that when the logarithm of average plant mass is plotted against the logarithm of density, the points form a straight 'self-thinning line'. The slope of this line is near -3/2 and has become a well-known ecological rule or law governing even-aged plant populations (Weller 1987). The application of this law has been widespread in studies of mono-specific stands for a wide range of plant types and growth forms. Sample plots at all three Northland sites are scattered along the line with no stands showing major deviation. It is apparent that sampled stands covering the wide range of ages from 16 to over 100 years are undergoing similarly intense within-stand competition.

Most studies demonstrating adherence to the '-3/2 thinning law' have been with single-species communities. However, there have been some studies demonstrating that mixed-species stands also adhere to the –3/2 thinning rule. Wilson and Lee (1988), investigating whether the self-thinning line was applicable to scrub communities, found that where all species, including dead stems, were included in size/density data from gorse-dominated communities ranging from pioneer to senescent stands around Dunedin, the fitted slope is close to the theoretical -3/2 line. Similarly, Bergin *et al.* (1995) found the relationship between stand density and basal area of mixed manuka/kanuka stands less than 30-years-old on the East Coast of the North Island formed a linear band of points close to the theoretical thinning line. In the Northland study, most stands less than 45-years-old were mixed-species communities with up to 80% of stem density comprising species other than totara (Table 6.6). A reasonable fit of these young mixed-species stands to the -3/2 law adds to the New Zealand-based scrub community studies, as well as to the small number of studies elsewhere (e.g., White 1985), providing further evidence that it can be applied to regenerating mixed-species stands.

6.5.7 Development of natural stands

A pictorial representation of a selection of stands shows the development of naturally regenerated totara-dominant stands assessed in this study. As indicated previously, a wide range of ages can be represented in each stand as invasion has been over several years if not decades. Mean stand age is, therefore, only a guide to determining age of each stand in relation to tree growth and form relative to other stands. Mixtures of early successional species as well as differences in site and management histories are reflected in the large variation in developmental stages and growth rates. Stem form and branching characteristics are assessed for these stands in greater detail in Chapter 9. The selected stages are:

- ***Dense sapling thicket*** - Regeneration amongst grass on steep hill slopes develops into small stands of saplings within 20 years where they are not grazed heavily or cleared regularly by landowners. Stem density in the LANE1 plot exceeds 60,000 stems ha^{-1} dominated by totara with a mean height of 2.6 m and DBH 3.3 cm (Figure 6.18).

- ***Mixed-species stand*** - Where totara has regenerated in the presence of other species which may have acted as a nurse or developed at the same time, density of totara is considerably less. Of the 15,000 stems ha^{-1} for all species in the OWEN2 plot, only one-fifth of the stems are totara. Estimated mean stand age is 26 years with mean height of 5.7 m and DBH of 5.3 cm.

- ***Older sapling stands*** - Developing stands of saplings are sometimes multi-stemmed with lower branches retained for several decades. Intense competition continues as saplings increase in height and diameter. Multi-leadered stems and retention of branches is evident with the 36-year-old DONE3 stand currently just under 10,000 stems ha^{-1} (Figure 6.19). Lower branches are beginning to die back as light levels reduce and intensive self-thinning takes place.

Figure 6.18: Regeneration amongst grass on steep hill slopes can develop into thickets of small saplings within 20 years on suitable sites. Stem density in the interior of this 19-year-old stand at Kaeo (LANE1) exceeds 60,000 stems ha^{-1} and is almost totally dominated by totara. Mean stand height is 2.6 m and DBH is 3.3 cm. Infilling of gaps around the edge of the stand is continuing making age estimates of such stands difficult.

- ***Pole stand*** **-** Within 60 years, a pole stand develops where intense competition has reduced stocking and stem form has improved markedly. Lower branches have died and broken off as seen in the DONE1 stand (Figure 6.20). Density is almost 10,000 stems ha^{-1} with a mean stand height of about 10 m and mean DBH of 11.3 cm. Evidence of higher earlier stocking can be seen in the numerous dead stems lying on the ground throughout this stand.

- ***Semi-mature stand*** – The final stage in this sequence is the development of trees where stocking has reduced to around 1000 stems ha^{-1} or less such as in the BRID1 stand (Figure 6.21). Mean stand age is estimated at 129 years with mean height exceeding 20 m and mean DBH over 30 cm. Boles exceeding 6 m high are free from branching. Dead standing and fallen stems indicate this stand was at much higher stocking previously.

Figure 6.19: A 36-year-old sapling stand at Glenbervie (DONE3) at a density of nearly 10,000 stems ha^{-1} has an average stand height of 5.4 m and mean DBH of 6.9 cm. Edge trees have been cut away to expose interior trees showing retention of branches to near ground level. Low light levels below the canopy have resulted in death of branches and with stock movement, brittle rotting branches are easily broken off lower stems. However, this site has been fenced within the last 5 years for planting of pines.

6.5.8 Implications for management

There are various implications for the management of natural stands as a long-term wood resource where stem density is high and growth is relatively slow. Intraspecific thinning within the naturally regenerating stands of totara, consistent with the –3/2 thinning model, is one of the most important processes occurring in stand development. Manipulative thinning to pre-empt intense competition and reduced growth rates as stands approach the theoretical thinning line is a practical management tool required for these natural stands.

Figure 6.20: It is likely this 60 year old naturally regenerated pole stand of totara at Glenbervie (DONE1), started as a dense, almost pure stand of totara as shown in Figures 6.18 and 6.19. Intensive competition has resulted in self-thinning to a density of 9750 stems ha^{-1}. Lower branches have died and rotted to leave clear stems up to 6 m high on many residual trees. Canopy height is 11.4 m and average diameter of the largest 1000 totara stems ha^{-1} is just under 20 cm. Evidence of higher density can be seen in the numerous dead stems lying on the ground throughout this stand.

The timing and intensity of thinning operations has a number of implications, including resources available to undertake management, increased lower branch development and ground vegetation due to opening of the canopy, and potential risks to stand stability. Intensive tending from an early age is likely to be impractical where stem densities are over 30,000 stems ha^{-1} for 20 year-old-stands (Figure 6.14), other than on a small scale. Stands double that age may still have 10,000 stems ha^{-1}. Several thinning operations rather than a single thinning will be required during the first few decades to incrementally reduce stand density to promote good stem form and stand stability.

Figure 6.21: The final stage in this sequence is the development of a semi-mature stand of trees where density has reduced to around 1000 stems ha^{-1} or less such as for the BRID1 stand at the Glenbervie study site. Mean stand age is estimated at 125 years. Height and DBH are 20.5 m and 30.1 cm respectively. Many trees have branch-free boles exceeding 6 m high. Numerous fallen smaller totara stems indicate this stand was at a much higher density previously. Dead standing and unthrifty trees are evidence that natural thinning is continuing.

An alternative to early intervention is to begin thinning when stands have reached pole stage (DBH 10-12 cm) which may take up to 50 years to occur. By then, stem densities have reduced to below 10,000 stems ha^{-1} (Figure 6.14). Such stands are easily accessible as lower branches have long since rotted or broken off to leave clear stems and many of the poor form trees have died naturally. Selection of good form crop trees is easily carried out and felling of unwanted trees that invariably have small crowns is accomplished without undue damage to the target crop element.

Based on the natural stands in Northland, the regression equation for stem density and DBH (Figure 6.15) at density of 800 stems ha^{-1} will give a stand mean DBH of 41 cm. The age and DBH regression equation (Figure 6.8) indicates that this would take 128 years. This growth rate, equating to a mean annual DBH increment of 3 mm, is slow compared with growth rates reported for planted stands established at considerably lower stem densities than those found in natural stands (Pardy *et al.* 1992). However, it is difficult to compare growth rates between plantations which are often planted on good fertile lowland sites with natural stands that have regenerated on exposed steep hill slopes with less soil development. Nevertheless, gains in growth rates are likely from thinning dense natural stands, particularly from an early age.

Trials are required to determine optimum timing and intensity of thinning operations, including pruning, which can be applied to natural totara stands on hill country of different stand ages. The aim is to provide landowners and managers with practical management options for improving stand productivity, tree form and wood quality. ***Forest Research*** has recently installed the first of a series of thinning trials in a dense pole stand on a Northland farm where several thinning treatments have been imposed in small blocks with Permanent Sample Plots established in each treatment (Figure 6.22). The mean age of the stand has been estimated to be around 40 years. Thinning treatments include stand densities of 1600, 1200 and 800 stems ha^{-1} as well as an unthinned control at 2500 stems ha^{-1}. Trees were pruned to at least 6 m and double leaders where they occurred were reduced to a single leader. The trial will be monitored in the long term for stand stability and growth response in the residual tree crop to the various thinning regimes. Further thinning trials in younger sapling stands are planned.

6.6 CONCLUSIONS

This is the first comprehensive study of the development of naturally regenerated totara-dominant stands in pasture covering a range of ages. Although there are difficulties in aging stands, particularly where trees have regenerated over several years or decades, age estimates of the largest 1000 stems ha^{-1} have given reasonable stand age estimates. Relatively slow growth rates of natural stands compared with plantations indicate the generally more difficult sites and although thinning is likely to increase growth, it is unlikely to match growth rates of planted stands on better sites.

Figure 6.22: The first of several proposed thinning trials in different aged stands of naturally regenerating totara in Northland was established at Herekino. The trial comprised separate thinned blocks with densities of 1600, 1200, and 800 stems ha^{-1} including an unthinned control of 2500 stems ha^{-1}. Trees have also been pruned to at least 6 m. Permanent Sample Plots have been established in each treatment block to monitor stand stability and long-term growth responses to thinning.

However, a major advantage in managing these naturally establishing totara stands as a potential long term source of specialty timber is that seedlings do not need to be raised in a nursery, planted out and then maintained for several years. Options available for management of developing natural stands require investigation. They include early intervention, delayed intervention or no intervention at all. Several thinning operations of dense saplings, while labour intensive, will boost early growth rates. If thinning is delayed until stands have reached pole stage, natural thinning will have already reduced stem density saving labour but will have compromised growth. Where there is no intervention, these stands will still continue to develop, albeit slowly, as a potential wood resource for future generations.

CHAPTER 7

EARLY PERFORMANCE OF PLANTED TOTARA COMPARED WITH OTHER INDIGENOUS CONIFERS

7.1 INTRODUCTION

Totara seedlings have been planted on many sites throughout the country for well over a century (Department of Lands 1909; Pardy *et al.* 1992). The establishment phase is the most critical stage in survival and growth of indigenous conifers where newly-planted small seedlings are regarded as slow starters (Beveridge 1977) in comparison with exotic conifers. In early years most species are vulnerable to competition from grass on open sites, and growth of competing ground ferns, tree ferns and shrub hardwood species in scrub and forest sites (Beveridge *et al.* 1985). Many plantings of indigenous conifers have either failed or have suffered poor growth and survival due to wrong site selection and lack of after-planting care and, on some sites, damage by browsing or grazing.

Planting programmes and trials over many years show that indigenous tree species can be established successfully on good sites where planted areas have been released of weeds and fencing maintained. Examples where planted indigenous conifers have established successfully in single- or mixed-species stands occur in many recreation parks and botanical gardens throughout the country, including Mair Park in Whangarei, Cornwall Park in Auckland, Holt's Forest Trust in Hawkes Bay, Pukekura Park in New Plymouth and Hagley Park in Christchurch. Numerous planted groves and small stands of conifers exist on private land and show equally good growth rates and survivals. In addition, a large number of successful planting trials have been established over many years by the Forest Research Institute and former New Zealand Forest Service, documenting a range of growth performances of the major conifer species. This includes large planting programmes of kauri during the 1970s and 1980s, and planting of podocarps in many North Island regions and on the West Coast of the South Island from the 1960s. The objectives for planting are varied and include establishing groves of indigenous trees in domains, parks and gardens for amenity and heritage values, providing seed sources lost in cleared landscapes, enhancing wildlife values, and replacing trees in partially logged forest where natural regeneration may be scarce or slow in developing (Bergin *et al.* 1988; Beveridge 1973; Beveridge *et al.* 1985; Pardy *et al.* 1992).

This chapter firstly outlines the efficacy of raising seedlings of totara for large-scale planting programmes for timber production, comparing it with the other major indigenous conifer tree species. Secondly, it summarises the early performance of establishment trials and general plantings of totara up to an age of 50 years, again with comparison to the performance of the other conifers. Lastly, the early performance of a selection of stands from a range of sites that have good documentation on establishment and management histories are covered in greater detail in order to provide insights into the ecological characteristics of each species with emphasis on totara.

7.2 METHODS

7.2.1 Seed collection and propagation

Information on seed collection, germination and raising of seedlings of the major indigenous conifer species has been reviewed, using both published and unpublished sources, with an emphasis on comparing totara with the other species.

7.2.2 Performance of planted totara

7.2.2.1 General planting

Existing databases from planting trials and management-scale planting programmes were interrogated and summarised to evaluate performance of totara. These were established mainly by the New Zealand Forest Service over the last 50 years with trials established and monitored by the Forest Research Institute. Planted stands established by other agencies were also included, such as the mid-1980s survey of indigenous plantations which covered mainly private and local authority land (Pardy *et al.* 1992). All stands that were known to exist and which had sufficient survival with some history of assessment were included. Growth parameters, stand information and site characteristics were tabulated for each planting trial and general planting. These included stand age, stand type (e.g., plantation, shelterbelt, underplanting, mixed-species stands, amenity and park planting), mean height, and for all but the younger stands, mean DBH (diameter at breast height taken at 1.4 m above ground). Mean annual increments for height and DBH were calculated and the range of growth rates for plantings was included where information was available. Survival figures are based on assessments undertaken during remeasurements or were estimated for the larger stands where clear information was available on original plant spacing. Other information on stand characteristics were briefly described, such as stem density, assessments of tree form, whether trees where dominant, co-dominant or suppressed, and any management history that may be significant for performance.

7.2.2.2 Site index

Site index (height at age 40 years) was estimated for totara covering all planted stands and trials assessed. The site index equation derived in Chapter 8 for planted totara stands was used for this. Site index was then tested against several site factors using ANOVA and LSD (SAS 1990). These site factors were:

- One of three cover categories based on degree of exposure:
    - open - stands established on open sites as plantations or small stands;
    - medium - seedlings planted within existing cover of manuka or forest in gaps or along lines and released initially at least;

  — shade - seedlings planted within forest or scrub under a canopy with little or no subsequent releasing.

- One of four fertility categories (high, medium, low-medium, low) based on broad classes of natural nutrient status of soil types from Soil Bureau (1954) for the North Island and Soil Bureau (1968) for the South Island.
- Altitude of planting sites.
- Region in which planting site occurred.

7.2.3 Comparison with other conifers

7.2.3.1 General planting

Establishment performance and site information was also collated for the other major indigenous conifers. Like totara, three of these species, rimu, kahikatea and kauri have been widely planted in many regions of New Zealand. The other three species are matai, miro and tanekaha.

In-depth statistical analysis proved difficult due to the significant variability in growth responses evident across all species being planted on a wide range of sites and with different histories of management. Site index was estimated for each species using the totara site index equation, as separate site index equations do not exist for the other species. A one-way ANOVA was used to compare site indices for the seven species.

7.2.3.2 Assessment of selected planting trials

An in-depth comparison of growth performances was carried out for a selection of planting trials where more detailed records of planting site, history of management and stand assessments had been made compared with the general database of planted stands. Most of these were planting trials. Sample sizes ranged from 20-200 trees per site. Comparison of different species and site treatments was possible for most trials.

To update some of these databases, several Forest Research Institute planting trials were remeasured from 1998 to 2000 in the Auckland region, the central North Island and the east coast of the North Island. These included plantings of totara, rimu, kahikatea, kauri and matai. All trials were planted from 10-40 years ago on a range of sites, including interplanting podocarps with eucalypts to provide shelter on exposed open sites. Representative samples of at least 20 trees of each species were remeasured, including height and DBH at each trial site. Tree form and stand characteristics were also recorded, including type and degree of any overtopping vegetation and ground cover. Growth and stand information was added to the species summary tables.

7.2.4 Review of the history of planting

A brief review of the history of large-scale planting programmes of indigenous conifers was undertaken over most of the last century. This focuses on planting programmes carried out by the Lands Department and then the New Zealand Forest Service as well as extensive trials established and maintained by the Forest Research Institute.

7.3 RESULTS

7.3.1 Review of seed collection and germination

7.3.1.1 Totara

Totara has annual seed crops that fluctuate in abundance but seed is easily obtained most years (Beveridge 1973). In a nationwide collection of seed for a provenance study on totara, sound seed was generally easier to collect from semi-mature stands on farmland than from mature trees in high forest (Bergin and Ecroyd 1987). These trees had relatively large crowns compared with those on tall mature trees which were often small and storm-damaged, and where possums were probably reducing tree vigour and seed crops. Possums are known to eat foliage, seed and fruit of totara with sometimes considerable damage evident on trees (Mason 1958).

Seed of totara is stored in moist cool conditions without significant loss of viability for at least two years (Forest Research Institute 1980b). Germination is usually successful for most seedlots although it can occur in two phases. The bulk of seedlings emerge in spring within four weeks of sowing followed by a second crop in autumn (Bergin and Ecroyd 1987). Delayed germination has also been reported for totara seed within forest duff collected from beneath seeding trees (Herbert 1976).

7.3.1.2 Comparison with other conifers

In a seven-year study of seed crop periodicity and seed abundance of a selection of conifer trees in high forest at Pureora Forest Park, Beveridge (1973) reported that rimu and kahikatea showed the most marked periodicity. Kahikatea produced the heaviest seed crops, while matai failed to produce good seed crops, largely due to insect attack. On the other hand, totara, and to lesser extent miro, had light but regular seed crops. Other studies show tanekaha has not only irregular seeding but also uneven seed ripening and a high incidence of empty seed. Much of the seed of rimu, matai and miro can be damaged by rodents (Forest Research Institute 1980). As with totara, Mason (1958) found that possums eat miro and matai fruits but not rimu fruit.

Seed of totara and most of the other conifers can be collected from beneath seeding trees during and immediately after seedfall. In contrast, kauri seed is more difficult to obtain as trees have to be climbed to collect cones before they shatter, scattering seed over a wide area (Halkett 1983).

There are no major differences in moist cool storage requirements of totara seed compared with the other conifers (Forest Research Institute 1980b). Dry cool storage is required for long-term storage of kauri seed (Preest 1979).

Similarly, there is generally good germination of rimu, kahikatea and kauri (Forest Research Institute 1980b). Matai and miro are renowned for delayed germination and this has prompted a range of experiments to enhance germination (e.g., Preest 1963) but no significant improvement has been achieved. With Hall's totara, Bergin and Ecroyd (1987) not only had difficulties in collecting significant quantities of seed, but also found high proportions of empty seed, resulting in poor germination of 15 seedlots collected from several regions. Impact of possums consuming Hall's totara seed reported by Nugent *et al.* (1997) may be a factor in reduced seed crops with this species.

7.3.2 Review of propagation

7.3.2.1 Totara

Extensive research and operational propagation programmes over the last 40 years have resulted in sufficient knowledge to allow raising of seedlings of most indigenous conifer tree species in large numbers at reasonable costs. Although at least some native conifer species can be vegetatively propagated from cuttings including totara (T. Faulds pers. comm.) and rimu (Dakin and Mearns 1975), for large-scale production it is cheaper to raise plants from seed (Forest Research Institute 1980b).

Totara seedlings can be raised either in open beds as bare-root stock or in containers (Beveridge *et al.* 1985). Seedlings grow from seed to a planting height of 50-80 cm in 3-5 years in nurseries on cooler upland sites such as at the Forest Research Institute nursery in Rotorua at 300 m a.s.l. (Forest Research Institute 1980b), with reduced times in nurseries on warmer lowland sites. Standard bare-root nursery practice in the 1980s was to broadcast-sow seed in open beds and then line-out seedlings in other beds at 15 cm x 15 cm spacing (van Dorsser and Bergin 1987). Lined-out seedlings were kept under shade cloth for 12 months, and depending on growth, remained in the beds for a further one or two years. Three months before planting in winter or early spring, seedlings underwent a period of root cutting and wrenching to encourage development of a compact fibrous root system and to facilitate lifting. Most of these operations were done with tractor machinery. Totara is among the easiest species to encourage a vigorous fibrous root system. Like most of the podocarps, totara has distinctive short roots that may become mycorrhizal (Baylis *et al.* 1963) where the infection of an endophytic fungus may assist with growth in poor soils.

Most nurseries currently raise seedlings in containers which allows more flexibility in holding stock over from one season to the next and enables seedlings to be planted over a greater range of months. Seed is broadcast onto seed trays and germination takes place within four weeks in a heated glasshouse. Once seedlings are 5-7 cm high, they are pricked individually into containers and transferred to larger containers depending on length of time stock will be grown in the nursery and size of seedlings required. Totara can be grown to height of 50-80 cm in two years in lowland nurseries, forming dense, fibrous root systems similar to those of well-conditioned open-grown seedlings.

Other methods for raising the conifers are from seed contained in forest humus and the transplanting of small seedlings, known as wildings, which are lifted directly from appropriate forest sites and then grown-on in the nursery. In a detailed account of raising seedlings from seed contained in forest duff raked from the ground on several sites, including a forest-shrubland ecotone, pole stands and individual trees at Pureora Forest, Herbert (1976) found good germination of totara. Beveridge (1962) showed that totara seedlings could be raised successfully from 5-25 cm high seedlings transplanted from disturbed sites at the forest edge to nursery beds.

7.3.2.2 Comparison with other conifers

As for totara, all the conifer seedlings can be raised either in open beds as bare-root stock or in containers (Beveridge *et al.* 1985). Kauri, in particular, has a tendency to form woody, vertically descending tap roots with a feeble network of fibrous feeding roots compared with the mass of fibrous roots of totara. The root systems of the major podocarp species are shown in Figure 7.1. These three-year-old seedlings were raised in open beds at the Forest Research Institute nursery during the mid-1980s.

Both the forest humus and wilding methods are particularly useful for producing seedlings of matai, miro and tanekaha which are slow to germinate from freshly collected seed. It is also worth considering for species that have irregular seed crops such as rimu. Large quantities of rimu seedlings can often be found under seeding trees along roadsides and similarly disturbed sites where the right combination of shelter and site disturbance favours germination and early growth. In general, however, for most of the indigenous conifers, collection of wildlings is labour-intensive for large-scale operations compared with raising seedlings from seed.

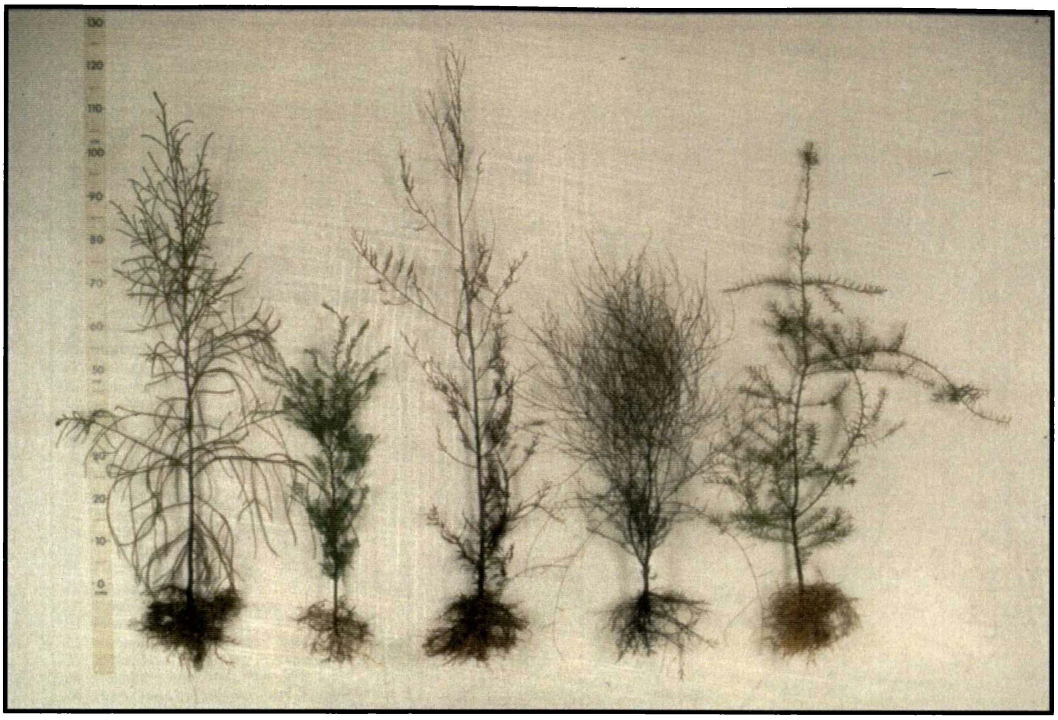


Figure 7.1: Bare-root 4-year-old seedlings of the five major podocarp species raised in open beds at the *Forest Research* Nursery. Species from left to right are: rimu, miro, kahikatea, matai, totara.

7.3.3 General performance of planted stands

7.3.3.1 Totara

The survival, growth performances, and stand and site characteristics of all planted stands of totara evaluated are given in Appendix 7.1. Most stands are located in the North Island (Figure 7.2). Survival and growth figures were available for only some stands, and mean DBH for all but the youngest stands. Mean height is given for all stands. Major differences in sites types and management after planting are evident from stand records as well as field inspections of some sites.

Survival of totara is often high, although it tends to decrease with increasing stand age. Most stands, particularly those that had been well maintained, had survivals in excess of 80% twenty years after planting.

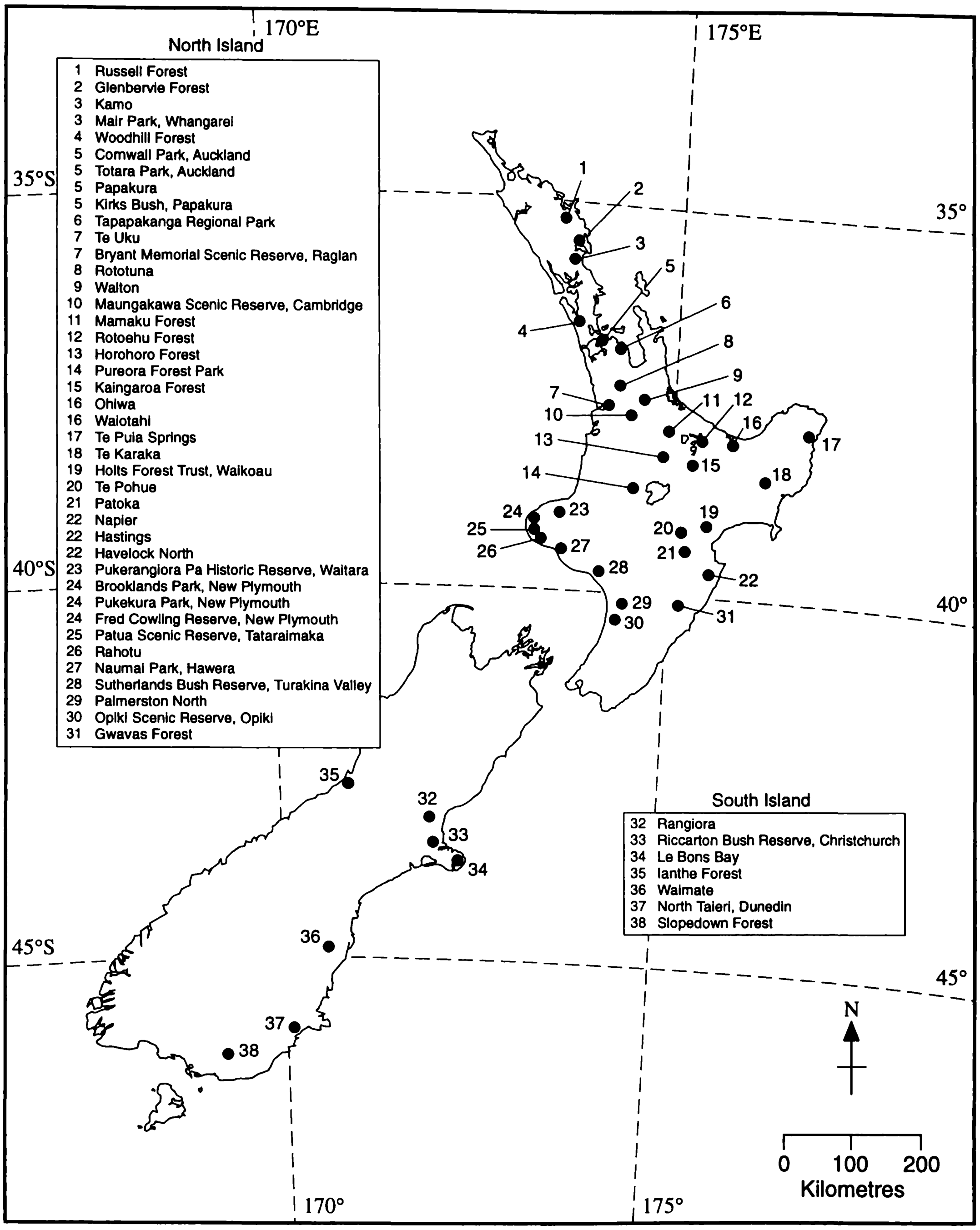


Figure 7.2: Location of planted stands, planting trials and amenity and shelterbelts of indigenous conifer tree species for which early performance data has been collated.

Despite the variability of the data, there are significant trends in growth of totara with faster height growth evident on open sites compared with the shaded sites (Table 7.1). Planted totara on open sites are estimated to have a higher site index of 12 m similar to totara planted in lines or gaps within forest or scrub cover. Both these cover categories are significantly higher than seedlings planted under heavy shade (Figure 7.3). There is also a significant difference in estimated site index of totara between the high and low fertility categories (Table 7.2). However, results for medium and low-medium fertility sites suggests shortcomings in using broad soil fertility categories (Figure 7.4).

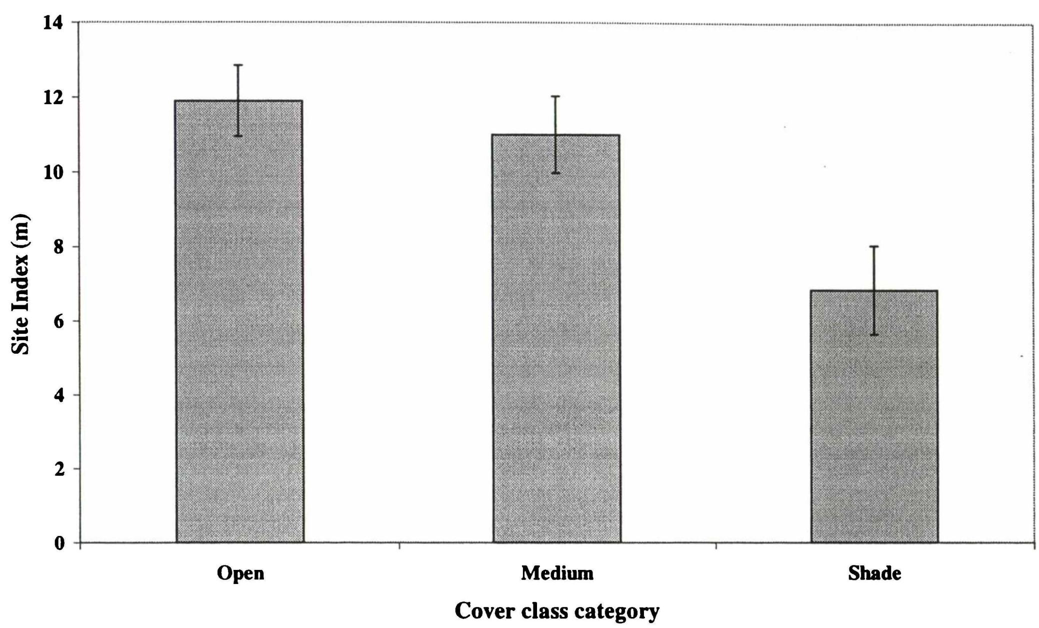


Figure 7.3: Estimated site index (height at age 40 years) for planted totara stands located throughout the country by cover class category. Error bars indicate standard errors.

7.3.3.2 Comparison with other conifers

The survival, growth performances, and stand and site characteristics of the six major indigenous conifer tree species rimu, kahikatea, kauri, tanekaha, matai, and miro are given separately in Appendices 7.2-7.7. As for totara, planted stands are located throughout the country with the bulk of stands in the North Island (Figure 7.2). For rimu, kahikatea and kauri, there is generally a good spread of ages for each species from planted stands under 10 years up to 50 years. The variable performance of all species reflects differences in site types and management histories of stands after planting.

Table 7.1: Estimated site index (height at age 40 years) for planted totara stands located throughout the country by cover class category. Site index values followed by the same letter are not significantly different ($p = 0.05$). Test for cover category differences, $F_{2,45} = 12.91$, $p < 0.0001$.

Cover category*	Number of trials	Site Index (m)	Standard error
Open	21	11.9 a	0.95
Medium	15	10.9 a	1.04
Shade	15	6.8 b	1.20

* Cover category: Open = stands established on open sites as plantations or small stands; Medium = seedlings planted within existing cover of manuka or forest in gaps or along lines and released initially at least; Shade = seedlings planted within forest or scrub under a canopy with little or no subsequent releasing

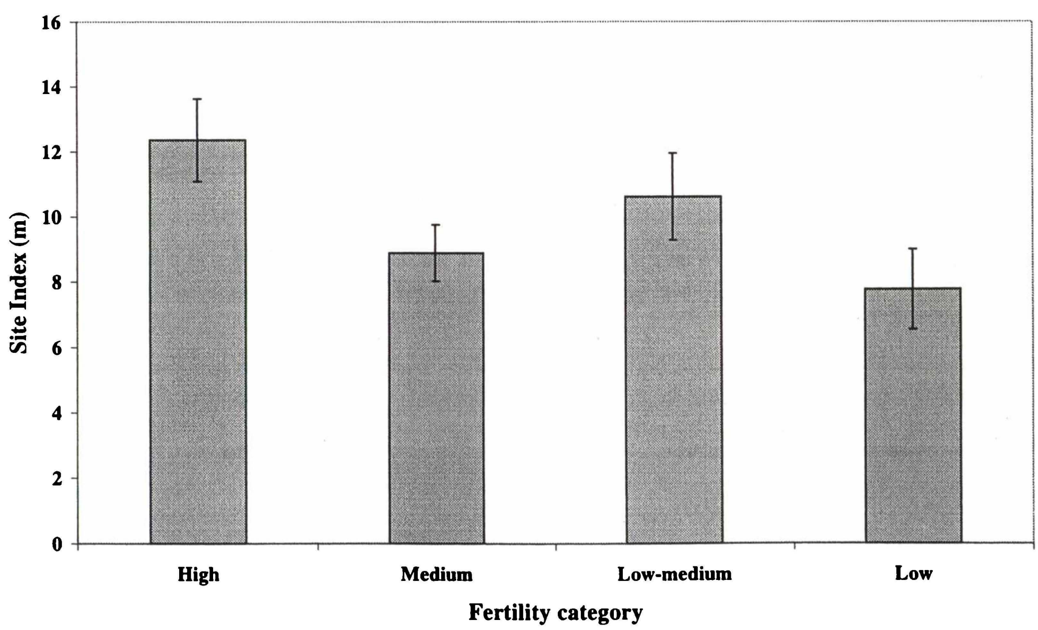


Figure 7.4: Estimated site index (height at age 40 years) for planted totara stands located throughout the country by fertility category for each site based on soil descriptions from Soil Bureau (1954) for the North Island and Soil Bureau (1968) for the South Island. Error bars indicate standard errors.

Table 7.2: Estimated site index (height at age 40 years) for planted totara stands located throughout the country by fertility category for each site based on soil descriptions from Soil Bureau (1954) for the North Island and Soil Bureau (1968) for the South Island. Site index values followed by the same letter are not significantly different ($p = 0.05$). Test for fertility category differences, $F_{3,45} = 3.76$, $p = 0.017$.

Fertility category	Number of trials	Site Index (m)	Standard error
High	9	12.3 a	1.27
Medium	17	8.9 b	0.87
Low-medium	12	10.6 ab	1.33
Low	13	7.8 b	1.23

For the three major podocarps, totara, rimu and kahikatea, average survival and growth rate are similar across all stands assessed (Table 7.3). Mean survival is 48-59%, mean annual DBH increment is 5-6 mm and mean annual height increment is 26-30 cm. Kauri has performed the best of all species at 85% survival, and MAI in DBH of 6.6 mm and MAI in height of 37 cm, reflecting the better sites that kauri was often planted on, often within recreational parks mostly located in lowland North Island regions.

Table 7.3: Average survival and mean annual DBH and height increments for all stands assessed for the indigenous conifer species.

Species	Number of trials	Survival (%)	MAI DBH (cm)	MAI Height (m)
Totara	51	59	6.0	26.1
Rimu	39	54	4.8	25.7
Kahikatea	39	48	5.0	29.6
Kauri	36	85	6.6	37.0
Tanekaha	23	62	3.8	21.2
Matai	9	46	3.4	14.6
Miro	5	-	4.7	24.4

Survival of rimu, kahikatea and kauri was often high, comparable to totara. The podocarps, totara, rimu and kahikatea in particular, show remarkable persistence on poor sites although with extremely slow growth rates. This was evident at Woodhill where mean annual DBH increments of 1-2 mm were recorded for the 50-80% of surviving seedlings 26 years after planting on this sandy, drought-prone site.

Estimated site index comparing the seven conifer species shows that kauri, at 14 m, is significantly higher than all other species (Figure 7.5). There is no significant difference in height of kahikatea, rimu and totara. Small sample sizes of miro and matai are reflected in the larger standard errors for these species (Table 7.4).

Table 7.4: Estimated site index (height at age 40 years) for the indigenous conifer tree species based on all stands located throughout the country. Within each column, values followed by the same letter are not significantly different ($p = 0.05$). Test for cover category differences, $F_{6,186} = 6.02$, $p < 0.0001$.

Species	Number of trials	Site Index (m)	Standard error
Kauri	36	14.1 a	0.77
Kahikatea	39	11.2 b	0.74
Rimu	39	10.2 bc	0.74
Totara	51	9.7 bc	0.65
Miro	5	9.1 bcd	2.07
Tanekaha	23	8.4 cd	0.99
Matai	9	5.3 d	1.54

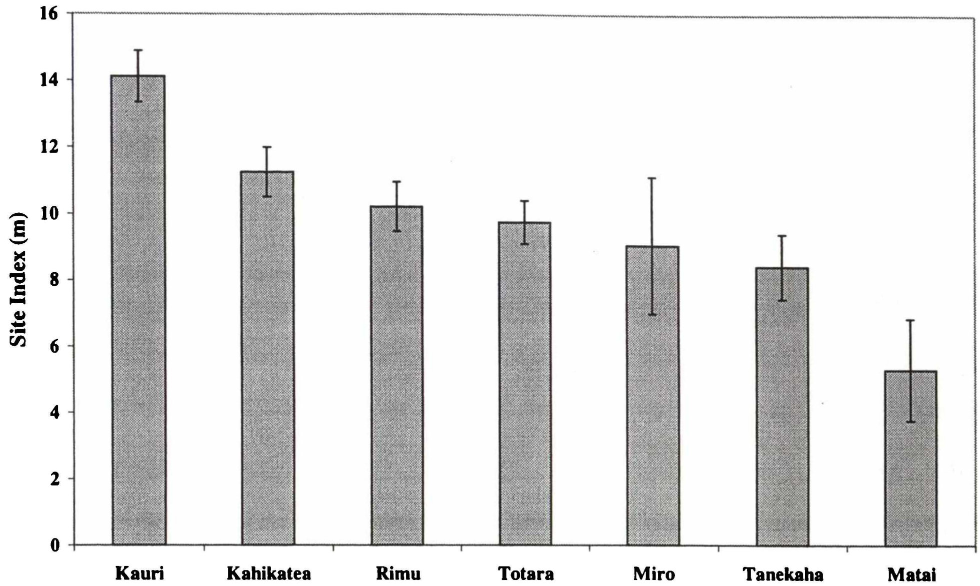


Figure 7.5: Estimated site index (height at age 40 years) for the indigenous conifer tree species based on all stands located throughout the country. Error bars indicate standard errors.

7.3.4 Performance of conifers in selected trials

Early growth performance of 15 well-documented planting trials is given in Table 7.5. This allows more detailed comparison of growth performances of the species where site type and stand management histories are known. Stands range in age from 10-40 years. Totara, rimu and kahikatea are planted at most sites, allowing direct comparisons of performance of these species. Two sites have only totara while kauri, tanekaha and matai are included in some sites where sufficient samples occurred.

Survival assessment was recorded for most stands and varies from less than 20% for totara at Ianthe Forest, South Westland, and up to 95% at Holt's Forest Trust, Hawkes Bay. Both diameters and heights varied widely. Mean annual increments gave clear indications of the extremes of growth rates between many sites across all species. The poorest performing sites for all species were Gwavas, Ianthe, Slopedown and Russell forests where nearly all trees had less than 3 cm DBH and were less than 3 m high 17-23 years after planting. Performance at Woodhill Forest was not much better, especially for trees planted under the kanuka canopy. The fastest growing stand was the youngest plantation of totara at Tapapakanga, established on a lowland farm site. Annual height increments of 20-25 cm and DBH of 2-4 mm for totara, rimu and kahikatea of about 20 years on the upland sites at Mamaku, Kaingaroa and Pureora (approximately 500 m a.s.l.) reflect the cooler climate and shorter growing seasons. Growth rate of podocarps often increases as planted trees approach pole stage (10 cm DBH) when leaders break through competing hardwood and fern vegetation 10-15 years after planting and can be seen in increased width of growth rings (Beveridge *et al.* 1985). Compared with the central North Island plantings, the faster growth rate of totara at Glenbervie, with a MAI of 30 cm height and 7 mm diameter, is a reflection of this warmer northern lowland site.

Site factors (eg., climate, exposure, soil type, drainage) and degree of after-planting care are major influences on performance. The southern cooler sites at Ianthe and Slopedown had no releasing after planting and Ianthe was poorly drained (Forest Research Institute 1984). Poor growth at Russell and the closed canopy site at Woodhill were largely a result of dense competition from weed growth and low light intensities under a canopy. The exceptionally droughty site at Woodhill located on an old sand dune is a major factor in the poor growth of all podocarps planted on this site. Growth of podocarp seedlings at Russell was also poor due to low-fertility, stony clay loam soils. Releasing of seedlings from competing vegetation, whether it was grass in early years as at Tapapakanga, or ferns and shrub hardwoods as at the Holt's and Glenbervie sites, has clearly improved growth of all indigenous conifers. Such growth is probably due as much to reduction of competition as it is to improved light levels (Beveridge 1973).

Within sites there a difference in relative performance between species that provides insights into their ecological characteristics. The poor drainage at Ianthe was reflected in low survival and growth of totara and rimu and the correspondingly better performance of kahikatea. At Woodhill, groups planted under canopy and in cut gaps with similar survival rates demonstrate the persistence of indigenous conifers, although increased light levels in the open canopy site is clearly beneficial as growth rates are significantly faster for height and diameter across all species. The poorest performing species on the sandy soils at Woodhill under an open canopy is kahikatea with a survival rate of only 54% compared with totara which has the highest survival of 87% 25 years after planting. Tanekaha had good survival and the fastest height growth while rimu also performed well on this site.

All species have the potential to be severely affected by insect attack or animal browsing. For instance, rimu, kahikatea and totara were damaged by severe possum browsing and cattle grazing and trampling at Gwavas Forest (Table 7.5). In general, however, totara is relatively unpalatable to most grazing animals except goats (A.E. Beveridge pers. comm.). Beveridge (1962) found totara seedlings under a podocarp forest canopy at Pureora with severe damage, particularly to new foliage, caused by defoliating caterpillars, which contrasts sharply with totara planted on open sites such as Tapapakanga, which are relatively free of insect damage.

7.3.5 History of major planting programmes

Hundreds of thousands of indigenous seedlings have been planted during the course of the last century. Planting of totara in the early 1900s by the Lands Department was in response to concerns over the diminishing natural forest resource in some regions. Some 546,500 totara seedlings were reported to have been planted at that time (Department of Lands 1909). Of these only a fraction are known to have survived, and can be found today in small remnant stands.

Table 7.5: Early growth performances of a selection of indigenous planting trials. Trials are listed in order of age at assessment from youngest to oldest. Mean annual increments (MAI) do not take into account planting height.

Trial site	Site and trial description and tending	Age at last assessment (years)	Species planted	Sample	Survival (%)	Average DBH (cm)	DBH MAI (mm)	Average height (m)	Height MAI (cm)
Tapapakanga Regional Park, Auckland	Plantation established in open on grass at 2mx2m spacing; coastal. Large crowns, coarse branching formed. Pre-plant grass control undertaken; regular maintenance.	10	totara	200	89	8.6	8.6	5.5	55
Gwavas Forest, Hawkes Bay	Line and group planting in shrubhardwood regrowth in logged beech forest; no releasing; severe damage by cattle and possums.	17	totara rimu kahikatea	96 85 87	71 69 75			1.9 2.1 2.1	11 12 12
Pureora Forest Park, central North Island (upland site)	Groups planted between *Eucalyptus delegatensis* on cleared podocarp forest site; minimal releasing; scattered mostly unthrifty eucalypt overwood. Altitude 600 m.	20	totara* rimu kahikatea	23 20 20		11.0 12.2 10.9	4.7 6.1 5.5	5.4 5.7 6.9	27 29 35
Ianthe Forest, West Coast (swamp forest site)	Groups planted in gaps cut in hardwood regrowth in strip-felled podocarp forest; no releasing from dense regrowth; poor drainage	20	totara rimu kahikatea	19 185 114	18 29 72	2.9 2.7 2.8	1.5 1.8 1.9	2.6 2.4 1.9	13 16 19
Slopedown Forest, Southland	Groups planted in gaps cut in kamahi/wineberry regrowth after beech logging; no releasing from dense *Fuchsia*.	22	totara rimu	42 46				2.2 1.4	9 5
Holt Forest Trust, Hawkes Bay	Lines planted in bracken; released annually; summer droughts occasionally	23	Totara rimu kauri	30 30 30	95 90 90	11.2 8.0 11.5	4.9 3.5 5.0	6.3 5.5 6.5	27 24 27
Russell Forest, Northland	Line planted in dense kanuka scrub and tree fern; some early releasing	23	Totara rimu kahikatea matai tanekaha	181 318 223 131 49	34 81 72 54 46			1.6 1.7 2.8 1.1 1.4	7 7 12 5 6

* Near upper altitudinal limit for totara at about 600 m a.s.l.

Table 7.5: (continued)

Trial site	Site and trial description and tending	Age at last assessment (years)	Species planted	Sample	Survival (%)	Average DBH (cm)	DBH MAI (mm)	Average height (m)	Height MAI (cm)
Woodhill Forest, Auckland	Closed canopy - 25 tree groups planted under a canopy of manuka and kanuka; old sand dune country; releasing only first 2 years; exceptionally droughty sites on old sand dune	25	totara rimu kahikatea tanekaha	207 150 39 80	92 86 52 80	4.2 2.8 1.0 4.1	1.7 1.1 0.4 1.6	2.7 2.7 1.1 4.4	9 9 5 16
Woodhill Forest, Auckland	Open canopy - 25 tree groups planted with cut gaps in manuka and kanuka; sand country; releasing only first 2 years.	25	totara rimu kahikatea matai tanekaha	196 176 81 120 72	87 64 54 60 72	4.5 6.8 1.9 1.1 6.6	1.8 2.7 0.8 0.4 2.6	3.3 5.9 2.5 2.8 6.3	13 22 9 10 24
Kaingaroa Forest, central North Island Plateau	Line planted beneath semi-mature *Pinus ponderosa*; provided shade and shelter; frosty cold pumice site	25	totara rimu kahikatea	137 140 91	58 62 50	7.4 6.9 4.0	3.0 2.8 1.6	5.9 5.0 4.2	24 20 17
Mamaku Forest, central North Island*	Large groups planted in logged podocarp/tawa forest in hand-cut gaps	26	totara rimu kahikatea	150 105 35	64 53 54	9.4 7.4 6.0	3.2 2.8 2.3	6.5 6.6 5.1	25 25 20
Mamaku Forest, central North Island*	Tractor cleared gaps in logged podocarp/tawa forest	26	totara rimu kahikatea	138 158 145	44 70 81	9.8 6.8 6.2	3.8 2.6 2.4	6.3 5.9 6.6	24 23 25
Mamaku Forest, central North Island*	Tractor cleared lanes in logged podocarp/tawa forest	26	totara rimu kahikatea	111 166 61	67 68 85	9.8 8.3 6.5	3.7 3.2 2.5	5.6 6.0 6.4	22 23 25
Glenbervie	Plantation established in scrub; some early releasing	35	totara kauri	17 29	85 90	24.9 25.5	7.1 7.3	10.4 14.6	30 42
Pureora Forest Park, central North Island (550 m a.s.l.)	Perham Ave- planted with eucalypts on cleared site; minor early releasing from tall grass and blackberry; tall eucalypt overwood.	40	totara	22		16.1	4.0	10.2	26

* Near upper altitudinal limit for totara. Natural Hall's totara present in residual forest.

A major planting programme of indigenous conifer species that included totara was initiated in the late 1950s when 500,000 seedlings of indigenous tree species, raised in the Forest Research Institute nursery, were planted out on a range of forest and scrub sites (Beveridge 1977). Seedlings were dispersed to New Zealand Forest Service (NZFS) Conservancies (especially for Westland planting), private owners, various agencies and authorities. At this time, several large-scale experimental plantings were undertaken, including some 30,000 seedlings planted in trials on the Mamaku Plateau, 10,000 seedlings planted on the Kaingaroa Plateau and 12,000 at Woodhill. The aim of this programme was to establish nursery-raised seedlings of indigenous conifers on previously logged or heavily disturbed sites where natural regeneration was generally scarce or absent (Pardy and Bergin 1992). Plants were then to be monitored and released from weed growth but some sites proved difficult to maintain where resources were limited. Some plantings did, however, have high survivals, and were included in this assessment of early performance.

From the mid-1970s, NZFS Conservancy nurseries started to grow large numbers of indigenous conifers, notably at Cambridge, Sweetwater and Kaingaroa nurseries in the North Island, and at Reefton and Rangiora nurseries in the South Island. Extensive enrichment planting took place in selectively logged podocarp forests at Pureora (e.g., Guest 1985) and Whirinaki. Up to 40,000 podocarps were planted annually at Pureora (Beveridge 1979) and this continued until the early 1980s. With the demise of the NZFS in 1987 and consequent lack of tending, release of overhead canopy and regular assessments of performance, as well as changing forest policy, many planted areas were abandoned, forgotten, lost or destroyed. Some of those that have survived were included in this analysis of early planting performance.

A similar picture has emerged with relatively large-scale planting of kauri undertaken during the 1970s and 1980s where up to 50,000 seedlings were raised annually at the NZFS Sweetwater Nursery, north of Kaitaia, Northland (Beveridge 1979; Halkett 1983). These seedlings were planted out in several forests in Northland, Great Barrier Island, Coromandel Peninsula and the Kaimai Ranges.

Seedlings were planted in small gaps or lines cut in scrub or under thinned tall kanuka stands where there was little or no effective natural regeneration of kauri (Beveridge and Herbert 1995). Unfortunately, from the hundreds of thousands of seedlings planted, at most sites there is little evidence of successful establishment of kauri where seedlings were not adequately released (e.g., Coromandel planting sites, Max Johnston pers. comm; own observations). There have been some successful planting of small stands of kauri such as on alluvial soil by streams on Great Barrier Island and on farmland at Victoria Valley, Northland, established in the 1950s.

7.4 DISCUSSION

Totara was initially the most commonly planted of all the indigenous conifer species (Department of Lands 1909) and this probably continued until the 1970s when large numbers of kauri were planted in the upper North Island. Factors that contributed to wide-scale and sustained planting of totara include its natural distribution throughout the country, its tolerance of and generally good performance on a wide range of sites, and the ease with which it is raised for large-scale planting programmes. Consequently millions of seedlings have been planted throughout the country over a century. However, there are virtually no extensive plantations of totara or of other indigenous conifers in existence today.

This evaluation of surviving planted stands and trials indicates that many were established on poor sites after the best land was converted to farming and exotic forestry landuses, and few received adequate post-planting maintenance, both critical factors in early performance and effective establishment. Subsequent changes in landuse and ownership, and changes in the direction of central government policies and initiatives, have also contributed to the lack of commitment to long-term stewardship and management of planted stands. All these factors have contributed to the perception that indigenous trees are not only difficult to establish, but are slow-growing.

Despite the variability in sites assessed in this study, analysis of site indices for totara across all plantings indicated a preference for open, fertile sites, consistent with previous observations and studies (e.g., Ebbett 1998). Overall, totara has a similar growth rate to the other widely planted podocarps, kahikatea and rimu with which it was often planted. Seedling growth studies of the three major podocarps have shown that totara responds to high fertility and high light intensities. In a comparison of growth responses to nutrition, Hawkins and Sweet (1989a) found totara seedlings gained the greatest dry weight compared with rimu and kahikatea after 8 months growth. When the five podocarp species, totara, rimu, kahikatea, matai and miro, were planted under different levels of shade cloth and under various light intensities beneath the canopy of different vegetation types, totara and kahikatea had the greatest height response in the highest light levels (Ebbett and Ogden 1998). In comparisons of shade tolerances between the conifers, in both experience with planted seedlings and in studies of natural regeneration, totara is the most light-demanding. Beveridge and Bergin (2000) indicate that the shade tolerances of planted conifers in the central North Island, based on field experience, increase from light-demanding to shade-tolerant in the following sequence – totara, tanekaha, kahikatea, matai, Hall's totara, rimu, miro. Similarly, Ogden and Stewart (1995) speculate that following massive disturbance in high forest, initial cohorts of podocarps establish in the sequence from most light-demanding to the most shade tolerant – totara, matai, rimu, miro. Although site variation in this evaluation has largely masked an evaluation of ecological preferences between species, results do show totara is less tolerant of shade than the other podocarps when planted together. Totara also tolerates drier sites showing a preference of open, warm, frost-free sites whereas kahikatea prefers moister sites. Performance of rimu improves on sheltered sites where risk of desiccation by wind and drought is reduced. The few sites where kauri and tanekaha were planted with podocarps shows that these species generally grow faster than the podocarps.

Compared with performance averaged across all stands covering a range of sites and management histories, growth rates from the best performing stands are a more accurate reflection of the potential of totara. Table 7.6 lists the best performing planted stands from all plantings evaluated in this study and demonstrates the potential growth of totara in comparison with the other major conifers (where there were reasonable sample sizes). Overall survival of the conifers is usually high as has been reported previously (e.g., Pardy *et al.* 1992; Beveridge *et al.* 1985; Beveridge and Bergin 2000). Totara can achieve annual growth rates of over 8 mm DBH and at least 40 cm height during the early years after planting. Similar growth rates of around 8-10 mm DBH and 40-50 cm height were achieved for rimu, kahikatea and kauri, and 6.5 mm DBH and 35 cm height for tanekaha. Without exception, all best performing stands listed in Table 7.6 were planted on sheltered, fertile lowland sites. Most are part of recreational parks, domains or large gardens where they received regular maintenance and were kept free of competing vegetation.

Recommendations for planting based on mainly podocarp trials on upland sites with adequate rainfall in the central North Island were made by Beveridge and Bergin (2000) for a range of sites. Matching the species to the appropriate site is important as well as selection of good microsites for seedlings. In disturbed forest, suitable microsites are canopy gaps where soil is disturbed and well-drained, free from dense growth of tree ferns and root mats of large trees. On exposed open sites, early shelter must be provided using natural or planted indigenous species such as manuka, kanuka, kohuhu, wineberry (*Aristotelia serrata*) and karamu (*Coprosma robusta*). Alternatively, where appropriate, exotic species can be planted to provide early shelter but must be removed before suppressing planted podocarps. On difficult sites with dense growth of vegetation, use of a small tractor to clear a gap and lightly cultivate the ground may be required. Vigorous grass cover on open sites needs to be controlled before planting.

A further consideration is the pattern of planting that will be determined not only by the site and species to be planted but also the objectives of planting. Cluster planting of 3-5 seedlings at 1-1.5 m spacing enables selection of suitable microsites in forest gaps, and groups are easily re-located for releasing. Compacted ground and areas of dense fern can be avoided.

Table 7.6: A selection of the more successful planted stands of indigenous conifers established for up to 50 years illustrating the potential growth rates from planted stands.

Species	Site	Stand age (years)	Sample	Survival* (%)	Mean DBH (cm)	DBH MAI (mm)	DBH range (cm)	Mean height (m)	Height MAI (cm)	Height range (m)	Stand and site characteristics
Totara	Tapapakanga	10	200	89	8.6	8.6	5.7-10.1	5.5	55	4.7-6.5	Fertile. lowland, ex-pasture site; regular releasing
	Kamo	32	14	95	32.5	10.2	21-45	14.4	44	13.7-15.2	Shelterbelt; large crown trees; fertile lowland site
Rimu	Holts Forest	6	31	95	2.8	4.7	2.0-4	2.9	43	2.4-3.6	Well maintained; pruning
	Cornwall Park	39	36	90	31.8	8.2	21.2-41.5	14.4	35	10.7-15.8	Well maintained; fertile lowland site
Kahikatea	Holts Forest	18	20	80	18.0	10.0	12-22.9	11.8	59	10.4-13.4	Well maintained
	Cornwall Park	21	19	70	21.8	10.4	15-30.3	10.3	48	8.2-12	Well maintained; fertile lowland site
Kauri	Pukekura	22	15	90	25.0	11.4	14.3-34.2	11.5	51	7.5-13.3	Fertile high rainfall site; regular maintenance
	Kirks	31	40	100	28.7	9.3	15.4-39.4	14.6	45	12.2-17.5	Fertile lowland site; sheletered; good maintenance
Tanekaha	TePohue	25	11	-	16.3	6.5	13.0-20	9.1	35	8.0-11	Sheltered large garden; well maintained
Matai	Pukekura	50	16	-	16.0	3.2	12.3-20	9.9	19	9.6-10.4	Fertile high rainfall site; regular maintenance
Miro	Pukekura	22	2	-	9.9	4.5	8.8-11.1	4.6	20	4.6-4.7	Fertile high rainfall site; regular maintenance

* Survival of tanekaha, matai and miro difficult to estimate from limited planting records

The use of large, well-conditioned nursery-raised stock over 60 cm in height will give better survival and early growth. However, larger seedlings are more expensive especially if raised in containers. The efficacy of using either container-grown or bare-root nursery stock for large-scale restoration programmes needs addressing (Dean 2000).

The overwhelming conclusion from the analysis of existing plantings is the need for adequate maintenance of seedlings after planting. Seedlings should be released from competing vegetation until they reach about 2 m in height, approximately five years after planting.

CHAPTER 8

GROWTH AND YIELD OF TOTARA FROM PLANTED STANDS

8.1 INTRODUCTION

Totara have been established as planted stands in many regions over the last century (Pardy *et al.* 1992). Reasons for planting vary and include restoring native forest remnants, providing shelter on farms, improving wildlife, providing amenity and recreational facilities, controlling erosion and improving water quality, as well as the long-term option of providing a resource of high-value specialty timber. Although most plantations are relatively small in extent or have performed poorly due to planting on difficult sites and receiving minimal post-planting care (e.g., Beveridge *et al.* 1985; Bergin and Pardy 1987), some stands provide an indication of the potential growth rates including timber yields from the older stands. Totara has been planted mostly as a single species in small stands and also as shelterbelts across a range of site types. This chapter describes the performance of a selection of these stands and gives a preliminary growth and yield table.

8.2 STUDY SITES AND HISTORY

In 1985-86 the Forest Research Institute undertook a survey to locate and assess established stands of indigenous trees planted throughout the country (Pardy *et al.* 1992). Of the 55 stands and shelterbelts located and measured, 13 stands were dominated by totara. These stands located during the survey of the mid-1980s were re-visited from 1996 to 1998 and assessed for performance. Twelve sites were located in the North Island and one in the South Island (Figure 8.1). Eleven sites comprised small plantations of totara and two were shelterbelts. Brief site descriptions and stand histories are given below and climatic and site data is given in Appendix 4.1. Soils descriptions are from Soil Bureau (1954) for the North Island and Soil Bureau (1968) for the South Island. Climate records are from New Zealand Meteorological Service (1983).

Ages ranged from 10 years to 94 years with stem density of nine of the plantations ranging from 975 to 2500 stems ha^{-1}. It was difficult to accurately estimate stockings for the two shelterbelts at Kamo, a small grove at Cornwall Park where trees had been planted at wide spacing where the stand had a large edge effect, and a stand of totara underplanted in pine at Kaingaroa.

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

An inspection of the stand in the mid-1950s indicated cattle were roaming through the heavily shaded stands and thinnings were of little value due to lack of heartwood. Today the remnants are located on dairy farmland and are still unfenced with no understorey vegetation. The two stands measured are approximately 500 m apart, one at a density of 1275 spha and the other at 1925 spha.

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

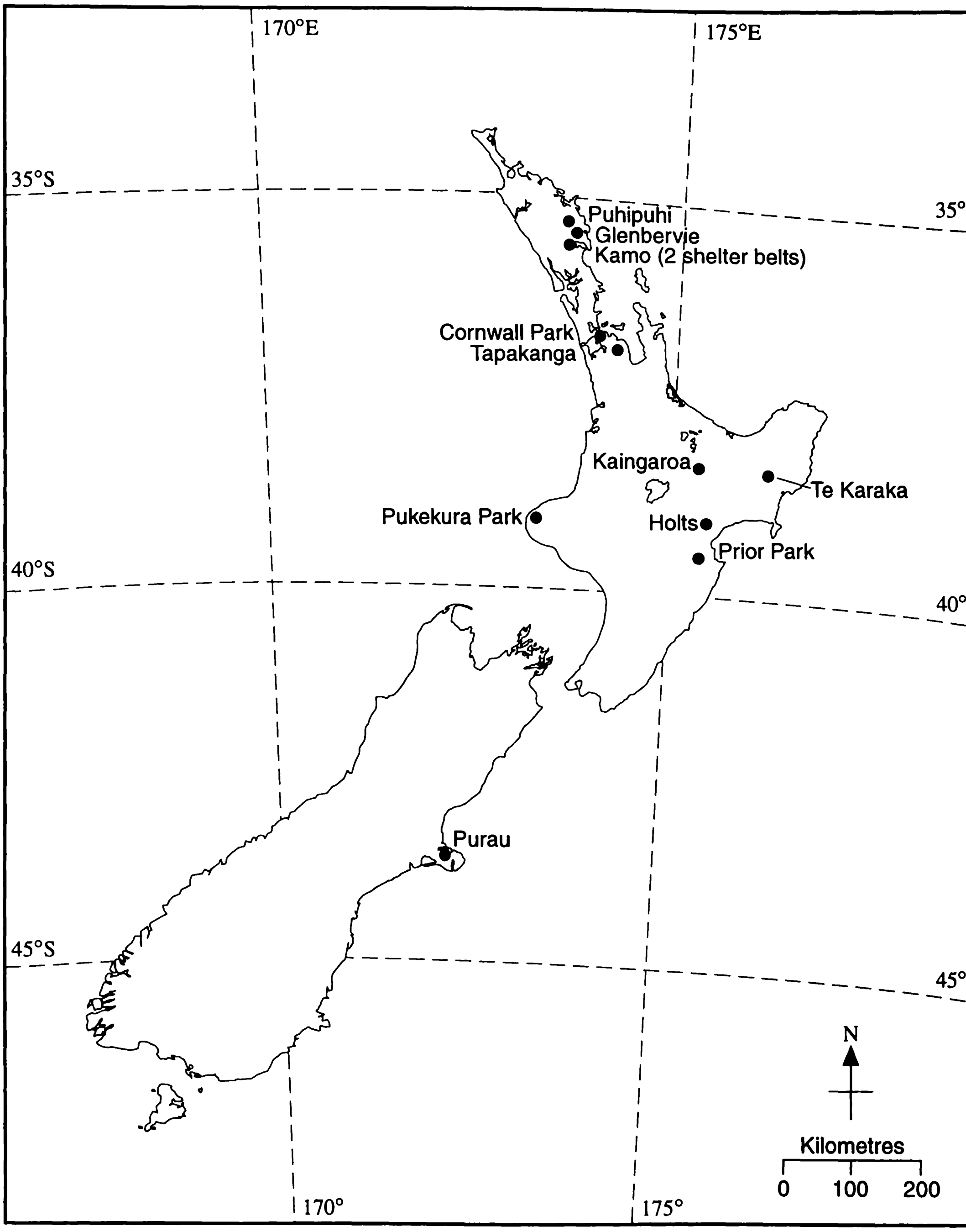


Figure 8.1: Location of the 11 plantations and two shelterbelts used to develop the growth and yield model for totara. Two stands were located at Puhipuhi.

Kamo, Whangarei – In 1955 a single row of totara were planted at approximately 1 m spacing along a fenceline as a shelterbelt. The shelterbelt is located at the based of a slope. The seedlings were temporarily fenced off from grazing stock during early years. There was high survival but tree form has been poor with no tending. The soil is Ohaeawai silt loam derived from basalt with medium to high natural fertility.

Kamo, Whangarei (older shelterbelt) – A double row shelterbelt of totara exists on a grassed site that was previously the site of the Ruatangata forest tree nursery. The rows were planted along the brow of a gentle slope adjacent to a cutting along which a railway line exists. It was planted at a spacing of 1.5 m in 1904 and as a result of early releasing has had good survival. Approximately half of the trees had single leaders with heavy branching on sides exposed to full light. One part of the shelterbelt has been adjacent to a small stand of large eucalypts which have recently been removed. As with the nearby younger shelterbelt, the soil is Ohaeawai silt loam derived from basalt.

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

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

Kaingaroa Forest – In 1962, over 24,000 podocarp seedlings were planted in Compartment 1071 in Kaingaroa Forest beneath a 36-year-old stand of ponderosa pine. The pines provided a light canopy to protect the seedlings on this cold upland site. The planting included almost 9000 totara established at a spacing of 3.6 m x 1.8 m and then left untended.

The site is flat with Pekepeke shallow sandy soil. At time of planting the understorey consisted of small tree ferns and ground ferns. Early inspections indicated that totara had high survival (85%) but average height growth of only 2 m was slow over the first 13 years since planting. By 1975 the vegetation beneath the thinning pines comprised tree ferns (*Dicksonia* and *Cyathea* spp.) up to 2.5 m high and abundant ground ferns, particularly kiokio, and blackberry (*Rubus* sp. (*R. fruticosus* agg.)). There was no difference in performance between totara that had been protected by a deer fence and trees that were not fenced.

Te Karaka, Gisborne – A 0.4 ha stand of totara was planted at Te Karaka northwest of Gisborne in 1947. The site was covered originally in kanuka and manuka. The soils on this steep to rolling hill country are Pouawa sandy loam hill soils of medium natural fertility. Totara seedlings were planted at 2-4 m spacing with the original purpose of reducing erosion above a water dam and to provide a future timber resource. Seedlings were released from grass competition in early years by cutting back with a slasher. On at least three occasions, trees were pruned with the last taking place in 1983.

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

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

Prior Park, Hawkes Bay – This plantation was planted in 1908 on a property known as Prior Park at Wharerangi about 15 km northwest of Napier (Hocking 1949). The site is fertile valley bottom with soils that are fairly compact grey brown loams. The stand covers an area of 0.3 ha with an original spacing of 2-2.5 m. There was good survival in early years with little mortality found during a 1948/1949 inspection within a completely closed stand. The dominant trees at this stage were 15-17 m high with occasional trees up to 30 cm in diameter. The green crown level was 8-10 m above ground with generally heavy branching and a considerable proportion of multiple leaders. There apparently was light early releasing in early years from grass but no pruning or thinning of the stand had taken place.

During the 1985 assessment, 144 trees were found to be alive with 15 dead trees present. Both cattle and sheep had access to the stand and were using it for shelter. Stock had broken lower dead branches from some trees.

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

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

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

When inspected in 1986 and in 1998, the stand was not fenced off and cattle trampling of root systems was evident. Gaps in the stand indicate some earlier mortality has occurred. For the age of the stand, growth was regarded as slow compared with totara measured on other sites of similar age. Stem form of interior trees was considered good for an untended stand with clear boles up to 7 m.

8.3 METHODS

8.3.1 Assessment of Stands

The assessment during the 1980's survey involved documenting the history of each stand including year planted, method and pattern of planting, and any information available on early growth and management (Pardy *et al.* 1992). In the larger stands, up to 30 trees within each stand were permanently identified using an aluminium numbered tag nailed on the trunk about 30 cm above ground level.

Other than the shelterbelts, trees located within stands were used in the assessment with heavily branched edge tree avoided. DBH (diameter at breast height, 1.4 m above ground) was measured for each numbered tree and a sample of up to 10 trees was measured for height using a hypsometer. Stem form and vigour of measured trees was also recorded. Locations of measured trees were mapped for future measurement.

Approximately 10 years later between 1996 and 1998, 13 totara-dominated stands were revisited and numbered trees located. All trees were remeasured for DBH and heights were taken of the same sample of trees as previously. In most stands, a circular Permanent Sample Plot (PSP) up to 22.8 m in diameter (0.04 ha) was installed to include most of the original measured stems (Ellis and Hayes 1997). The PSPs were used to give a stocking density estimate for each stand. Identification tags were repositioned at most sites to 1.4 m above ground to improve accuracy of future DBH measurements.

Increment cores were taken from a selection of trees within most stands where permission had been gained from landowners or managers. Cores were taken at 1.4 m above ground using standard tree borers from 20-35 cm long depending on the size of the tree. Holes were immediately plugged with petroleum jelly to prevent entry of water and insects into core holes. There was some difficulty in obtaining cores passing through or near the pith. Cores from up to 20 trees covering the range of small, medium and large diameters were taken from each stand. Cores were then mounted in blocks and sanded down using progressively finer grades of sandpaper. The number of rings was counted and distance between each ring was recorded using an ADDO-X ring counting machine with data entered directly onto an attached computer.

8.3.2 Data Analysis

8.3.2.1 Height/DBH curves by stand

For each stand, a height/age curve was fitted using those trees measured for height. The following equation was used:

$$H=aD^b$$

where H = height, D = DBH, *a* and *b* are coefficients estimated by nonlinear regression. Estimates of heights were obtained from these curves for those trees not measured for height. Mean heights were then obtained for each stand, using estimated and measured heights.

8.3.2.2 Height/age curves

Various height/age functions were tested against the height data (Table 8.1). The Weibull equation is the cumulative form of a widely used probability distribution function that has proved to be a good model of tree growth (Yang *et al.* 1978). The Chapman-Richards equation (Richards 1959) is one of the most commonly used forestry growth equations, as is the Schumacher equation (Schumacher 1939). In addition to the above three-parameter growth functions, a simple power function requiring only two parameters was tested. The functions were all assigned an intercept of 0.5m to account for height of seedlings at planting.

Table 8.1: Equations of height/age and DBH/age curves.

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

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

8.3.2.3 DBH/age curves

Mean DBH from the 1996-1998 assessment were supplemented, where possible, using diameters derived from core measurements for 10, 20 and 30 years prior to the last measurement. These core diameter estimates were used in preference to the 1986 DBH measurements because of the longer time series represented. This produced up to 4 diameter measurements spaced at 10-year intervals for seven stands using between 3 and 19 cores per stand (Table 8.2).

Table 8.2: Increment cores used to extrapolate diameter growth back from last stand measurement for selected planted stands of totara. One ring is assumed to equal one year of growth.

Location	Stand age (years)	No. of cores used to measure diameter growth	Number of years extrapolated back from last stand assessment
Holts Forest	33	4	20
Kamo	43	3	20
TeKaraka	50	6	20
Prior	88	4	30
Purau	86	7	30
Puhipuhi (1925 stem ha^{-1})	89	19	30
Puhipuhi (1275 stems ha^{-1})	91	7	30

The same growth functions used for the height/age analysis were tested for suitability as DBH/age functions. The equations were modified to give a predicted DBH of zero at age five to account for the time taken for seedlings to reach breast height of 1.4m (Table 8.1). The functions were then fitted using NLINMIX to the DBH/age data. Both anamorphic and polymorphic forms of the equations were tested.

8.3.2.4 Basal area and volume versus age curves

Total stem volume was derived from the basal area (obtained from the DBH/age equation) and height (from the height/age equation) using the kauri pole stands volume table of Ellis (1979):

$$V = 2.071\ln(D) + 0.8386\ln(H) - 3.14$$

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

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

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

8.4 RESULTS

8.4.1 Stand performance

There were major differences in performance among stands in growth and yield (Table 8.3). This was particularly evident with DBH growth and in particular between the plantations and the shelterbelts and the widely spaced grove in Cornwall Park. The average MAI for DBH across all nine plantations was 4.8 mm compared to an average of 8.3 mm for the two Kamo shelterbelts and Cornwall Park. There was less variation in height growth rate with average height increment across all 13 stands of 26 cm. In the two Puhipuhi stands the influence of stocking on DBH is apparent with average diameters 10 cm greater in the less densely stocked stand (35 cm) compared with the dense stand (25.9 cm). For the similarly aged 94-year-old shelterbelt at Kamo, also in Northland, trees had an average DBH of 48.3 cm compared to the smaller diameters for both Puhipuhi stands reflecting less competition between trees in the double-row shelterbelt at Kamo.

The widely spaced trees at Cornwall Park stand had an average DBH (73.6 cm) over double that of similarly aged stands at higher stockings at Prior Park, Hawke's Bay and Pukekura Park, New Plymouth. Relatively slow growth was recorded for stands in Te Karaka, Kaingaroa and Banks Peninsula. For example, average DBH at Te Karaka (19.6 cm) was less than the slightly younger stand at

Glenbervie (29.2 cm). For stockings of 1000 stems ha^{-1} or more, and for stands over 60 years of age, volumes ranged from 380 m^3ha^{-1} at the poorly managed only South Island site at Purau to 1297 m^3ha^{-1} at Northland site at Puhipuhi with mean annual increments ranging from 4-16 m^3ha^{-1}.

8.4.2 Growth prediction equations

8.4.2.1 Height/age function

The three-parameter height/age growth functions tested fitted the data better than the two-parameter power function (Table 8.4). In all cases, anamorphic curves were superior to polymorphic curves. Although all three-parameter models gave very similar fits, the Chapman-Richards equation was chosen because its asymptote was considered more realistic than the other models:

$$H = 0.5 + a\left(1 - e^{bT}\right)^c$$

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

Table 8.4: Log likelihood values for height/age and DBH/age equations used to determine the most appropriate height/age and diameter/age curves for the totara plantation data.

Equation	Height/age equation		DBH/age equation	
	anamorphic	**polmorphic**	**anamorphic**	**Polmorphic**
Power	-41.07	-41.77	84.71	76.32
Weibull	-40.15	-41.65	84.92	82.83
Chapman-Richards	-40.15	-41.65	83.59	Nc*
Schumacher	-40.05	-40.41	84.71	Nc*

* did not converge

Table 8.3: Stand characteristics and performance of 13 planted stands of totara. Stands are arranged from youngest to oldest.

Location	Stand type	Age (years)	Stocking (stems ha^{-1})	Mean DBH* (cm)	DBH MAI (mm per year)	Mean height (m)	Height MAI (cm per year)	Basal Area (m^2ha^{-1})	Total stem volume (m^3ha^{-1})	Total stem volume MAI ($m^3ha^{-1}yr^{-1}$)
Tapapkanga	Plantation	10	2500	8.0	8.0	4.4	44	13.4	31	3.2
Holts Forest	Plantation	33	1975	15.4	4.7	9.3	28	37.5	167	5.1
Kaingaroa*	Underplanted	36	-	12.9	3.6	7.8	22			
Kamo	Shelterbelt	43	-	39.9	9.3	17.0	40			
Glenbervie	Plantation	46	975	29.2	6.3	12.3	27	67.9	393	8.6
TeKaraka	Plantation	50	1100	19.6	3.9	12.0	24	34.7	197	4.0
Pukekura	Plantation	62	1078	35.6	5.7	18.6	30	118.9	992	16.1
Cornwall Park#	Small grove	70	-	73.6	10.5	20.3	29			
Purau	Plantation	86	1100	27.7	3.2	11.2	13	70.3	380	4.4
Prior	Plantation	88	1000	39.4	4.5	18.3	21	128.0	1141	13.0
Puhipuhi	Plantation	89	1925	25.9	2.9	20.0	22	101.2	972	11.0
Puhipuhi	Plantation	91	1275	35.0	3.8	22.9	25	128.3	1297	14.2
Kamo (older)	Shelterbelt	94	-	48.3	5.1	20.2	21			

* Stocking not determined as totara planted within a stand of semi-mature ponderosa pine.

\# Difficult to determine stocking due to large edge effect for this small stand.

Growth trajectories plotted against measurements are shown in Figure 8.2 and indicate considerable variability in performance. Early height growth of totara in the best performing stands is up to 50 cm per year although this growth rate slows with age as trees approach 25 m high by age 100 years on good sites. However, only half this growth rate is found for the slowest growing stands.

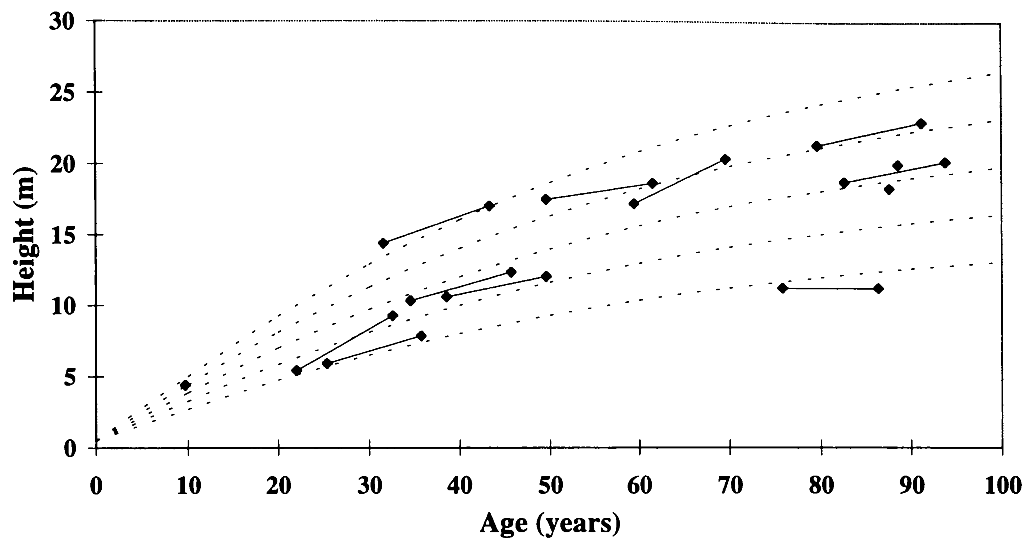


Figure 8.2: Height/age curve for totara derived from measurement of planted stands where two measurements were taken about 10 years apart at most sites.

8.4.2.2 DBH/age function

Considerable difficulty in obtaining convergence was experienced while fitting the three-parameter growth functions to DBH/age data. This was clearly caused by the fact that the DBH growth showed little or no tendency to slow, even though stands approaching 100 years were included in the data. The asymptotic parameter could therefore not be estimated with any confidence. The simpler two-parameter Power growth curve gave nearly as good a fit as the best three-parameter curve, and was therefore adopted as the standard DBH/age curve:

$$D = a \times (T - 5)^{0.790}$$

where T is stand age and D is DBH. The random site parameter, *a*, had a mean value of 0.0139. Growth trajectories plotted against measurements are shown in Figure 8.3 and as for the height function, showed large variation in growth between stands. While many stands fell within DBH of 30 cm from around 60 years onwards, faster growing stands indicated a DBH of at least twice that could be achieved.

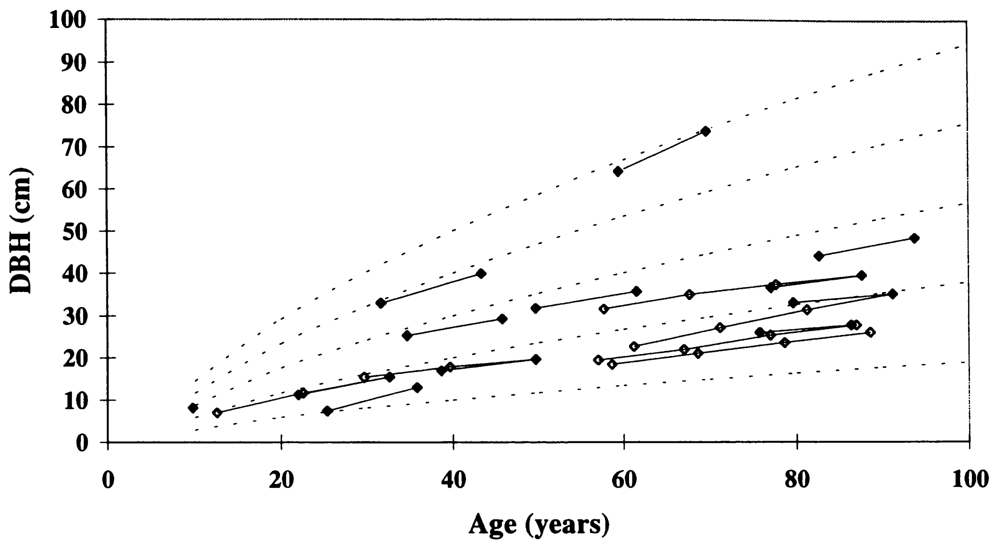


Figure 8.3: DBH/age curve for totara derived from measurement of planted stands.

8.4.3 Site index and DBH at 40 years

By straightforward algebraic manipulation, a more convenient form of the height/age equation can be obtained in which site index, H_{40}, replaces the asymptote parameter:

$$H = 0.5 + (H_{40} - 0.5) \times e^{7.69\left(\frac{1}{40^{0.403}} - \frac{1}{T^{0.403}}\right)}$$

An equation for estimating site index from a height measurement at a known age can be obtained by rearranging this equation:

$$H_{40} = 0.5 + (H - 0.5) \times e^{7.69\left(\frac{1}{T^{0.403}} - \frac{1}{40^{0.403}}\right)}$$

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

$$D = D_{40} \times \left(\frac{T - 5}{36}\right)^{0.790}$$

An equation for estimating D_{40} from a DBH measurement at a known age can be obtained by rearranging this equation:

$$D_{40} = D \times \left(\frac{36}{T - 5}\right)^{0.790}$$

Site indices (H_{40}) and DBH at age 40 were estimated using the above equations for 11 of the study stands (Table 8.5). Estimated height at age 40 years varies from 7.3 m at Purau to 16 m for the shelterbelt at Kamo. Estimated DBH ranges from 14.9 cm for the dense stand at Puhipuhi to 50.4 cm at Cornwall Park. The poorest performing stand in terms of DBH growth in particular are Purau while the best performing stands are the wide-spaced stand at Cornwall Park and the shelterbelts at Kamo. Average height and DBH for totara across all stands at age 40 is estimated at 12.3 m and 25.8 cm.

8.4.4 Basal area and volume

A basal area/age curve (Figure 8.4) based on 9 stands and volume/age curve (Figure 8.5) based on 8 stands were developed. Plotting individual stands against the mean curve shows large variation in performance and is reflecting major differences in site and climatic types and stand management histories described earlier. Initial growth is slow particularly for volume but begins to increase from about 40 years. An 80-year-old stand has a basal area approximately 100 m^2ha^{-1} (Figure 8.4) with overall volume at 80 years exceeding 800 m^3ha^{-1} (Figure 8.5).

Predicted growth of stands at 1000 stems ha^{-1} was calculated based on the 13 stands (Table 8.6). Predictions for basal area and volume beyond about 80 years may be excessive as the model does not take into account mortality that may have occurred since planting. Because stands have not been monitored regularly and information on stand maintenance is largely anecdotal, it would be difficult to determine when trees have died and the rate of mortality. However, there is lack of evidence of major recent self-thinning occurring in the stands assessed. Most mortality may have been during early years and not the result of competition between planted trees. At 80 years, mean height is predicted to be over 17 m with a mean DBH of 36 cm. Basal area and volume over the same period is predicted at 103 m^2ha^{-1} and 803 m^3ha^{-1}, respectively, with a mean annual volume increment of almost 10 $m^3ha^{-1}year^{-1}$.

Table 8.5: Estimated site index (stand height at age 40 years) and DBH at age 40 years for the 11 totara stands based on the latest stand measurements for height and increment core measurements for diameter. The underplanted stand at Kaingaroa and the young stand at Tapapkanga were excluded. Actual stocking of plantations is also given.

Stand	Estimated site index (H_{40}) (m)	Estimated DBH_{40} (cm)	Stocking (stems ha^{-1})
Holt's Forest	10.8	18.1	1975
Kamo	16.0	38.7	-
Glenbervie	11.2	27.0	975
TeKaraka	10.4	17.2	1100
Pukekura	14.1	27.6	1078
Cornwall Park	14.4	50.4	-
Purau	7.3	16.6	1100
Prior	11.6	25.5	1000
Puhipuhi (1925sph)	12.7	14.9	1925
Puhipuhi (1275sph)	14.4	20.1	1275
Kamo (older)	12.5	27.4	-
Average	**12.3**	**25.8**	
Range	**7.3 – 16.0**	**14.9 – 50.4**	

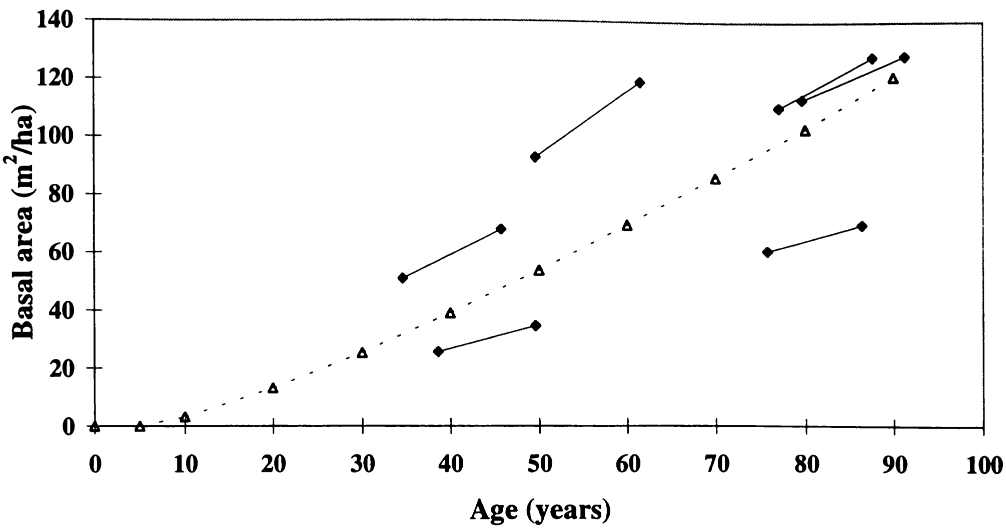


Figure 8.4: Basal area/age curve for totara derived from measurement of 10 planted stands located on a range of sites.

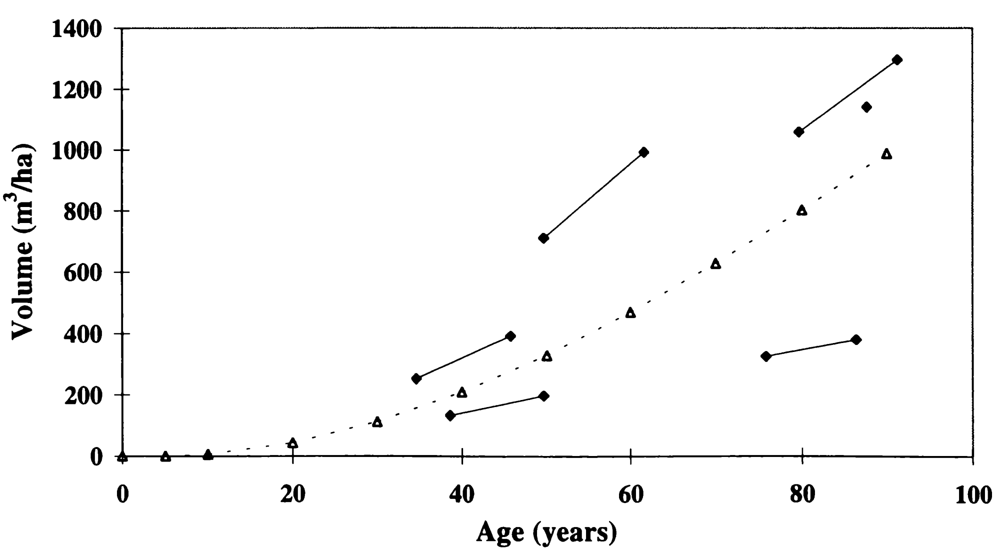


Figure 8.5: Volume/age curve for totara derived from measurement of eight planted stands located on a range of sites. Volume is based on total tree height.

8.5 DISCUSSION

8.5.1 Growth rates

The 13 planted stands assessed in this paper indicate a wide variation in growth rate in both height (Figure 8.2) and diameter (Figure 8.3) reflecting the range of sites stands had been established on as well as different management histories. Diameter growth tended to be more linear than height growth and was also influenced by stocking (Figure 8.6). On the best sites and with good management, average annual height increments of 50 cm and annual diameter increments approaching 10 mm are possible. However less than one-third of this growth is achieved on poor sites. The stands used in this analysis are relatively young compared to longevity of totara in old-growth forest where age is often estimated to be several centuries old where mature trees are up to 30 m high with diameters up to 2 m (Allan 1961). Although the faster growing plantations are approaching heights of trees in natural forest, they have considerably smaller stem diameters.

Table 8.6: Predictions of stand growth for totara at 1000 stems ha^{-1} based on assessments of six plantations with comparable actual stockings located on a range of sites. Volumes are based on total tree heights and volume equation for kauri pole stands (Ellis 1979) as a volume equation for totara does not exist.

Age (years)	Mean height (m)	Mean diameter (cm)	Basal Area (m^2ha^{-1})	Volume (m^3ha^{-1})	Mean annual increment ($m^3ha^{-1}year^{-1}$)	Current annual increment ($m^3ha^{-1}year^{-1}$)
10	3.7	6.4	3.3	6.1	0.6	0.6
20	6.7	13.0	13.3	43.1	2.2	3.7
30	9.3	18.0	25.4	111.5	3.7	6.8
40	11.5	22.3	39.1	208.0	5.2	9.7
50	13.4	26.2	53.8	328.9	6.6	12.1
60	14.9	33.1	69.5	470.4	7.8	14.2
70	16.2	35.7	86.0	629.3	9.0	15.9
80	17.3	36.3	103.3	802.9	10.0	17.4
90	18.2	39.3	121.2	988.8	11.0	18.6

The average annual growth rates of nearly 26 cm for height and 4.8 mm for DBH are similar to average growth rates of totara in other studies of both planted and young naturally regenerating stands. Pardy *et al.* (1992) reported around 6 mm per year for DBH and approximately 30 cm per year for height for a wider sample of totara in gardens, parks, shelterbelts and plantations. Similar growth rates were achieved for podocarps planted in early ***Forest Research*** trials on cool, upland sites of the North Island (Beveridge *et al.* 1985). In comparison with estimates of kauri growth based on two well-managed stands on fertile sheltered sites at New Plymouth (Herbert *et al.* 1996), height of kauri was greater (25 m) and DBH comparable (34 cm) to those estimated for totara (height 17 m and DBH 36 cm) at age 80 years (Table 8.6). However, average height growth rates for young kauri stands (Ecroyd *et al.* 1993) and for the beeches (Wardle 1984) of 40 cm are greater than for totara. At that age, total stand volume estimates for kauri (1103 m^3ha^{-1}) at a stocking of 1300 stems ha^{-1} were comparable to estimated volumes for totara (803 m^3ha^{-1}) but at a lower stocking of 1000 stems ha^{-1}.

Average diameter growth rates of nearly 5 mm and height of 25 cm per year were found for totara in an 80-year-old natural podocarp pole stand regenerating on land formerly cleared and burnt by Maori for cultivation in the upland central North Island (Katz 1980). In this stand totara had a total basal area of 71 m^2ha^{-1} compared to 103 m^2ha^{-1} predicted for planted totara stands in this study.

Both basal area (Figure 8.4) and volume growth (Figure 8.5) curves indicate that totara has an exponential growth although growth over the first 20-30 years is slow. However, the trial planted at Tapapakanga does indicate that totara is capable of good initial growth rates when high quality seedlings are planted on a favourable lowland site and plants are kept free of weed growth in early years. The fastest growth rates in the lower-density stands and shelterbelts is not unexpected as these trees have less competition and larger crowns compared to higher stocked plantations. However, the average growth rates of the highly variable plantations assessed in this study are not likely to be reflecting optimum performance of totara.

8.5.2 Site Differences

The performance of totara described in this paper is based on stands that are widely scattered from Puhipuhi in Northland to Pigeon Bay on Banks Peninsula. In addition to obvious differences in site and climate among stands, a range of factors have clearly influenced performance including the type of stand (e.g., shelterbelt vs plantation), tree age, stocking, and the history of stand management. The slower growing stands located at Te Karaka, Kaingaroa and Purau (Table 8.3) illustrate some of the complex of factors that are likely to be influencing growth. Te Karaka has a warm but dry climate. Kaingaroa, where totara was planted within a stand of ponderosa pine, is a cold upland site and severe competition from the pines as well as blackberry and fern ground cover has occurred. The stand at Purau, Banks Peninsula, with a cool, dry climate, has been adversely affected by trampling damage from cattle to exposed root systems over many years. Among the faster growing stands are Cornwall Park and the younger shelterbelt at Kamo where trees are established on well-drained, relatively fertile and sheltered sites at low density allowing development of large crowns. The young Tapapakanga stand is also achieving good growth on a fertile, ex-pasture, lowland site where trees have been kept free of weed growth during the early establishment phase.

Early records and performance of totara stands indicated that management of the stands varied considerably. Most had received poor after-planting care with consequent poor early growth. Furthermore, some stands were located on poor or inappropriate sites. Considerably better growth can therefore be expected on good quality lowland sites and where seedlings are kept free of weed competition in early years.

8.5.3 Stocking

Although growth of plantations was clearly influenced by site and history of stand maintenance, some differences in performance were due to stand density. Average DBH predicted for each stand at age 40 years shows a clear trend of decreasing diameter with increasing stocking (Figure 8.6) where the two shelterbelts and the Cornwall plantation planted at a wide spacing have been assigned a nominal stocking of 100 stems ha^{-1}. These latter plantings are virtually open-grown and have average diameters of over 35 cm at age 40 compared to 20 cm for trees at around 1000 stems ha^{-1} and only 15 cm for stands at around 2000 stems ha^{-1}. The best open-grown stand at Cornwall Park averaged nearly 50 cm at age 40 years.

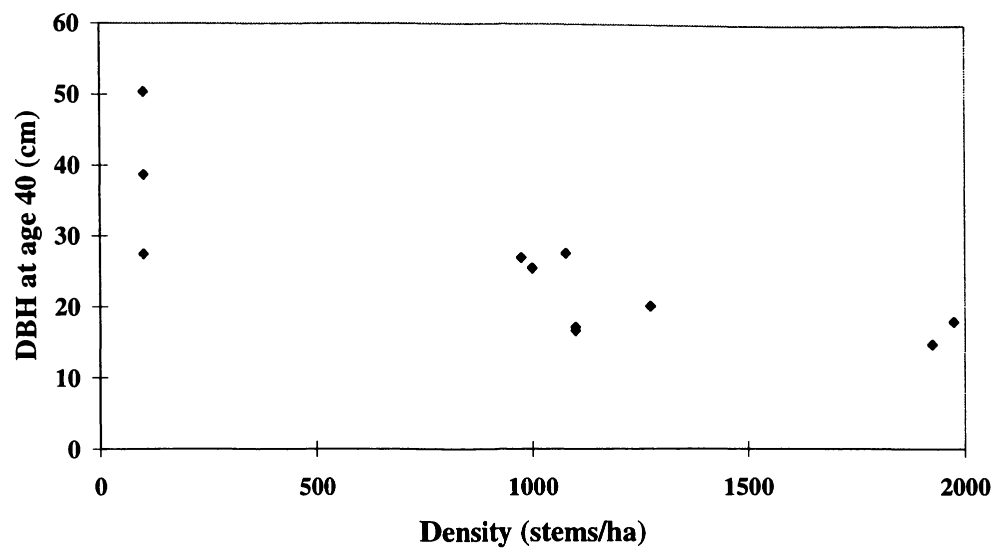


Figure 8.6: Estimated DBH at age 40 versus stocking for 11 planted totara stands. The underplanted stand at Kaingaroa and the young stand at Tapapkanga were excluded. A nominal stocking of 100 stems ha^{-1} were assigned to the two shelterbelts at Kamo and the wide-spaced stand at Cornwall Park.

In contrast to diameter, no clear relationship between stocking and height growth at age 40 (site index) was apparent (Figure 8.7).

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

8.5.4 Implications for management

Optimum densities for the planting of totara will depend on the objectives of establishing a plantation and the resources available. Planting totara at 2 m x 2 m spacing (2500 stems ha^{-1}) at the Tapapakanga stand has resulted in canopy closure within 10 years and faster growing trees over 5 m high and 10 cm in DBH on this good site. Within the next 10-20 years, growth will become severely affected by competition although good stem form will be enhanced by the high stocking as has occurred in the densely stocked 91-year-old Puhipuhi plantation which has not been tended since planting. To maintain good growth, at least half of the planted totara at the Tapapakanga stand will need to be removed eventually. Several silviculture regimes are intended for this trial to test timing and intensity of thinning and pruning operations.

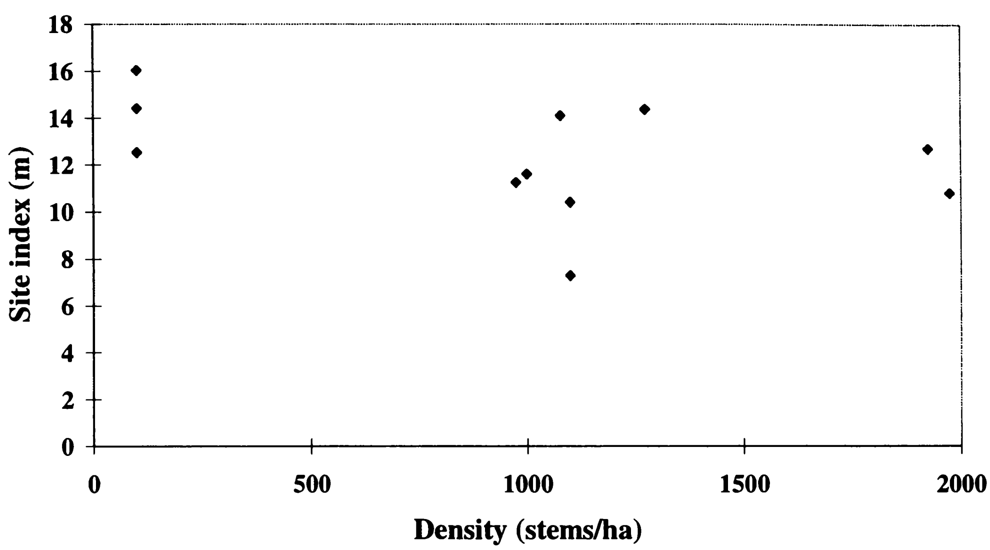
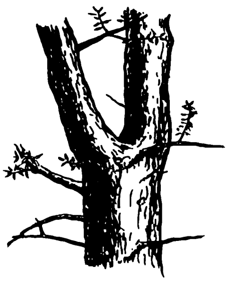


Figure 8.7: Estimated site index (height age 40) versus stocking for 11 planted totara stands. The underplanted stand at Kaingaroa and the young stand at Tapapakanga were excluded. A nominal stocking of 100 stems ha^{-1} were assigned to the two shelterbelts at Kamo and the wide-spaced stand at Cornwall Park.

The other extreme of planting at low density is exhibited by the Cornwall Park stands where lack of competition between planted trees has resulted in fast diameter growth and the development of multi-leadered trees with very large crowns. It is likely this stand effectively comprised open planted totara for at least the first 20 years after planting before canopy closure began by which time poor tree form had been formed.

For planting and management of totara for timber production, there is a compromise between the planting of densely stocked stands to achieve good stem form and the planting of trees at wide spacing to save on establishment costs but with increased incidence of poor form trees. Planting totara at high density and thinning to waste within 2-3 decades of planting is expensive as cost of good quality nursery-raised seedling are usually in the vicinity of $3-5 each. On the other hand, intensive pruning of trees planted at wide spacings is likely to be prohibitive where long rotations are envisaged.

Further research is required in determining other options for planting totara at various spacings and monitoring a range of thinning and pruning regimes. Planting totara within a nurse of planted or naturally regenerating hardy species such a manuka or kanuka or disturbance induced hardwood species such as wineberry is currently being investigated. On open sites where natural regeneration is unlikely, planting of manuka or kanuka at 2-3 m spacing several years before planting of totara at near final spacings of 4-6 m may be a less costly option. The nurse species will provide side shelter during the establishment phase and improve form of developing totara, which will eventually overtop shelter species to occupy the site in 20-30 years depending on the site and local climate.



CHAPTER 9

STEM FORM, BRANCHING CHARACTERISTICS AND WOOD QUALITY OF TOTARA

9.1 INTRODUCTION

Old growth indigenous forest has been the primary, if not only, source of timber for a wide range of cultural, construction and high-value wood product uses in New Zealand (McConchie 2000). These uses have been widely documented (Kirk 1874; Perceval 1895; Hinds and Reid 1957; Clifton 1990). Maori appreciated the wood properties of totara especially its ease of working, light weight and durability. Consequently, they used it extensively for construction, decorative carving and waka (Best 1942).

Heartwood totara was used by early European settlers for a wide range of building purposes, especially where durability was required. In addition, the timber is easily split lengthwise and was readily available on well-drained land being converted to farming. This led to large quantities of totara being used for post and batten fences in early days (Wardle 1974).

The reputation that totara has for excellent durability and ease of working has been gained almost entirely from the use of heartwood timber milled from large mature trees in old-growth forests. Trees would invariably have been several hundred years old with tall straight boles and large diameters (e.g., Esler 1978). Hinds and Reid (1957) report that length of the average sawlog milled in the central North Island at that time was 4.3 m and over 80 cm in diameter. Felled trees yielded high quality heartwood although a honeycomb-type decay of the heartwood (kaikaka) was common in the oldest trees.

With increasing interest in planting of indigenous trees to provide timber for specialty uses, there is a need to determine the quality of wood sourced from planted stands. These trees are likely to be relatively fast growing on most sites compared with trees in old-growth totara forest. There has been no study of tree form, branching characteristics, log type and log size in planted or relatively young naturally regenerating stands of totara that are potential resources of wood. There are indications that heartwood development is slow in young, fast-growing totara (Bergin and Pardy 1987) but no assessment of this has been undertaken.

Tree growth, crown architecture and branching characteristics are all factors that influence wood quality (e.g., Bamber 1987) and it is these factors that need investigation in totara from plantations and young natural stands. This chapter focuses on the influence of stand density and age on stem form and branching characteristics of totara in plantations assessed for growth and yield studies (Chapter 8) and for totara in natural stands (Chapter 6). The wood quality study, based on a limited sample of log sections, includes quantifying log defects and grading of sawn boards. An initial study of heartwood formation using cross-sectional discs was also undertaken. A preliminary descriptive model of stem form and branching development is given along with recommendations to improve form of young trees in early years.

9.2 OBJECTIVES

The overall objective is to gain a greater understanding of the relationship between stand characteristics with that of stem form and branching characteristics of totara in existing planted stands and young natural stands. Specific aims are:

- to quantify stem form and branching characteristics of totara using a pre-harvest log inventory system;
- to determine whether stand parameters such as stocking and stand age influence branch size and stem form;

- to describe and quantify wood quality characteristics from a limited sample of log sections, sawn boards and cross-sectional discs.

9.3 METHODS

9.3.1 Inventory

The MircroMARVL inventory system was used to describe and quantify stem form, branching characteristics and potential product yield for both totara-dominant natural stands and plantations (Forest Research Institute 1990; Goulding *et al.* 1993). The inventory involved sampling all totara trees that were included in either the Permanent Sample Plots or the Reconnaissance Plots that were established in natural stands (Chapter 6) and planted stands (Chapter 8). Each tree was assessed for size, tree form and log type based on stem length and straightness, presence of forks, frequency and size of branching, and any stem defects such as sweep (deviation from straightness) and butt rot. DBH was recorded for all trees and heights taken using a clinometer for a minimum of 12 canopy trees per stand covering the range of diameter sizes. Data was analysed two ways: first, to quantify tree architecture and branching characteristics and, second, to determine potential volume yields by log type for a selection of the older stands.

9.3.2 Stem form and branching

Data was analysed to quantify stem form and branching characteristics for each stand by:

- determining the total length of stems with no branches (A logs), small branches (S logs) or large branches (L logs);
- determining the proportion of trees with forking;
- determining the average height at which the first defect (fork, waste, or unmerchantable categories) occurred above ground level; and,
- an assessment of log types restricted to the lower bole. The lower bole was defined as from ground level to 4 m or 6 m high, referred to as the butt log. The proportion of trees with butt logs that met the minimum criteria of A, S and L logs were determined. All A type butt logs did not have branches but

S logs could include a proportion of A log (A+S) and, similarly, L logs could include a proportion of A and S log types (A+S+L).

A 'quality code dictionary' required for the inventory and analysis was developed (Table 9.1). This comprised codes covering stem qualities considered appropriate for various log types and defects present in the range of totara stands sampled. Stem and branching characteristics were then compared with stand parameters such as stocking and site characteristics for each stand, as well as changes over time from the range of different-aged stands that were sampled.

Table 9.1: Categories used to describe stem form in terms of log descriptions based on the MicroMARVL inventory system (Forest Research Institute 1990).

Code	Description
A	Pruned or where stems have naturally lost branches
S	Saw log with small branches < 7 cm diameter
L	Saw log with large branches > 7 cm diameter
W	Waste – sections of stem that have rot, severe stem malformation, excessive heavy branching
F	Fork of main stem into two or more leaders
X	Unmerchantable – includes poor form trees from ground level, section of tree beyond where main stem breaks into crown, dead standing trees

9.3.3 Log type and volume yield

The second approach to analysing inventory data involved using the MicroMARVL computer package (Forest Research Institute 1990) to determine potential product yield. As MicroMARVL is a predictive tool for estimating quantities of wood in established stands by certain log type, only the older totara stands, both planted and natural, were analysed.

A random sample of height-diameter pairs within each plot was used to obtain a height-diameter relationship specific to each stand. MicroMARVL then fitted a least-squares regression function to the data to obtain stand height required for analysis. The same stem quality code dictionary (Table 9.1) used in the first analysis was adopted for this analysis. In addition, a log specification or cutting strategy was developed for the range of sampled totara stands. As the

MicroMARVL method was being used to determine stem and branching characteristics for a wide age range of stands, relatively low limits were set for log length and small end diameter (SED) in the cutting strategy. Several options for cutting up logs to give practical information on timber yield and stem form that have implications on stand management were tested. A cutting strategy file was then developed for analysing stands containing the log specifications used by MicroMARVL (Table 9.2).

Table 9.2: Cutting strategy file used for logs from both planted and naturally regenerated stands of totara based on the MicroMARVL inventory system (Forest Research Institute 1990). Minimum SED was set at 2 cm and maximum SED and LED were set at 150 cm. Log length was set at 1-14 m.

Log type*	Log categories included in log type
A	A
S	A+S
L	A+S+L

* Log types are defined in Table 9.1.

To enable volumes to be calculated, volume and taper functions are required for MicroMARVL. However, specific volume and taper functions for totara do not exist. Consequently, for the analysis, the volume equation for kauri covering all pole stands (listed as V130 in the MircroMARVL programme) and the taper equation for Podocarpaceae from West Coast (listed as T332) were used. While not ideal, it was considered that these equations are the best available for estimating volume of young totara pole stands.

Analysis of covariance (ANOVA) and least significant difference (LSD) tests were used to test for significant differences in mean length of log categories, proportion of trees with forks, mean height of forks and mean height of merchantable stem with stand density, adjusting for mean stand height. For the analysis, stands were placed into one of four density categories. These were:

- natural high density stands – includes fully stocked natural stands;
- planted high density stands – includes stands where stocking is about 2000 stems ha^{-1} or greater;
- planted medium density stands – includes stands where stocking is around 1000 stems ha^{-1}; and,

- planted low density stands – stands where trees are established at wide spacing including shelterbelts.

9.3.4 External log assessment

Sixteen short log sections representing a range of diameter size classes were taken from one natural stand and one planted stand for assessment of wood quality. The SED, LED (large end diameter), bark thickness at both ends and sweep was recorded for each log section based on the methods described by Park and Leman (1983). Assessment of the external defects involved measuring the size of the defect as well as the position of the defect on the log. The defect categories were:

- TOB - trace of branch;
- DB - dead branch;
- RP - rot pocket;
- LB - living branch;
- CB - cluster of small branches.

To quantify the location of each defect on the log, a taut stringline was attached to each end of the log. The distance from the butt end of the log (LED) was then measured to the centre of each defect. The distance around the circumference of the log in a clockwise direction (when facing the small end) was then taken from the stringline to the centre of each defect along with the total circumference of the log at that point. The length and width of each defect was also recorded.

9.3.5 Wood quality assessment

Each log was sawn into slabs using a Wood-Mizer LT40HD band saw permanently mounted at Bartle's Sawmill, Rotorua. Logs were sawn into 25 mm thick flitches and numbered separately using the 'live sawing' pattern as shown in Figure 9.1. Cut surfaces of flitches were relatively smooth and required only minor sanding and clearing of sawdust in order to assess them for wood characteristics.

A cutting strategy was developed to obtain the maximum amount of wood from the live-sawn random-width flitches by theoretically edging each flitch into standard board widths of 5 cm, 7.5 cm, 10 cm, 12.5 cm, 15 cm, 17.5 cm, 20 cm, 22.5 cm, 25 cm, 27.5 cm or 30 cm. Board sizes were marked on the smallest face of each slab. The largest board widths possible were obtained from each flitch. The minimum piece length was 60 cm. In some cases more than one board was obtained from a single random-width flitch.

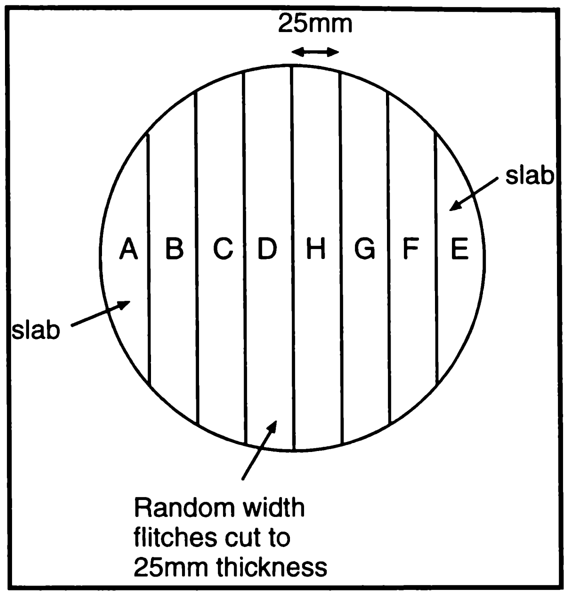


Figure 9.1: Saw pattern used for the 'live sawing' of log sections.

A visual grading assessment was carried out for each marked board so the internal defects could be related back to the external log assessment. Only one face of the board was assessed. Grading was based on the 'New Zealand Timber Grading Rules' using the indigenous softwoods timber grouping (Standards Association of New Zealand 1988) with some simplification of grade categories and criteria. All boards were placed into one of five grades based on wood characteristics or defects, which are listed and defined in Appendix 9.1. In practice, visual grading focussed on presence and size of knots with other criteria considered as secondary grading categories. Name and criteria used for each grade were:

- ***Clear*** – no knots; maximum of one resin streak 5 mm wide x 100 mm long; maximum of three surface checks 0.5 mm wide x 50 mm long; straight grain; no warp;
- ***Premium*** – maximum two pin knots; resin streaks maximum 5 mm wide and the sum of the lengths must be < 300 mm;

- ***Dressing*** – intergrown or partially intergrown knots up to 75 mm diameter; combinations of knots must not exceed one-third width of board; tight encased knots up to 15 mm; resin streaks maximum 10 mm wide and the sum of the lengths must be < 300 mm; surface checks 0.5 mm wide x 100 mm long;
- ***Building*** – holes and all knots; combinations of knots must not exceed one-third of 150 mm wide boards and one-quarter of wider boards; kaikaka not exceeding 5 mm diameter and must be > 20 mm apart; resin streaks not exceeding one-fifth width and one-third length of board; splits and shakes not exceeding length equal to one-quarter width of piece;
- ***Box*** – decay present; combinations of knots exceed one-third width of board; any combination of defects provided piece holds together in normal handling.

Total volume for the different board sizes and grades was obtained for each log and recovery estimates of board volume compared with log volume were obtained.

A comparison of recovery rate by board grade type between planted and natural stands was analysed using ANOVA. Standard errors for external log characteristics and proportion of board grades were calculated. Pearson correlation coefficients were calculated between external log defects including SED, maximum diameter of defect, number of defects per metre and sums of the diameter of defects for total board recovery and for board grade recovery.

9.3.6 Sapwood and heartwood development

Cross-sectional discs of totara were taken from a random selection of felled trees within a natural stand. They were also taken from trees within a plantation and from the edge of the same plantation. This allowed comparison of the relative proportion of heartwood development between and within stands. Both stands were located in Northland: the plantation at Puhipuhi, 25 km north of Whangarei, was 90-years-old, and a natural stand, estimated at 101 years based on ring counts, was in Glenbervie, 10 km northeast of the city. Using a chainsaw, discs were taken at stump height, approximately 30 cm above ground level, and removed for

sanding and assessment. A total of 46 discs were taken – 21 from the natural stand, 15 from within the plantation and 12 plantation edge trees.
Discs were sanded using a belt sander with progressively finer grades of sand paper from 80 to 320 grit. Eight equidistant transects from the chronological centre or pith to the outermost edge (bark) were marked on each disc. Discs were then examined by unaided eye for boundaries between sapwood and heartwood, and any possible transition zones based on changes in wood colour. In general, differentiation between the pale-coloured outer sapwood and darker-coloured heartwood provides a fairly reliable estimate of the sapwood/heartwood boundary for many species (Bamber 1987). The mean lengths of sapwood and heartwood were determined from the eight transects and used to calculate the basal areas for each disc.

There were various difficulties in identifying precisely sapwood/heartwood boundaries on discs. Where there were differences in colour between disc centres and outerwood, discs were scored on difficulty of identifying boundaries into one of three categories:

- 1 - well defined boundary;
- 2 - partially distinct where boundaries were not clear over at least half of the disc circumference; and,
- 3 - indistinct where only boundary was diffuse zone of gradual colour change around most of the disc circumference.

For all discs with distinct or partially distinct sapwood/heartwood boundaries (categories 1 and 2), the mean length of sapwood and of heartwood along transects on each disc were calculated and basal area determined based on disc diameter. Attempts to improve the visibility of the sapwood/heartwood boundary, including the use of a chemical formulation of 20% concentrated hydrochloric acid and 80% ethanol (Lawry 1980), light oil or moisture on the finely sanded surface of the disc, did not prove successful. In practice, the non-sanded side of each disc was reliable in identifying a clear sapwood/heartwood boundary on some discs whereas the sanded side proved more useful on other discs. Overall, it was difficult to precisely locate the sapwood/heartwood boundary as an apparent transition zone often blurred it. Where a transition zone occurred, it was included in the heartwood measurements. Consequently, estimates of sapwood and heartwood areas are only approximate. ANOVA was used to test for significant differences in the proportion of heartwood BA and radial length with disc diameter.

The number of growth rings were counted along two transects placed at greater than right angles to each other on each disc following sections where there was good ring definition from pith to bark. These counts were then averaged to give a ring count for each disc and were used to compare ring counts with actual age of the planted stand and to estimate the age of the natural stand. Any correlations between ring count and sapwood/heartwood development were then investigated.

9.4 RESULTS

9.4.1 Stem form and branching

Stem characteristics including mean length by log type based on the stand inventory were recorded for both planted and natural stands of totara (Table 9.3). There are trends in stem form and branching with age, type of stand, stocking and management history. Average length of logs with no branches (A log) increase from less than 0.5 m for the youngest planted stand at Tapapakanga (TAPA) to around 10 m for the oldest 90-year-old plantations at Puhipuhi (BROU1 and BROU2) (Figure 9.2). The relatively low mean length of A log evident at four of the older planted stands is due to various site factors. Cornwall Park (CORN) and to a lesser extent Prior Park (PRIOR) were established at very low stockings and hence developed very poor form (Figure 9.3). The most southerly stand in this study at Banks Peninsula (PURAU) had the slowest growth rate and poor management, and the two-row shelterbelt at Kamo (KAMO1) has a large edge-effect contributing to poor stem form (Figure 9.4). Most of these stands also have short mean merchantable stems.

Natural stands show a clear trend of increasing length of clear stems (A logs) with age exceeding an average length of 6 m within 100 years for many stands (Table 9.3). The mean length of small-branched logs tends to be consistent from young to older stands, while mean length of stems with large branches increases with age and merchantable height increases.

Table 9.3: Log type and stem characteristics based on MicroMARVL inventory of planted and naturally regenerating stands of totara.

Stand	Planted (P) or Natural (N)	Mean stand age (years)	Stand density (stems ha^{-1}) Stand type	Mean length of A log (m)	Mean length of S log (m)	Mean length of L log (m)	Mean length of waste (m)	Proportion of trees with forks (%)	Mean height of fork (m)	Mean height of merchantable stem (m)
TAPA	P	9	2500	0.43	4.46	0.22	0.02	50	0.88	3.87
HOLT	P	33	1975	3.34	7.14	0.29	0.01	10	3.87	10.19
KIANG	P	36	Underplanted	1.2	2.82	0.82	0.09	31	2.59	4.46
KAMO2	P	44	Shelterbelt	2.42	2.43	1.72	0.15	17	7.14	6.23
GLEN	P	46	975	2.63	1.69	3.33	0.26	31	4.12	7.45
HOLD	P	50	1100	2.9	6.21	0.28	0.15	7	3.16	9.25
PUKE1	P	62	1078	6.05	2.75	3.34	0.57	47	3.71	9.57
CORN	P	70	Wide spaced grove	0.38	0	0.79	0.21	8	5.96	1.25
PUKE7	P	83	Scattered forest	7.08	0.68	7.15	0.38	69	5.14	13.62
PURAU	P	86	1100	1.25	2.21	1.2	0.21	6	2.18	4.77
PRIOR	P	88	1000	2.51	7.12	1.61	0.2	48	5.33	10.07
BROU2	P	90	1925	10.51	4.05	0.32	0.16	17	6.25	13.98
BROU1	P	91	1275	9.56	2.62	4.04	0.26	25	5.52	14.53
KAMO1	P	94	Shelterbelt	2.74	1.04	5.3	0.31	6	6.18	9.17
LANE1	N	19	64000	0	1.16	0	0.02	2	5.85	1.14
LANE2	N	21	49000	0	2.19	0.09	0	2	0.25	2.23
QUIN1	N	24	9750	0.58	4.83	0.22	0.1	1	2.19	5.33
OWEN2	N	26	15250	0	3.67	0.41	0	0	1.4	4.08
OWEN1	N	27	12500	0	4.3	0	0.05	0	1.4	4.35
COOP1	N	31	23750	0.35	3.26	0	0	7	0.93	3.45
COOP2	N	34	21000	0.64	3.57	0	0	0	0.3	4.21
DONE3	N	36	9500	0	4.24	0	0.08	18	0.86	3.92
DONE4	N	36	9250	2.5	5.45	0.79	0.39	5	1.6	8.95
DONE2	N	37	4250	0.06	8.26	0	0.09	53	0.52	5.46
COOP3	N	39	9000	0.47	4.74	0	0.04	14	1.59	4.8
QUIN2	N	40	6369	2.64	2.18	0.12	0.04	0	3.1	4.98
COOP4	N	41	2293	3.77	2.22	0.38	0	0	2.1	6.37
COOP7	N	43	12367	1.24	5.73	0.23	0.08	13	4.1	6.83
LANE 3	N	55	5860	4.31	1.97	0.09	0.07	0	0.5	6.43
DONE1	N	60	9750	5.04	3.7	0	0.19	12	3.11	8.34
BRID2	N	77	3567	5.84	3.11	0.25	0	7	7.56	9.02
DONE6	N	82	1078	6.02	2.37	3.08	0.15	17	7.21	10.81
MACK2	N	83	1544	6.66	5.32	2.16	0.12	2	4.61	12.45
MACK1	N	94	1348	5.67	3.73	4.17	0.3	4	3.61	11.91
DONE5	N	118	1520	3.21	3.32	2.4	0.25	9	0.96	8.46
BRID1	N	129	735	8.72	3.06	2.71	0.06	11	5.34	14.09
REED	N	140	882	10.63	2.66	3.21	0.16	18	13.09	16.16

Figure 9.2: Average length of A log (stem without branches) was 10 m for the high-density 90-year-old plantation at Puhipuhi (BROU).

There is no consistent trend with age between proportion of stems and incidence of forking (Table 9.3). However, there is a general trend of increasing mean height to the first fork with age, particularly for natural stands. This suggests canopy closure and subsequent low light levels in the understorey result in dieback of lower, forking stems or natural thinning of poorly formed trees, and thus, an improvement in tree form within stands over time. The 62-year-old totara plantation at Pukekura Park (PUKE1), New Plymouth, has the highest incidence of stem classes as waste as well as the highest number of trees forked into two or more stems. This reflects observations of the unusually high degree of malformation in this stand compared with similarly aged stands. The Pukekura plantation is surrounded by other indigenous conifers that were densely planted at the same time as the totara, where it would be expected to have encouraged good form. Other factors may have contributed to dieback of leaders in early years resulting in poor form. These include damage to growing tops by insects or possums or out of season frost. The low incidence of forking and relatively high mean merchantable stem for the 33-year-old stand at Holts Forest Trust (HOLT) reflects the intensive management of this stand. Trees were kept released from weed growth in early years and stems have been pruned on a regular basis to remove double leaders and lower branches.

Figure 9.3: Establishment of this 70-year-old stand at very wide spacing of 5 m between trees at Cornwall Park (CORN) has resulted in poor form and no merchantable stems.

For the plantations, improved stem form is consistent with increasing age of trees. This is reflected in larger proportions of 4 m and 6 m butt logs with no branching

(Table 9.4). The proportion of trees with small-branched butt logs decreases as branches are shed or thinning of low branching trees occurs over time, thus increasing the A log component of stands. In contrast, trees established at wide spacing, including shelterbelts, retained lower large branches contributing to the higher incidence of poor quality logs from these stands. There were no merchantable logs for the Cornwall Park stand (Fig. 9.3) and no A logs for Prior Park (Fig. 9.4). Only a low proportion of A logs were identified at the 94-year-old shelterbelt at Kamo due to wide spacing. In contrast, the densely-stocked stand at Puhipuhi (BROU2) had the highest proportion of 4 m and 6 m long A logs and the lowest proportion of unmerchantable logs. The poor growth and management of the Banks Peninsula stand (PURAU) contributed to the high proportion of unmerchantable logs.

Figure 9.4: Totara in this 94-year-old shelterbelt at Kamo, north of Whangarei, have coarsely branched stems to low levels due to the near-open growing conditions.

Table 9.4: Proportion of trees with 4 m and 6 m butt log lengths by log type for planted and natural stands 50 years and older.

Stand	Planted (P) or Natural (N)	Mean stand age (years)	Mean height of merchantable stem (m)	Proportion of trees with 4 m butt log within log categories (%)				Proportion of trees with 6 m butt log within log categories (%)			
				A log	S log	L log	X	A log	S log	L log	X
HOLD	P	50	9.25	8.9	44.4	13.3	33.3	.	40.0	11.1	48.9
PUKE1	P	62	9.57	20.0	.	20.0	60.0	6.7	.	20.0	73.3
CORN	P	70	1.25	.	.	.	100.0	.	.	.	100.0
PUKE7	P	83	13.62	46.2	.	15.4	38.5	38.5	.	15.4	46.2
PURAU	P	86	4.77	9.1	24.2	15.2	51.5	3.0	12.1	9.1	75.8
PRIOR	P	88	10.07	.	36.0	36.0	28.0	.	16.0	24.0	60.0
BROU2	P	90	13.98	89.6	.	.	10.4	77.9	2.6	2.6	16.9
BROU1	P	91	14.53	66.1	1.8	16.1	16.1	33.9	3.6	23.2	39.3
KAMO1	P	94	9.17	8.3	11.1	47.2	33.3	2.8	5.6	41.7	50.0
LANE 3	N	55	6.43	65.4	15.4	.	19.2	15.4	30.8	3.9	50.0
DONE1	N	60	8.34	80.0	.	.	20.0	20.0	48.0	.	32.0
BRID2	N	77	9.02	85.2	11.1	.	3.7	40.7	44.4	7.4	7.4
DONE6	N	82	10.81	65.9	4.9	2.4	26.8	43.9	4.9	12.2	39.0
MACK2	N	83	12.45	42.0	12.0	18.0	28.0	18.0	18.0	28.0	36.0
MACK1	N	94	11.91	16.7	4.2	37.5	41.7	4.2	4.2	37.5	54.2
DONE5	N	118	8.46	26.5	8.8	8.8	55.9	8.8	8.8	14.7	67.7
BRID1	N	129	14.09	96.3	3.7	.	.	77.8	7.4	7.4	7.4
REED	N	140	16.16	97.1	.	.	2.9	91.2	2.9	2.9	2.9

The natural stands at the Reed Memorial Reserve (REED), Whangarei, and the nearby stand at Glenbervie (BRID1) had the highest proportions of 4 m and 6 m A logs (Table 9.4). These were the oldest stands sampled with a stand density of 735-882 stems ha^{-1}. In contrast, the two next oldest stands (MACK1 and DONE5) have a high proportion of logs with small or large branches or were unmerchantable. These stands have high stocking (1348-1520 stems ha^{-1}) and typically comprise stems covering a wide range of size and age classes where many trees with poor stem form and lower branching are still present. With continued intense within-stand competition, it is likely that many of these trees will be thinned out over the next few years. This will result in an improvement in average stem form for the stands.

When planted stands were divided into the three stem density categories (high, medium, low) and compared with the high density natural stands, there is a consistently decreasing trend in mean length across all log categories (Figure 9.5). There was also a decrease in merchantable height (Figure 9.6) with decreasing density. The lengths and merchantable height were adjusted for mean stand height and despite the small sample sizes and variation between stands, stand density is significantly influencing stem form and branching (Table 9.5). Compared with the medium and high density stands, mean length of A log, accumulated log categories A+S and A+S+L, and mean merchantable height are significantly lower in the low density stands.

9.4.2 Log type and volume yield

Estimated total merchantable volume varies from 96 m^{3}ha^{-1} for the 55-year-old natural Kaeo stand (LANE3) to 1150 m^{3}ha^{-1} for the planted 91-year-old plantation at Puhipuhi (BROU1) (Table 9.6). There are larger differences between total tree volumes and merchantable volume for the youngest natural stands (55-60 years) but these differences decrease with age for most stands. The two planted stands are not only faster growing compared with natural stands, but also have a much greater proportion of higher grade A log volume (34-40%) compared with less than 10% for similarly aged natural stands. For stands over 80 years of age, 54-79% of the merchantable volume is categorised as large branched logs (L). The high density young natural stands have a low proportion of L logs. Similarly, the higher density planted stand has a lower proportion of L logs compared with the lower density planted stand.

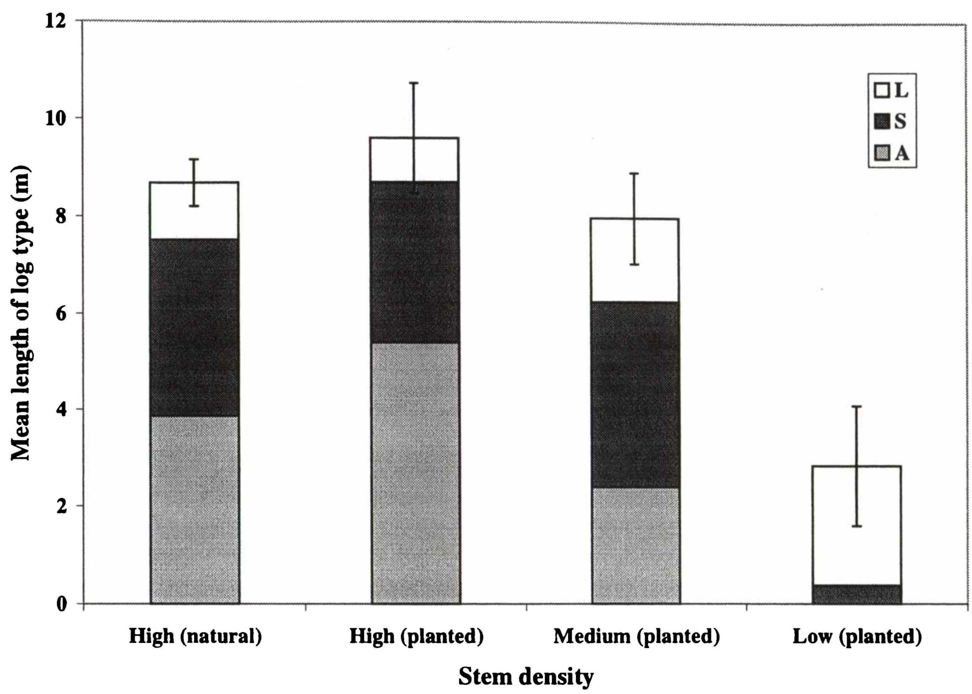


Figure 9.5: Mean length of logs by category for natural stands with high stem densities, and planted stands at three stem density classes - high (2000 stems ha^{-1}), medium (1000 stems ha^{-1}) and low (shelterbelts and wide-spaced groves).

9.4.3 External log characteristics

Log length, LED, SED and other log measurements for the 16 log sections from the planted and natural stands are given in Table 9.7. SEDs varied from 12.1-32.7 cm with little sweep in log sections sampled. Log taper generally increased with age for the natural stands but was variable for the planted stand. Across all log sections, log taper averaged 17 mm per metre. Bark thickness increased with age averaging 3.6 mm at the large end and 3.3 mm at the small end. Between three and 11 boards of 25 mm thickness were obtained from each of the 16 log sections.

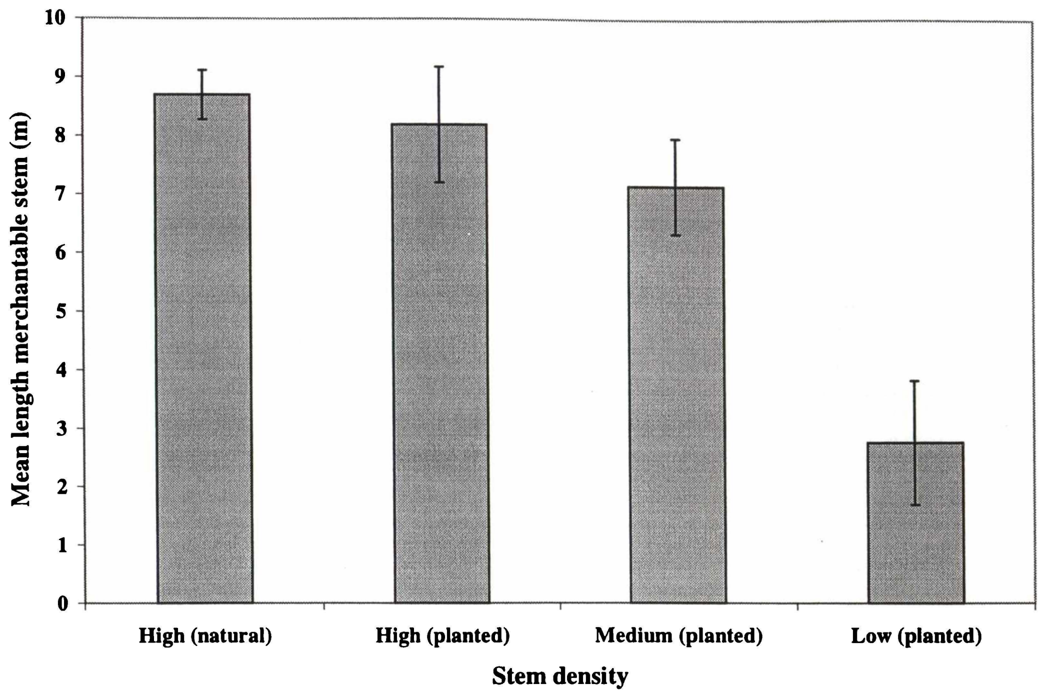


Figure 9.6: Mean merchantable height for natural stands with high stem densities, and planted stands at three stem density classes - high (2000 stems ha^{-1}), medium (1000 stems ha^{-1}) and low (shelterbelts and wide-spaced groves). Log categories are accumulative with decreasing log quality.

Table 9.5: Mean length of logs by category and mean merchantable height for natural stands with high stem densities, and planted stands at three stem density classes - high (2000 stems ha^{-1}), medium (1000 stems ha^{-1}) and low (shelterbelts and wide spaced groves). Analysis of log categories and merchantable height was adjusted for mean stand height. Within each column, values followed by the same letter are not significantly different ($p = 0.05$).

Stand type	Stem density category	Mean length of log categories (m)			Merchantable Height (m)
		A	A+S	A+S+L	
Natural stands	High	3.9 ab	7.5 a	8.7 a	8.2 a
Planted stands	High	5.4 a	8.7 a	9.6 a	8.7 a
	Medium	2.4 b	6.2 a	8.0 a	7.2 a
	Low	0 c	0.4 b	2.0 b	2.8 b

Table 9.6: Merchantable volume by log type using MicroMARVL for two planted stands and older naturally regenerated totara-dominant stands located in Northland.

Plot	Stand age (years)	Density of totara (stems ha^{-1})	Total tree volume of totara^{+} (m^{3}ha^{-1})	Merchantable volume$^{\#}$ (m^{3}ha^{-1})	Merchantable volume m^{3}ha^{-1} (%)		
					A log	S log	L log
BROU1*	91	1275	1297.0	1149.4	389.6 (34)	268.3 (23)	491.6 (43)
BROU2*	89	1925	972.0	802.4	320.2 (40)	406.3 (51)	75.9 (9)
LANE3	55	5860	220.0	95.7	16.8 (18)	62.3 (65)	16.6 (17)
DONE1	60	9750	468.0	168.6	43.3 (26)	125.3 (74)	0 (0)
BRID2	77	3566	337.4	279.6	33.8 (12)	182.2 (65)	63.6 (23)
DONE6	82	1078	348.5	330.0	53.3 (16)	66.5 (20)	210.2 (64)
MACK2	83	1544	466.5	413.3	16.8 (4)	95.4 (23)	301.2 (73)
MACK1	94	1348	636.9	514.2	35.0 (7)	72.3 (14)	407.0 (79)
DONE5	118	1520	1283.6	598.7	39.8 (7)	145.9 (24)	413.0 (69)
BRID1	129	735	685.5	608.4	67.7 (11)	200.9 (33)	339.8 (56)
REED1	140	882	788.8	730.1	118.4 (16)	218.2 (30)	393.5 (54)

* Planted stands.
\+ Total volume of totara is based on total tree volume derived from Ellis (1979).
\# Merchantable volume allows for cutting waste and is derived from MircoMARVL survey.

Number of defects found on logs varied from 0-8.7 per metre with mean diameter of defects varying from 1-6.5 cm (Table 9.8). The most common feature was branch traces (TOB) making up at least one-third of all external defects on most logs. Dead branches (DB) was the next most common defect occurring on almost half of the log sections and evidence of rot pockets (RP) on one quarter of logs assessed.

9.4.4 Timber grade recovery

Recovery of sawn timber from logs was generally very high due to the small minimum piece size that was used (Table 9.9). Total recovery varied from 47-88% and, as expected, was larger with increasing SED (Figure 9.7). The largest diameter log section (log No. 5) gave the only significant recovery of clear timber, with other large log sections having significant quantities of premium grade. Most timber was graded as dressing. There was no significant difference in recovery rate by board grade between log sections from the planted and natural stands (Table 9.10). Similarly, due to the wide variation in range of defects and the small sample of log sections and sawn boards, there were no significant correlations between external log characteristics and board grades across all 16 log sections (Table 9.11). There were no significant correlations between external log defects and timber grading of boards sawn from each log other than for total recovery with SED and for clear grade with SED, although the latter only involved a small proportion of the total timber recovered (Table 9.12).

Table 9.7: Log sections of both natural stands and the plantation (BROU2) of totara used for examination of external log characteristics and 'live sawing' for wood quality assessments (in order of increasing SED for natural stands and plantation).

Stand	Log No.	SED (cm)	LED (cm)	Length (m)	Sweep (mm per metre)	Taper (mm per metre)	SE bark thickness (mm)	LE bark thickness (mm)	No. of 25 mm boards cut*
DONE2	8	12.6	15.2	2.30	0	11	3	3	3
DONE1	1	15.4	17.4	2.25	20	9	4	2	3
DONE1	2	17.4	20.1	2.05	14	13	3	4	5
DONE5	13	17.9	21.5	2.08	0	17	3	2	5
DONE1	3	19.1	23.6	2.23	0	20	4	3	6
DONE5	4	28.0	32.4	2.14	0	21	4	5	9
DONE5	12	29.3	33.5	2.05	0	21	5	6	9
DONE5	5	32.4	35.7	0.78	0	42	5	6	9
DONED	7	32.7	36.2	1.05	0	33	6	5	11
BROU2	20	12.1	13.6	1.44	45	10	1	1	3
BROU2	19	13.8	15.5	1.46	0	12	2	2	4
BROU2	15	18.6	20.4	1.37	30	13	3	3	4
BROU2	17	19.5	20.3	1.47	0	5	3	3	5
BROU2	16	21.0	22.7	1.46	0	12	2	2	7
BROU2	14	23.0	25.8	1.54	0	18	3	4	7
BROU2	18	26.0	27.0	1.08	0	9	3	6	8

* The number of 25 mm wide thick boards cut from the log excluding the two outer slabs.

Table 9.8: External log defects assessed on 16 log sections from natural stands and the plantation of semi-mature totara (in order of increasing SED for natural stands and plantation).

Stand	Log No.	SED (cm)	No. of defects	No. of defects per metre of log length	Mean diameter of defects	Type of defect (%)*					
						TOB	DB	RP	BS	LB	CB
DONE2	8	12.6	20	8.7	3.34		30.0			65.0	4.6
DONE1	1	15.4	7	3.1	1.83	71.4	28.6				
DONE1	2	17.4	13	6.3	1.65	92.3	7.7				
DONE5	13	17.9	3	1.4	6.50	33.3	33.3		33		
DONE1	3	19.1	4	1.8	1.63	75.0		25			
DONE5	4	28.0	3	1.4	3.67	33.3	33.3	33.3			
DONE5	12	29.3	12	5.9	1.85	100.0					
DONE5	5	32.4	0	0							
DONED	7	32.7	1	1.0	1.50	100.0					
BROU2	20	12.1	8	5.6	1.69	37.5	12.5	37.5		12.5	
BROU2	19	13.8	3	2.1	1.00	100.0					
BROU2	15	18.6	10	7.3	3.20	50.0	50				
BROU2	17	19.5	6	4.1	2.72	83.3		16.7			
BROU2	16	21.0	10	6.8	1.88	100.0					
BROU2	14	23.0	11	7.1	2.36	100.0					
BROU2	18	26.0	2	1.9	2.75	100.0					

* Definition of defect codes:
- TOB - trace of branch
- DB - dead branch
- RP - rot pocket
- LB - living branch
- CB - cluster of small branches

A large number of pin knots were located within the central parts of log sections when visually assessed. These encased knots were less than 10 mm with most only 5 mm in diameter. Dieback of occasional large branches had left small pockets of rot, some of which had become encased with subsequent tree growth.

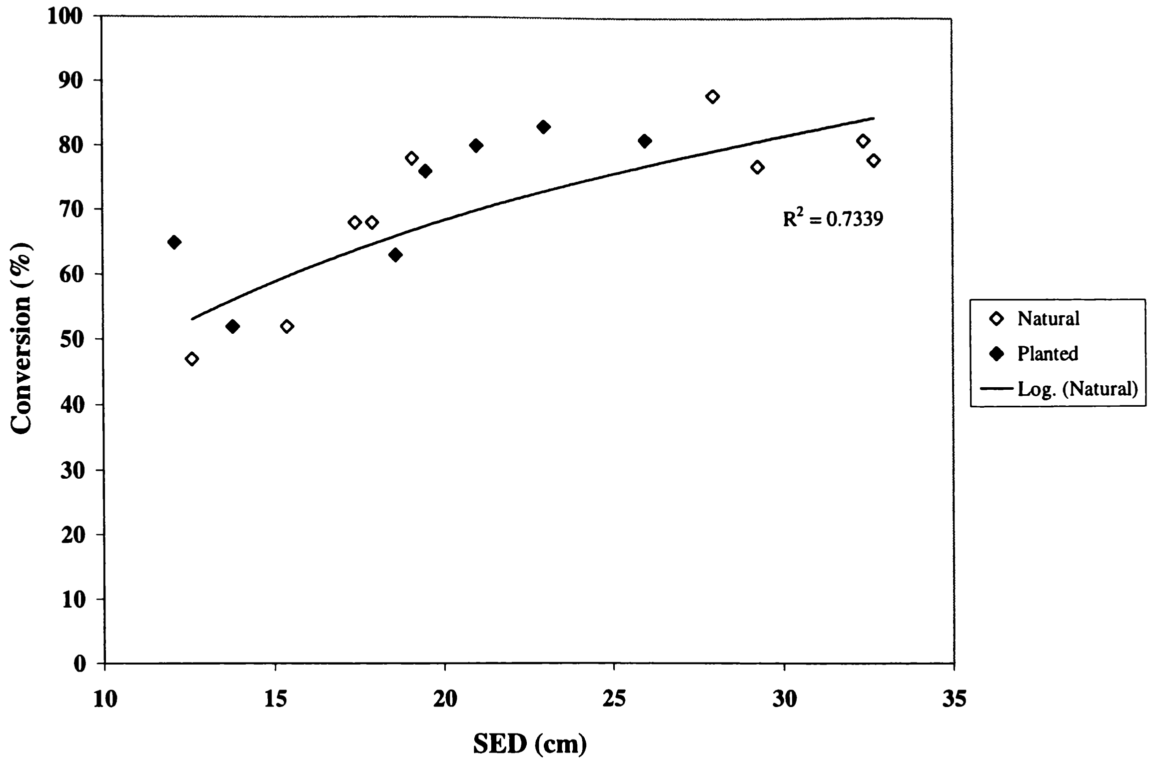


Figure 9.7: Conversion of log sections to timber versus small end diameter (SED) for each of the 16 sawn log sections of totara.

9.4.5 Sapwood and heartwood development

Boundaries between heartwood, transition and sapwood tended to be convoluted and did not follow single growth rings around the circumference of the tree (Appendix 9.2). They also varied from sharply defined to diffuse, within and between discs from both the planted and natural stand. Only those discs which had heartwood/sapwood boundary definitions that were either well-defined or classed as intermediate, were used for assessing heartwood formation. Two discs from the planted stand and four from the natural stand had poorly defined boundaries and were not analysed further. Disc diameter, growth ring count, mean transect length and BA of sapwood and heartwood, and proportion of heartwood are given in Appendix 9.2 for the 17 discs from the natural stand, 13 from the plantation and 12 from plantation edge trees.

Table 9.9: Summary of board grades and volume recoveries of log sections of totara. Minimum length of boards was 60 cm. Stands are in order of increasing SED for natural stands and the plantation.

Stand	Log No.	SED (cm)	Log volume per log (m^3)	Board volume per log (m^3)	Total recovery (%)	Recovery by grade (accumulative %)				
						Clear	Premium	Dressing	Building	Box
DONE2	8	12.6	0.025	0.012	47	0	0	100	100	100
DONE1	1	15.4	0.034	0.018	52	0	29	100	100	100
DONE1	2	17.4	0.040	0.027	68	4	22	72	100	100
DONE5	13	17.9	0.045	0.030	68	0	0	20	20	100
DONE1	3	19.1	0.056	0.044	78	9	9	20	83	100
DONE5	4	28.0	0.106	0.094	88	9	31	72	100	100
DONE5	12	29.3	0.120	0.080	77	3	12	85	100	100
DONE5	5	32.4	0.049	0.039	81	27	60	87	87	100
DONED	7	32.7	0.068	0.053	78	0	14	87	100	100
BROU2	20	12.1	0.013	0.009	65	0	27	65	100	100
BROU2	19	13.8	0.018	0.009	52	0	17	100	100	100
BROU2	15	18.6	0.029	0.018	63	0	0	100	100	100
BROU2	17	19.5	0.032	0.024	76	0	11	100	100	100
BROU2	16	21.0	0.038	0.031	80	0	6	80	100	100
BROU2	14	23.0	0.050	0.040	83	0	35	100	100	100
BROU2	18	26.0	0.041	0.033	81	12	37	100	100	100

Table 9.10: Comparison of recovery rates by board grade for the planted stand and natural stands.

	Planted stand		Natural stand	
	Recovery (%)	Standard error	Recovery (%)	Standard error
Total	74.5	3.05	68.4	2.68
Clear	2.9	2.49	4.9	2.18
Premium	21.3	6.11	17.9	5.36
Dressing	93.8	9.80	70.1	8.60
Building	100.0	7.84	87.0	6.88

Table 9.11: Comparison of external log defects and board recovery by grade for the 16 log sections sampled.

	Variable	Mean	Standard error
External log characteristics	SED (cm)	21.2	1.69
	Maximum diameter of defect per metre (cm)	7.0	2.14
	Number of defects per metre	4.1	0.67
	Sum of diameter of defects (cm)	0.11	0.02
Board grades (%)	Clear	4.0	1.83
	Clear + Premium	19.4	4.12
	Clear + Premium + Dressing	80.4	6.62
	Clear + Premium + Dressing + Building	93.1	5.04

Table 9.12: Correlations between external log defects and total and board grade recovery.

	Total recovery	Clear	Premium	Dressing	Building
SED	0.77*	0.56*	0.44	0.10	0.07
Max. diameter of defect	-0.40	0.10	-0.17	0.02	-0.25
No. of defects	-0.30	-0.46	-0.36	0.34	0.36
Sum of diameters of defects	-0.25	0.03	-0.12	0.31	0.06

* Significant at $P < 0.05$

Plantation edge trees were significantly larger with more growth rings than trees from within the stand (Table 9.13). The number of growth rings of trees within the plantation ranged from 58.5-85.5 with a mean ring count of 74.6 compared with edge trees which had a range of 82.5-117.5 and a mean count of 113.2. This is consistent with the aging study (Chapter 3) where fast-growing large trees tended to form more than one ring in some years, and suppressed small trees were not forming visible rings every year. Despite this, mean ring count from the total of 27 discs sampled from the plantation of 93.1 is close to the actual stand age of 90 years. However, compared with the plantation, there is greater variability in growth ring count and disc diameter for trees in the natural stand (Figure 9.8). This is also consistent with the age studies of natural stands where recruitment of totara on regenerating sites is likely to span several years before canopy closure occurs (Chapter 6). Variability in growth rings and disc diameter was less for trees within the plantation compared with plantation edge trees and those from the natural stand (Figure 9.8).

Table 9.13: Proportion of heartwood basal area (BA) and radial length in cross-sectional discs from trees within a natural stand, within a 90-year-old plantation and edge trees from the same plantation. Correlations have been adjusted for diameter of sampled cross-sectional discs. Standard errors are given in parentheses. Within each column, values followed by the same letter are not significantly different (p = 0.05).

Stand type	Mean diameter of disc (cm)	Mean growth ring count	Mean BA of heartwood (cm^2)	Proportion of heartwood BA (%)	Proportion of heartwood radius (%)
Natural stand	39.2 a	101.2 a	294.6 a	25 a (4.7)	44.9 a (5.3)
Plantation	15.5 b	74.6 b	69.8 b	43 b (6.1)	61.3 a (6.8)
Plantation edge	35.5 a	113.2 a	268.5 a	30 ab (5.2)	53.0 a (5.9)

Proportion of heartwood cross-sectional area varied from 0-79% for discs from the natural stand, 0-64% for the plantation and 16-50% for plantation edge trees (Appendix 9.2). Basal area of heartwood generally increased with increasing disc diameter for all stand types. Trees within plantations had significantly less heartwood basal area than trees from the other two stands, merely reflecting differences in tree size (Table 9.13). There was a significant difference between stand types in the proportion of heartwood BA formed, but not in proportion of radial diameter identified as heartwood, where correlations had been adjusted for disc diameter. In general, the proportion of heartwood tended to be greater for the smaller plantation trees when compared with the larger trees in the other stand types.

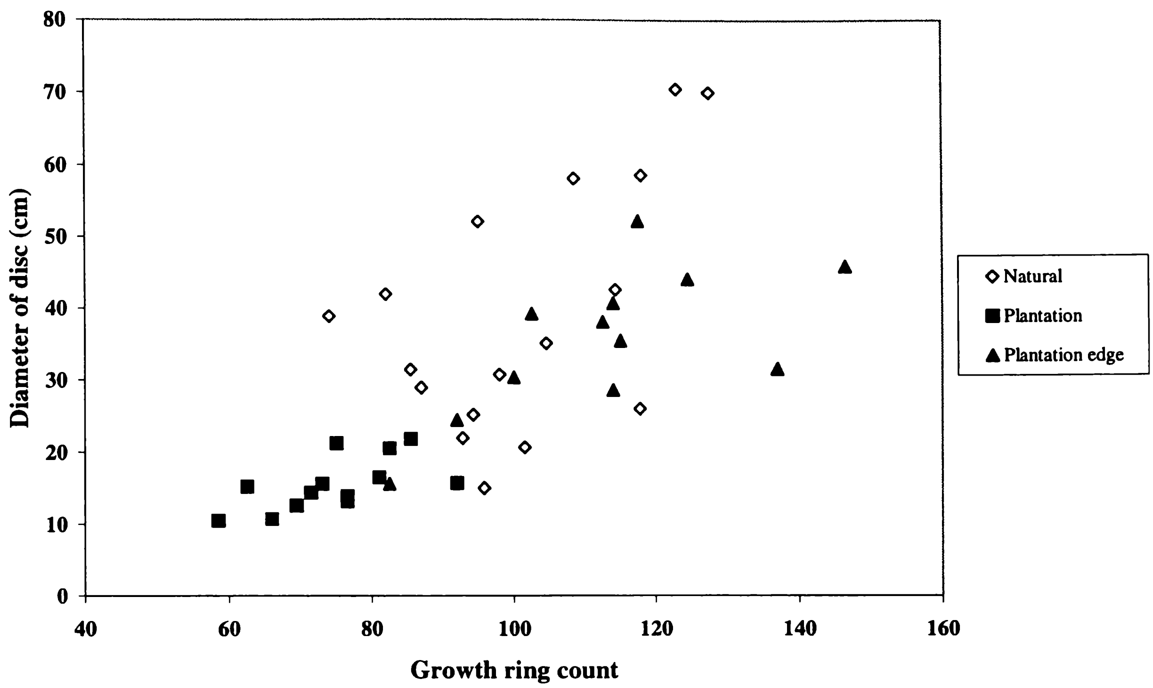


Figure 9.8: Correlation between growth ring count and diameter of cross-sectional discs for trees within a natural stand, within a plantation, and edge trees of the same plantation. Estimated mean age of the natural stand was 101 years based on ring counts. The plantation was 90 years old.

9.5 DISCUSSION

9.5.1 Stem form and branching

Stem form of totara is clearly linked to the degree of intraspecific competition. Dense stocking promotes better stem form with long clear boles and small branching. Even in the absence of tending, average stem form improves where stands remain at high densities during the first 100 years. It is only in the low-stocked planted stands, including shelterbelts, that a high proportion of trees retain multiple stems and large branching in response to high light levels (Figure 9.5).

For natural stands, intense within-stand competition for space and light has resulted in natural thinning particularly in early years. This is when establishment densities in the tens of thousands of stems per ha reduce to a thousand stems per ha or less over time. While some mortality is borne by multi-leadered and coarsely branched trees, it is also evident that trees with multiple stems are improving in form with age. Less dominant leaders and apically dominant large branches often die back to leave single leaders. Subsequently, better-form trees progressively increase in proportion in the stand over time. This is shown in the increasing length of clear logs and generally increasing height to first fork (Table 9.3) with time, especially evident in natural stands.

Branch shedding appears to occur by gradual disintegration of dead branches as wood dries, becomes brittle, and is easily broken off. Stock movement breaks off the lower dead branches in young stands and wind contributes to removal of upper dead branches. Large branches tend to progressively rot down to a stub that eventually becomes intergrown as the stem increases in diameter. Some intergrown knots were evident in sawn logs although occasional rot pockets appeared to be associated with dieback of large branches.

In the same way that planting density predetermines early stem form, the pattern of establishment in natural stands also influences tree form. In very high density natural stands that have established over a short time, relatively even-size trees with good lower stem form often dominate stands as they undergo severe intraspecific competition. For stands that establish at wider spacing in combination with manuka, kanuka and gorse, or have only slowly colonised pasture sites, tree form and growth is variable. While relatively even-sized trees were sampled in this study, stands were observed with extremes in stem size, especially where large multi-stemmed totara were surrounded by densely stocked single-leadered totara. These early entrants are likely to have been the seed source of the later surrounding entrants. Seeding of totara and germination of seedlings at the Tapapakanga provenance trial (Chapter 3) was observed within 10 years of planting confirming that early entrants in natural stands have the potential to produce seed within a decade of establishment.

9.5.2 Wood quality

A comparison of two plantations with seven semi-mature natural stands with at least 1000 stems ha^{-1}, indicates that planted stands not only grow faster, but where stand density is relatively high, log quality is also higher (Table 9.6). Due partly to high initial stem densities and subsequent severe natural thinning, natural stands are taking at least 40 years longer to produce similar merchantable volumes to 90-year-old plantations. Site factors are likely to also have a role. The plantations at Puhipuhi are on flat fertile sites compared with the natural stands located on moderate to steep hillsides with less well-developed soils. The intense competition as natural stands develop has not improved stem log quality to the same extent as planted stands.

The 80% conversion of log flitches to sawn boards for an SED of 30 cm for totara is relatively high, reflecting the minimum board lengths applied in this study (60 cm). Milling old-growth totara from the central North Island during the 1950s averaged a conversion rate of 54% (Hinds and Reid 1957). There was substantial wastage due to abundance of wood, poorer milling techniques and machinery, and low incentives to maximise wood production. In this study, as expected, the conversion of logs to boards increased with increasing SED.

The preliminary assessment of wood quality indicates that logs from the planted and natural stands are relatively similar in the type and quantity of defects. External log characteristics and board grades were largely consistent throughout the sample. High quality board grade recovery was, on average, very high where up to one quarter of boards were rated as clear or premium grade and 70% of the timber was graded as dressing or better (Table 9.10). In comparison, timber conversion from milling large trees from old-growth forest yielded average rates of 54% for finishing grade, 34% for building and 12% graded as rough (Hinds and Reid 1957).

Figure 9.9: Dieback of double leaders and steep angle branches was observed in sapling and pole stands undergoing intense intraspecific competition. Subdominant leaders and branches become shaded and die. Brittle and rotten branches are broken off by cattle at low levels or by wind higher up.

This preliminary study of wood quality indicates there are likely to be no major defect problems in timber from plantations or from relatively young, naturally regenerating stands, even in the absence of any tending such as pruning or thinning. The major determinant of good stem form and branch shedding from lower boles is stem density. Stands approaching 100 years of age with at least 1000 stems ha^{-1} have significantly better form than trees growing at wide spacing. However, a more comprehensive study sampling a greater range of plantations and young natural stands is required for an in-depth analysis of site and stand factors that influence wood quality.

9.5.3 Development of heartwood

This investigation of heartwood development in relatively young totara indicates there is considerable variation between trees within stands and was similar for both the natural stand and the plantation. No significant correlation between heartwood development and tree size was established with the small sample evaluated. Widescale sampling would be required to determine whether heartwood formation in totara is a function of age or tree size, and whether environmental factors have an influence. Nevertheless, the study based on visual assessments has shown that one quarter of the cross-sectional area of totara from natural stands around 100 years of age with a mean diameter of nearly 40 cm was either transition wood or heartwood.

Parham (1929) found that totara has a clear boundary from sapwood to heartwood and no intermediate zone visible to the naked eye. In contrast, a visible transition zone between sapwood and heartwood was apparent on many discs from both the planted and natural stands.

A major issue for totara will be rotation length in relation to development of heartwood. Other research indicates a range of factors can influence heartwood/sapwood formation. Although heartwood is known to increase with tree age (e.g., Yang and Hazenberg 1991), it is also influenced by growth rates (Worbes 1988), silvicultural manipulation (e.g., Margolis *et al.* 1988), site factors (Ahn *et al.* 1986), and provenance (e.g., Purnell 1988). Sapwood cross-sectional area is likely to be a function of foliage biomass (e.g., Long *et al.* 1981) hence influencing development of heartwood. Within a species, Bamber (1987) indicates that wider sapwood is correlated with fast-growing dominant trees, more favourable environment and young trees.

Anecdotal evidence from milling of occasional fast-grown totara indicates that it is likely to give similar results to that of relatively young kauri. In an evaluation of second-crop kauri, logs with an SED less than 60 cm are unlikely to produce any heartwood timber (Gibson 1983). Ring counts indicated the trees were at least 120 years old (Halkett and Sale 1986). The recovery of clear timber was lower from these small logs compared with large logs of mature kauri due to knots and damage from kauri gum bleeding practices. Manufacturers had a preference for heartwood kauri as timber from second-crop stands required treatment for boat building (Gibson 1983). Its appearance and softness was not suited for furniture and was even less desirable for wood craft and turnery products, and the high proportion of sapwood along with knots, pith and gum stains would likely lead to buyer resistance for panelling purposes.

Although Hinds and Ried (1957) indicate that sapwood is moderately resistant to preservation, totara posts have been successfully pressure preservative treated with Copper Chrome Arsenic (CCA) and in service for at least 30 years with no significant visible deterioration of wood quality (N. Donelley pers. comm.; own observation). In contrast to the heartwood, sapwood of totara is not durable below ground although it is durable for woodwork in buildings (Hinds and Reid 1957). Studies of fallen totara in old-growth forest indicate that heartwood in large trees can remain sound for many centuries long after sapwood had disappeared. Smale *et al.* (1997) aged a large fallen totara by radio-carbon dating at 740 (±50) years and an estimated coring age of 600 years. Using ring counts of hardwood trees that had since established on the fallen trunk, they found that the tree had been on the ground for at least 300 years. While the outer sapwood had rotted away long ago, heartwood appeared to be in good condition (M. Smale pers. comm.).

Detailed research beyond the scope of this project is required to determine whether there are correlations between heartwood formation in totara and silvicultural practices, site differences and genetic factors. Even so, there are not likely to be any recommendations for dramatic decreases in rotation length. Because of the lack of durability, wood density, colour and figure characteristics of sapwood, the financial value of timber from fast-grown trees will be reduced and hence the viability of growing such species in medium-length rotations may be diminished. The development of an adequate quantity of heartwood is likely to remain a major influence in determining length of rotation for totara.

9.5.4 Tree form

Incidence of forking and pattern of branching is clearly influenced by stand stocking. In general, coarse branching and development of multi-leaders is a feature of wide-spaced trees and conversely, single leader stems with smaller branching is evident in densely stocked stands. However, observations suggest two distinct size classes and angles of branches are evident on many trees established in stands with a range of stem densities. These are large branches at acute angles to the stem, and small diameter branches that are mostly perpendicular to the stem. Some of the large branches show strong apical dominance and may have been competing with the leader at an earlier stage of tree growth. Smaller branches are most prevalent when plants are young, and persist on exposed seedlings and saplings until stands have attained canopy closure.

A significant proportion of trees in many stands has multiple leaders irrespective of stem density (Table 9.3). This may be related to the initial density of plants at establishment, invasion patterns of natural regeneration on open sites and time taken for canopy closure to occur. A relatively low initial stocking such as at the planted 11-year-old stand at Tapapakanga has resulted in 50% of trees with multiple leaders and most trees coarsely branched. Clumping of natural regeneration (Chapter 5) and slow infilling of gaps would encourage more poor form trees than densely planted or regenerating stands.

9.5.5 Management options

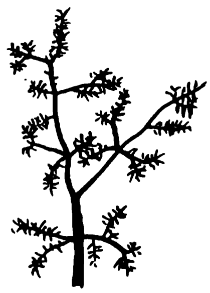
Of the few plantations assessed in this study, only two stands were pruned, one located near Gisborne (HOLD) and the other north of Napier (HOLT) (Figure 9.10). Although tending systems for totara have not been adequately tested, these two plantations, along with observations and anecdotal information on pruning of totara elsewhere, indicate that the species can be pruned to improve stem form. Where trees are planted at densities of 1000 stems ha^{-1} or more, a significant proportion of trees will eventually develop good form over time, even without pruning. However, where planting density is less than around 1000 stems ha^{-1}, branch development will be coarse until after canopy closure occurs. Pruning may be a desirable option for some landowners keen to establish trees at lower densities to save planting costs but actively manage trees for good form. Of interest is identifying the optimum time for improving stem form of trees by tending to maximise relatively clear boles for long-term timber production.

Similarities in tree form, apical dominance of leaders and branching patterns to the cypress species suggest silvicultural practices being developed for the cypresses may be more appropriate for totara than are radiata pine regimes. High initial stockings of 1000-2000 stems ha^{-1} are recommended for cypresses to promote canopy closure, suppress weeds, reduce branch size and provide a large number of stems from which to choose crop trees (Miller and Knowles 1992). They indicate that drastic pruning regimes, as carried out with radiata pine silviculture, usually removes an overly large portion of cypress crowns resulting in adjacent unpruned trees expanding their crowns and promoting heavy branching. Rather, they recommend pruning of acute angle coarse branches and removal of double leaders as likely to be worthwhile from an early age to improve stem form.

It is suggested that a similar tending regime could be practical for totara where emphasis is on removal of occasional, large steep-angle branches and double leaders. Examination of wood quality of totara log sections undertaken in this study indicates that pruning of all small branches on the lower stem may not be essential. Pin knots identified in boards and probably originating from these small horizontal branches do not appear to degrade sawn timber and are confined to a relatively small knotty core. While maintaining a high stocking is likely to minimise knot size, thinning of malformed trees from plantations that have been planted at sufficient density allows selection of better form trees. ***Forest Research*** trials established within the last 5 years are evaluating the removal of occasional, coarse steep-angle branches soon after planting of totara within a planted nurse crop of manuka and high density. Trees are now up to 3.5 m high with single leaders and only light horizontal lower branching.

Figure 9.10: A 33-year-old plantation of totara at Holts Forest Trust (HOLT), Hawkes Bay. Trees were planted at 2000 stems ha^{-1} and have been pruned up to 3 m over 10 years ago.

As densely stocked natural stands promote good stem form with clear boles and small branching over the first 100 years from establishment, no tending is required. However, there may be scope for improving growth rates by thinning and this has been the impetus for a joint Landowner and ***Forest Research*** thinning trial in one natural totara pole stand already established (Chapter 6). However, the timing and intensity of thinning and the influence of these factors on lower branch development and tree form will require investigation where young trees have not yet developed long branch-free lower boles.



CHAPTER 10

DISCUSSION AND CONCLUSIONS

10.1 INTRODUCTION

This chapter discusses the main study of the growth and management of totara with emphasis on wood production. Areas that merit further investigation are also indicated. A descriptive model of the establishment, growth and form of totara following four developmental pathways based on natural and planted stands is presented. Management considerations including economics of timber and non-timber values, hill country sustainability issues and long-term harvesting options are discussed. Suggestions are presented for growing totara as a long-term timber resource by planting or managing young natural stands. The chapter concludes with a summary of the major characteristics of the ecology and growth of totara.

10.2 MAJOR RESULTS

A review of the ecology and silviculture of totara relevant to management revealed a lack of quantitative information on growth, productivity and wood characteristics of the species from both plantations and young stands regenerated on previously cleared sites. The objective of this thesis has been to examine a range of aspects influencing growth of totara for specialty timber production. These included:

- quantifying genetic variation within the species;
- improving aging techniques so that growth characteristics of naturally regenerating stands of unknown age could be evaluated;

- describing and quantifying establishment and development of natural stands;
- analysing early performance of planted stands and comparing this with other indigenous conifer trees;
- developing a growth and yield model based on existing planted stands; and,
- describing development of tree form and branching pattern in plantations and natural stands, and aspects of wood quality.

10.2.1 Genetic variation

The Tapapakanga provenance trial located near Auckland compared growth and form of progeny from 36 populations of totara located throughout the country (Chapter 3). This is the only long-term genetics trial that exists for a New Zealand indigenous conifer tree. Results confirmed earlier nursery-based assessments that indicated significant provenance differences are evident for height and diameter growth, and stem form. These differences were significantly correlated with latitude and mean annual temperature of provenance origin. Totara from northern latitudes grew faster and had better form than provenances from southern latitudes. There is considerable variation within populations, indicating that improvement of totara traits for growth and stem form is possible within local populations. This may have particular significance for Maori who desire to use local genetic resources. Breeding trials that capitalise on the genetic variation within and between provenances in totara are likely to provide significant improvement in productivity and wood quality, as has also been found in other conifer species. This would include selection of trees with improved stem form with fewer large, steep angle branches that have the potential to degrade wood quality.

The youngest totara to have been observed producing viable seed was at the Tapapakanga trial. Ten years after planting, numerous seedlings were found in canopy gaps and along stand edges.

10.2.2 Aging of totara

Extensive coring of totara from a range of planted stands of known ages indicated difficulties in using ring counts to estimate stand age accurately. This is consistent with most, but not all, previous studies (Chapter 4). Mean stand estimates based on up to 20 cores from each stand were within 10-15% of actual age. Growth rings on increment cores with clear dark lines of latewood gave more accurate ages than cores with diffuse bands. Age estimates were significantly improved by avoiding small, suppressed trees, which tended to produce underestimates of age. Fast-growing trees such as edge trees had less distinct rings and counting of the few cores with distinct rings tended to give overestimates.

For aging natural stands of unknown age, avoiding slow-growing suppressed trees as well as obvious larger diameter trees, possible outliers representing a much earlier cohort, should be avoided. Sampling trees within natural stands that have average stem size are likely to give more accurate stand age estimates.

10.2.3 Natural regeneration

Regeneration patterns for totara in pastoral hill country on a Northland site (Chapter 5) has provided further support for Burns' (2000) view that totara fits the catastrophic regeneration mode of Veblen (1992). Indeed, clearance of original forest by early pioneers and settlers for recovery of timber and conversion to farmland was a catastrophic disturbance and thus provided conditions in which totara successfully regenerates. The study also confirms earlier observations that totara regenerates readily in pasture (e.g., Beveridge 1977). The Northland hill country site indicated that regeneration favours steep hill slopes covered in weedy, open grass rather than flatter areas dominated by dense pasture species. Significantly, more bare ground on steep slopes and the effects of continued grazing are considered to be important factors contributing to successful establishment of the relatively unpalatable totara.

The study of natural regeneration in pasture in Northland suggests totara, like the seral species manuka, kanuka and gorse, is acting as a pioneer. It is a successful coloniser on open, lightly grazed sites in primary or secondary successions. In contrast to these other species, totara relies on birds for distribution of its seed, so the presence of a local seed source and adequate bird populations are likely to be an important influence of the rate of colonisation. Spatial cluster regeneration patterns observed on this Northland site are similar to successional patterns in other plant communities described elsewhere involving bird-distributed species (Silvester 1964; Wardle 1991). Aspects of regeneration patterns of totara on hill country sites for further research include: distance from nearest seed source; status and role of local bird populations; and farm management regimes including degree of grazing and fertiliser application.

Further studies are warranted to confirm whether regeneration patterns on grazed hill country sites, both in Northland and other regions, are similar to those described here. A comparison of regeneration patterns between hill country sites and other open sites, such as freshly deposited alluvium along riparian areas on farmland, also merits investigation.

10.2.4 Development of natural stands

Developing stands of totara on relatively steep hill country pasture have not been described or quantified before, nor have these stands been considered as a potential wood resource (Chapter 6). Spatial and temporal patterns of regeneration vary from site to site. Most stands that achieve canopy closure eventually develop into pole and semi-mature stands that are relatively uniform in stem size and form regardless of site, as natural thinning occurs with age. With continued grazing, no other forest tree species has a chance to regenerate and a monoculture of totara eventuates. It firstly overtops manuka, then gorse in 2-3 decades, and finally kanuka, as seen in the older stands around 100 years of age.

Growth rates of natural stands studied were slower compared with plantations of totara assessed in Chapter 8. They reflect both severe intraspecific competition as well as the generally more difficult exposed hill slope that natural stands were regenerating on. Improved growth rates of natural stands could probably be achieved by thinning, although this requires investigation. However, without intervention, natural stands eventually develop into a utilisable wood resource.

10.2.5 Early planting performance

Historically, more totara has been planted than other major indigenous conifer timber trees. This reflects its widespread natural range, ease of cultivation and good performance after planting on a range of sites (Chapter 7). However, most stands have been established on poor sites unsuited to other land uses such as exotic forestry or farming. Many planted stands also received minimal or no after-planting care. This contributed to the perception that indigenous species are slow growing and not worth planting as a long-term timber resource.

Examination of a wide range of planted stands and trials of indigenous conifers indicates that totara is the most tolerant of dry, exposed sites. It is also the most light-demanding. Despite the large variation in sites and management histories, the estimated site index of planted totara stands indicates significantly better growth on open, fertile sites. Average survival of totara is 60%, with mean annual diameter increment of 6 mm and mean annual height increment of 26 cm, similar to that of rimu and kahikatea over the first 50 years of growth. More successful plantations indicate that growth can be significantly greater with a mean annual diameter increment of 10 mm for totara, similar to that of kahikatea and kauri, and a mean annual height increment of up to 55 cm.

10.2.6 Growth and yield over time

Chapter 8 presents the first attempt at producing growth and yield equations for totara. The study indicated that while total stem volume growth is slow over the first 50 years, yield increases significantly over the following 50 years. A mean basal area of about 100 m^2ha^{-1} and mean volume of 800 m^3ha^{-1} is predicted at age 80 years, based on six stands. While current annual volume increment is less than 7 m^3ha^{-1} at age 30, this increases to 14 m^3ha^{-1} at age 60, although no allowance was made for mortality. This current annual increment is less than that predicted for two exceptional 60-year-old kauri stands (18 m^3ha^{-1}) on a Taranaki site (Herbert *et al.* 1996).

In comparison with average growth rates of the two most widely planted exotic conifers in New Zealand, radiata pine and Douglas-fir, growth of totara is much slower. Predicted total tree volume of just over 100 m^3ha^{-1} for totara at 30 years

(Table 8.6) is only a fraction of typical total volume yields for radiata pine which ranges from 400 to over 900 m^3ha^{-1} in 25-30 years, depending on the management regime and site (Maclaren 1993). At 30 years, mean annual volume increments of 25-30 $m^3ha^{-1}year^{-1}$ are typical on good sites for radiata pine but may be only 11 $m^3ha^{-1}year^{-1}$ on drier South Island sites (Burdon and Miller 1992b). This compares with an average of 3.7 $m^3ha^{-1}year^{-1}$ for totara covering a range of sites (Table 8.6). Growth rates of totara are less than half those of Douglas-fir. The average MAI of recoverable volume for Douglas-fir in New Zealand is 16 $m^3ha^{-1}year^{-1}$ at 60 years of age compared to 7.8 $m^3ha^{-1}year^{-1}$ predicted for total tree volume of totara over the same rotation (Table 8.6). Like totara, Douglas-fir is relatively slow starter over the first part of the rotation until about 30 years of age (Miller and Knowles 1994), although Douglas-fir is overall considerably faster growing.

New Zealand cypress plantations (*Cupressus macrocarpa* and *C. lusitanica*) have, like totara, generally suffered from widespread silvicultural neglect, particularly lack of thinning (Miller and Knowles 1992). Mean annual increments of late-thinned cypress stands range from 6-15 m^3ha^{-1}. Unthinned stands over 40 years show wide variation in productivity from to 200 m^3ha^{-1} total volume for stands on poor sites to over 1000 m^3ha^{-1} on exceptional sites. The poor-site growth is similar to that predicted for totara plantations at a similar age (Table 8.6).

Growth and yield of totara in natural stands is considerably slower than in plantations when predicted growth variables at 1000 stems ha^{-1} and 60 years of age are compared (Table 10.1). However, actual stand density of natural stands, derived from the stem density/age function (Chapter 6), averaged approximately 3500 stems ha^{-1}. The largest 1000 stems ha^{-1} of totara in these dense natural stands are the most likely component of the final crop. DBH growth for average plantations (33 cm) is nearly twice that found in natural stands (17 cm). Clearly, natural stands are undergoing intensive competition that is suppressing diameter growth. Mean height in plantations at 60 years is nearly 15 m compared with 11 m for natural stands, suggesting that site factors on exposed hill slopes are also suppressing growth. Such factors are likely to include increased exposure and less well developed soils for natural regeneration on hill sites compared with the better sites of many of the plantations. Basal area and volume yields are significantly higher for planted stands compared with natural stands of the same age. Plantations had a mean volume of 470 m^3ha^{-1} at 60 years but natural stands were estimated to be around 100 years before achieving a similar volume (Figure 6.13).

Table 10.1: Comparison of growth rates between the largest 1000 stems ha^{-1} of totara (considered to be the likely crop trees) in naturally regenerating stands (from Chapter 6) with predicted growth of totara plantations at 1000 stems ha^{-1} (from Chapter 8) both at 60 years of age.

	Plantations	Natural stands*
DBH (cm)	33.1	16.9
Height (m)	14.9	10.6
Basal Area (m^2ha^{-1})	69.5	21.8
Volume (m^3ha^{-1})	470.4	107.7
Volume MAI ($m^3ha^{-1}year^{-1}$)	7.8	1.8
Volume CAI ($m^3ha^{-1}year^{-1}$)	14.2	5.6

* Actual stem density of natural stands at 60 years is approximately 3550 stems ha^{-1}

Thinning of dense natural stands to 1000 stems ha^{-1} or less may improve growth of residual crop trees. However, it is not likely that this will yield gains in growth equivalent to growth rates of plantations assessed in this study due to the site differences. Further investigation is underway to determine the efficacy of thinning natural stands compared with leaving them to develop naturally.

10.2.7 Tree form and branching characteristics

Stem form of totara is closely linked to pattern of establishment, degree of intraspecific competition and the rate at which canopy closure on an open site takes place (Chapter 9). Widely spaced planted or naturally established trees have a high proportion of multiple stems and coarse branching in response to the high light levels. With increased stocking rate, particularly from early establishment stages, major differences in form occur with a greater proportion of trees having single leaders and only small branches on lower boles.

The small sample of log sections and discs in this study has provided limited opportunities for correlating stand and site parameters with wood quality and heartwood formation. Timber generally had few major defects other than small knots from a knotty core and occasional rot pockets, probably related to slow rotting of steep angle large branches. While heartwood is forming in trees from the near 100-year-old plantation and the natural stand sampled, no correlation was found between its development and site, stand or tree characteristics.

Further investigation should include: investigating silvicultural practices to improve tree form such as form pruning to remove occasional large branches as practiced with the cypresses (Miller and Knowles 1992); relating development of tree form and branching pattern to the wood quality from fast-grown stands; determining factors influencing heartwood formation and whether there are any genetic, ecological or site factors which predominate; and whether silvicultural practices can be developed to increase the rate of heartwood formation in totara. A volume equation for totara to improve estimates of volume predictions from semi-mature planted and natural stands is also required.

10.3 A DESCRIPTIVE MODEL OF GROWTH AND FORM

A semi-quantitative descriptive model based on several pathways by which both natural and planted totara stands develop over time is presented. This describes establishment, growth and stem form, and branching patterns. Several scenarios influenced by stand stocking, stand management history and site factors are apparent. Schematic diagrams for each pathway include tree height, diameters and stocking rates given for most stages based on actual stand parameters surveyed in this study (Figure 10.1). For natural stands, tree height and DBH measurements are taken from Table 6.4, and plantations from Table 8.3. Log measurements are from Table 9.3 and log type descriptions are given in Table 9.1.

10.3.1 Densely-stocked natural stands (Figure 10.1 – A)

- Where there is an abundant seed source, bare sites can become established over a relatively short time (5-10 years) to form dense stands of tens of thousands of seedlings per ha.
- These form sapling thickets (1-10 cm DBH) with densities that can exceed 50,000 stems ha^{-1} at age 20 years, comprising a mixture of trees with

straight stems and those with multiple leaders. Small branches are retained to low levels but are dead or dying under a dense canopy. A relatively high proportion of trees with good lower stem form is pre-determined by an early age.

- Rapid self-thinning then occurs as density reduces to 10-20,000 stems ha^{-1} over the next 1-2 decades. Suppressed, slower growing, shorter trees suffer greatest mortality (possibly last entrants during the regeneration phase) in favour of faster growing, larger canopy dominants (possibly early entrants or on better microsites). Mortality rates vary from site to site but pole stands with canopy heights approaching 10 m and 12 cm DBH at this stage have a high proportion of lower stems with no branches or only small branches.
- With increasing age, self-thinning continues but at a slower rate, with stem density declining to less than 1000 stems ha^{-1} for stands well over 100 years of age. Mean canopy height exceeds 20 m, mean DBH is over 30 cm, with at least 6 m of clear bole. Standing volume tends to be upwards of 600 m^3ha^{-1}.

10.3.2 Plantations established on open sites (Figure 10.1 – B)

- Plantations established at relatively high stockings of 2-3000 stems ha^{-1} on open sites are at densities considerably less than dense natural regeneration. Totara seedlings planted in the open are straggly with little apparent apical dominance of the leader. Any insect or other damage to the leader results in a lateral branch taking over as leader. As with low-stocked and unevenly developing natural stands, tree form is often poor in early years.
- Canopy closure has taken nearly 10 years for totara planted at the Tapapakanga stand planted at 2500 stems ha^{-1}. Half the trees have forks at less than a metre from the ground and rounded crowns have developed with coarse branching. It is likely to take another five years before stand competition begins to improve stem form with dieback of lower branches.
- Stem and low branch pruning from an early age eliminates multiple leaders and maintains straights stems. It also reduces coarse branching over the first two decades from planting. Examples are Holts Forest Trust and Te Karaka stands.

A – Densely-stocked natural stands

Dense regeneration – 5-10 years (Kaeo regeneration site) 1-2 m high

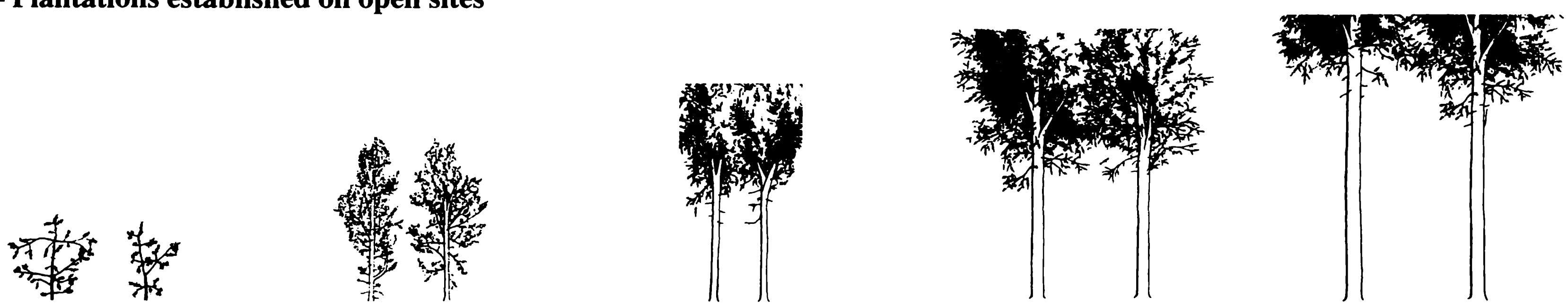
Sapling 20 years, 50,000 stems ha^{-1} (LANE1 and LANE2) 1-10 cm DBH; 2.5-3 m high

Pole 36 years, 10,000 stems ha^{-1} (DONE 3)

Pole 60 years 10,000 stems ha^{-1} (DONE1) 12 cm DBH; 10 m high

Semi-mature 130 years 700 stems ha^{-1} (BRID1) 30 cm DBH; 20 m high

B – Plantations established on open sites



Seedlings planted in open 3-5 years, 2-3000 stems ha^{-1} 1-2 m high

Plantation, 10 years 2500 stems ha^{-1} (TAPA), 8 cm DBH; 4.4 m high

Plantation, 33 years pruned to 3 m 2000 stems ha^{-1} (HOLT) 15 cm DBH; 9 m high

Plantation, 50 years low pruned 1100 stems ha^{-1} (HOLD) 20 cm DBH; 12 m high

Plantation, 90 years 1275 stems ha^{-1} (BROU1) 35 cm DBH; 23 m high

Figure 10.1 A - B: Growth, stem form and branching pattern development of seedlings, saplings, poles and semi-mature trees of totara based on observations and field measurements in planted and naturally regenerating stands of totara. Plot codes and mean tree measurements indicated for each stage.

C – Low-stocked natural or planted stands

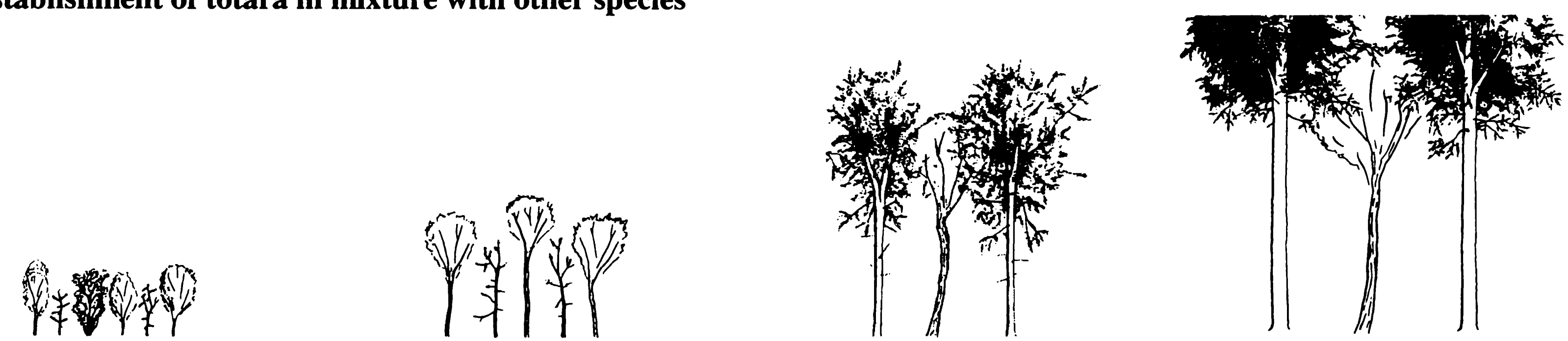
Uneven/scattered regeneration or wide spaced planting (scattered seedlings, Kaeo site)

ide spaced shelterbelt 40 years (KAMO2) 40 cm DBH; 17 m high

Wide-spaced planting 400 stems ha^{-1} 70 years (CORN) 74 cm DBH; 20 m high

Wide spaced shelterbelt 94 years (KAMO1) 50 cm DBH; 20 m high

D – Establishment of totara in mixture with other species



Mixture of totara regenerating with manuka, kanuka, gorse 1-2 m high

Natural stand 60% manuka, 30 years 15,000 stems ha^{-1} (OWEN1 & OWEN2) 5 cm DBH; 6 m high

Natural stand some kanuka 55 years 7000 stems ha^{-1} (LANE3) 9 cm DBH; 13 m high

Natural stand minor kanuka 99 years, 1300 stems ha^{-1}(MACK1) 27 cm DBH; 16 m high

Figure 10.1 C - D: Growth, stem form and branching pattern development of seedlings, saplings, poles and semi-mature trees of totara based on observations and field measurements in planted and naturally regenerating stands of totara. Plot codes and mean tree measurements indicated for each stage.

- The Puhipuhi stands indicate that where stocking remains high, good stem form eventually develops with time, although dense stocking is likely to give slower growth rates than wider spaced stands where form pruning may be desirable (See Figure 9.2).

10.3.3 Low-stocked natural or planted stands (Figure 10.1 – C)

- Uneven development of scattered natural regeneration over 1-3 decades can occur on some sites due to erratic grazing pressure, short-term changes in farm management, intermittent and selective weed control, or uneven temporal or spatial recruitment due to distant seeding trees, and erratic seed production and dispersal.
- Widely spaced trees form rounded crowns with short boles, coarse branching and multiple leaders. These are similar to scattered, naturally established totara on farmland, as well as trees planted in the open or in shelterbelts (eg., KAMO2).
- Competition between trees in low-stocked stands does not occur for decades, as in the 70-year-old Cornwall Park (CORN) stand planted at 400 stems ha^{-1} (see Figure 9.3).
- Trees in the older shelterbelt at KAMO1 continue to have coarsely branched stems due to the near-open growing conditions (see Figure 9.4).

10.3.4 Establishment of totara mixed with other species (Figure 10.1 – D)

- Natural regeneration of totara seedlings on farmland often occurs under manuka, gorse and kanuka in various proportions that provide shelter. Manuka and kanuka can also be planted on open sites to provide a 'nurse' for later planting of totara seedlings.
- Dense, mixed-species natural stands develop within 25 years. The OWEN plots have a density of 15,000 stems ha^{-1} comprised mostly of manuka but with varying proportions of gorse and kanuka that are sheltering totara. In contrast to open sites, stems have small branches with low incidence of forking. The relatively short-lived manuka and gorse will be overtopped by totara 3-4 decades after establishment.

- In contrast, where present, taller and longer-lived kanuka are likely to influence stem form for several decades. Totara is estimated to be 55 years old in LANE3 and comprises 6000 of the 7000 stems ha^{-1}, with the remaining species being mainly kanuka. Totara have up to 6 m of clear lower stem or with small branching.
- Occasional older natural stands (MACK1) show evidence of a kanuka component that is dying out as totara dominates these stands at around 100 years of age.

10.4 MANAGEMENT CONSIDERATIONS

10.4.1 Choice of silvicultural method

In most countries, efforts at silvicultural operations in indigenous forest has followed a similar pattern; firstly highly selective and barely controlled logging; then an interest in plantations to compensate for loss of natural forests; then development of some form of sustained yield management of natural forest; and finally a second wave of interest in establishing plantations as a means of maintaining a timber supply (Baur 1964). Management of most of the major indigenous conifer trees in New Zealand has undergone a similar pattern. Early exploitation provided cheap timber supplies and cleared land for other land uses and there were early attempts at establishing a plantation resource such as the 120 ha of totara planted at Puhipuhi in Northland in the early 1900s (Chapter 8). Clearfelling and partial logging that creamed indigenous forests of merchantable stems of favoured species continued up until the 1970s (Edmonds 1978). Selection management systems were trialed from the late 1950s with the last trial established in 1979 (Beveridge 1984) only a few years before logging ceased in most Crown-owned indigenous forests largely due to public pressure.

Florence (1996) suggests that a number factors influence the process of determining a suitable silvicultural decision including the ecology of the species and forest types; market and economic factors; efficiencies of silvicultural methods; and environmental and social considerations. Some of these factors are considered in relation to management of totara.

10.4.2 Non-timber values of growing totara

The expected rotations in excess of 100 years for totara and most, if not all, the indigenous conifers make investment in planted indigenous production forestry uneconomic (Horgan 2000). However, if non-market benefits are considered, these may be more than sufficient to justify planting of indigenous trees. In addition to production of high quality timber for specialty uses there are long-term cultural and heritage values associated with the growing of totara in particular. Other non-timber benefits for planting and managing totara and other indigenous tree species include: restoration of indigenous forest; provision of seed sources; provision of shelter; enhancement of wildlife and species biodiversity; provision of amenity areas; control of erosion; and improvement of aesthetic values (Forest Research Institute 1997). In recent years, carbon sequestration has become a further dimension that could justify planting and managing of indigenous forest (Herbert *et al.* 1996).

With a relatively long-rotation species such as totara, silvicultural systems that have minimal inputs to stand development are economically advantageous. Use of a nurse crop of manuka (Forest Research Institute 1997) to reduce establishment costs and improve tree form of plantations is a cost-effective alternative to dense planting of expensive totara seedlings requiring intensive tending. The development of naturally regenerating stands allows opportunistic management of such stands for long-term timber production with minimal input required, particularly where intervention is delayed until pole stands have formed. Although these may take 50 years or more to develop, stem densities are likely to be sufficient to allow thinning of poor form trees to boost growth of selected crop trees for the remainder of the rotation. Earlier intervention is an option to increase growth but costs will be carried over a longer period where rotations may not have been significantly reduced.

As with planted stands, the rationale for managing natural stands that have regenerated on previously farmed sties for timber production also requires justification on the basis of non-market benefits. Natural groves of totara on less productive steep hillsides are likely to improve property values in terms of aesthetics and shelter. Along with fenced off riparian areas, such stands in a pastoral landscape would improve biodiversity and wildlife values.

10.4.3 Sustainable hill country land-use

Management of naturally regenerating stands of totara on some sites is likely to be compatible with increasing concern for sustainable land use patterns on hill country pastoral landscapes. Blaschke *et al.* (1992) argue that most farms in New Zealand steepland regions are marginally economic. Widespread erosion of steep slopes over 28° in the Taranaki region has resulted in loss of much of their soil mantle accompanied by significant production losses. In the Gisborne-East Coast region, short-term production losses range from 2-39% in any one year depending on terrain and storm frequency (Hicks 1991). Regeneration on erosion scars with scattered manuka and kanuka, and poor quality pasture grasses and herbs is slow on these exposed, bare surfaces (Smale *et al.* 1997). Leaving the most erosion-prone and steepest hillsides to revert to relatively unpalatable pioneer species such as manuka and kanuka, as well as totara (where there is a seed source) before erosion occurs is a management option for farmers.

The effect of woody vegetation on slope stability is well documented. For example, on mean slopes of 26°, Bergin *et al.* (1995) found that the percentage area affected by landslide damage on pasture varied from 6-35% as a result of Cyclone Bola in the late 1980s. Slip damage showed a rapid and highly significant reduction with increasing age of scrub cover, amounting to 65% reduction in damage under 10-year-old scrub and 90% reduction under 20-year-old stands. With the high ecological, social and economic costs of erosion on hill country and downstream, allowing natural regeneration of unpalatable woody species, particularly where fencing is uneconomic, is likely to become a practical option in the future. With the reversion of hill country to woody species in many regions and the potential for some of these sites to grow totara, a large long-term resource could develop over the next century, much of which could be suited to management for timber.

10.4.4 Ecological characteristics

Consideration of the ecological characteristics and regeneration strategies of totara is relevant in determining appropriate long-term forest management systems for the species even where long-term objectives are to manage a totara-dominant high forest. The study clearly shows that totara is a light-demanding, pioneer species that establishes successfully on exposed, open sites consistent with the catastrophic regeneration mode described by Veblen (1992) and discussed in detail in Chapter 5. Studies in old-growth podocarp forest also show that flooding, catastrophic windthrow and synchronous collapse of the canopy create conditions suitable for the establishment of the podocarps such as kahikatea, rimu and totara (Duncan 1993; Foweraker 1929).

Where harvesting for timber is an option, forest management systems that create relatively open sites are, therefore, most likely to encourage successful regeneration of the podocarps. For totara, canopy disturbance akin to clear-felling management regimes is more likely to promote regeneration than single-tree or small-group selective management systems favoured for continuous forest management practices. On steep hill country sites such as those described in this study in Northland, relatively exposed surfaces that are advantageous to regeneration of totara are being maintained in the landscape. Small-scale erosion exacerbated by disturbance from grazing animals is impeding good soil development, reducing grass competition and preventing regeneration of more competitive hardwood species. For small stands of totara that have developed on these steep faces on farmland, a clear-felling management system is likely to be the only practical option to ensure adequate establishment and early growth of regeneration of the next rotation. Retention of some seeding trees in the vicinity of the cleared area will be essential to ensure an abundant natural seed source. Continual light grazing will prevent regeneration of other tree species and keep weed and fern growth to a minimum to assist the establishment of totara. Small, even-aged stands scattered across hill country farmland at different stages of development could be managed on a sustainable basis. Whole stands would be clear-felled at or near maturity allowing development of natural regeneration.

10.4.5 Multiple-use forestry

Multiple-use forestry lends itself to mixed age/mixed species management where low-impact logging regimes preserve high forest values (Benecke 1996). For hill country, continuous forestry management would have the advantage of maintaining a cover of forest that would reduce soil erosion and sedimentation of waterways. With continuous tracts of forest dominated by totara, clear felling of whole stands with its attendant destruction of high forest structure is not likely to be an option on all sites. In such stands, group selection systems (Troup 1928) could be considered whereby a cluster of several canopy trees is removed to allow sufficient light for regeneration of totara. Over time, new gaps are created so that the whole stand is regenerated without loss of continuous cover. Eventually, the forests would become a single-species stand comprising large even-aged patches at different stages of development. However, it is not known how large these gaps will have to be to ensure development of young totara and what degree of ground disturbance is required to promote natural regeneration. In addition, there are considerable economic and practical difficulties in continuous cover management including access to stands, felling and extraction without damaging residual trees (Baur 1964).

Wardle (1984) recommended a group selection system for the light-demanding beeches. He suggested gap sizes of 20-30 m across where 10-20 trees are removed to provide ideal conditions for regeneration. This encouraged good growth rates of seedlings and saplings, and eventually leads to improved forest stability. However, Wardle (1984) also indicated that there are disadvantages with selection forestry management including physical and economic problems in harvesting isolated groups of trees as well as potential damage to the residual tree crop during extraction.

For totara, some form of large group selection management system similar to that described for beech could fulfil many of the non-timber benefits that are associated with retaining a high forest structure. However, the suitability of selection management of totara forest where the aim is to encourage a second generation of the same species is highly speculative. Observations and studies consistently indicate the shade intolerance of totara seedlings (e.g., Ebbett and

Ogden 1998; Norton 1991; Beveridge and Bergin 2000). Ogden and Stewart (1995) suggest that totara requires massive disturbance to establish and unlikely to regenerate following progressive collapse of a high forest canopy. McSweeney (1982) suggests that totara is acting like a pioneer in South Westland forests and is unable to regenerate under a closed canopy or even in small canopy gaps. In a study of lowland totara in the South Island, Ebbett (1998) found no evidence that totara regenerates under a senescing totara canopy and that such sites will become dominated by other species. Where the objective is sustainable management of successive crops of totara for timber supply from a site, systems that comprise very large gaps akin to small clear-felled coupes is probably required to ensure effective recruitment of the next generation of totara.

In the absence of grazing, species composition in such managed stands of totara will increase to include other indigenous tree species such as kohekohe and taraire (*Beilschmiedia tarairi*). These are more shade tolerant (Wardle 1991) and their development in fenced totara stands offer opportunities to manage these species for timber production. Small group selection or irregular shelter-wood silvicultural systems have long been used in European forests. The young crop becomes established under the shelter (overhead or lateral) of the old crop, a system favouring shade-tolerant species (Troup 1928). Such forests become uneven-aged mixed-species stands for which Benecke (1996) advocates a near-natural forest management system that fulfils ecological, productive and social objectives. Unless there is a major opening of the canopy, local seed source, and suitable conditions for germination and early growth, totara will become a significantly smaller component of such forest.

10.5 DEVELOPING A RESOURCE OF TOTARA FOR TIMBER

The objective of this thesis is to add new information on the ecology of totara to existing knowledge, useful to those interested in planting and managing the species with an emphasis on long-term timber production. This investigation supports previous observations and discussions that totara is tolerant of a range of sites and growing conditions, reflected in its widescale distribution in most lowland forest types throughout the country. This makes it amenable to silviculture for a wide range of objectives as seen by the long history of planting and the success of planted stands in many regions. The pioneering attributes of totara make it a species capable of taking full advantage of catastrophically disturbed sites, whether naturally induced or man-induced, such as hill country pastoral landscapes described in this study.

Based on the performance of stands under different developmental regimes in the descriptive model of the previous section, some suggestions are offered for growing totara as a production timber species on new sites. Detailed guidelines are beyond the scope of this thesis but options for developing a timber resource of totara, whether by planting on new sites or managing young natural stands, are briefly discussed.

10.5.1 Establishing planted stands

Planting offers the fastest way of establishing a long-term timber resource of totara when good sites can be targeted to give significantly better growth rates than naturally regenerating totara that are generally occurs on poorer quality sites. A major disincentive is the cost of seedlings and labour to plant with follow-up care. All nurseries currently produce totara in a variety of containers at a minimum cost of $3 per seedling for stock up to 2-years-old and about 50 cm high, the planting height preferred for most sites. With refined nursery techniques and large-scale production, cost of seedlings in containers should be reduced. Alternatively, large-scale bare-root production, as practiced in forest tree nurseries in the mid- to late 1900s (Forest Research Institute 1980b), would reduce seedling costs significantly. Some suggestions are made for planting either on open sites or within established scrub, including reverting farmland.

10.5.1.1 Planting on open sites

Planting density for a plantation on an open site is a compromise between intensive management required for low stockings to improve stem form, and less intensive management of higher stocked stands which rely on competition to assist the development of good form. Planting at a dense stocking of over 2000 stems ha^{-1} will achieve early canopy closure within 10 years on good sites. This has the advantage of relatively early weed control and early control of stem form and branch size. Disadvantages include high initial establishment costs where large numbers of seedlings are required, and a slowing of growth rate as competition between trees increases from about 20-30 years after planting. At this time thinning could be considered but care would be required not to open the stand up too early. This would encourage coarse branching and development of low crowns. Planting at a lower stocking of 1000 stems ha^{-1} will require more intensive silvicultural tending to encourage straight single stems with minimal branching. Within the first 10 years of planting, removing double leaders and large acute-angled branches will be required on young 3-5 m high trees with further intermittent pruning lifts over the next 2-3 decades. Thinning to lower stockings will depend on growth rates. The stands will need to be monitored so that timing of thinning can be targeted to encourage growth.

10.5.1.2 Planting within a nurse crop

The use of a hardy seral type nurse species such as manuka or kanuka to improve performance and stem form of totara may be a practical alternative on many sites. Where a cover already exists, preferably less than 6 m high, lines can be cut at regular intervals for interplanting of totara. For open sites, nurse crop species can be established at 2-3 m spacings to control grass growth and provide shelter before planting totara 3-5 years later. The exotic woody legume, tree lucerne has also proven to be a useful species as a nurse crop on some sites. Advantages of a nurse crop for growth of interplanted totara include the shelter benefits on exposed sites, side shade encouraging good apical dominance with reduced branch size lower incidence of multiple leaders, and lesser cost of establishing manuka or tree lucerne at dense stocking compared to dense planting of totara. Disadvantages include maintenance required once totara are planted to ensure the nurse crop canopy does not close, reducing light levels for interplanted totara and forward planning required to establish nurse species ahead of the target tree species.

10.5.2 Management of natural stands

While natural regeneration of totara occurs throughout the country on a range of sites such as along riparian areas described by others (eg., Wardle 1991; Duncan 1993) and have the potential for management for timber production, this study has focussed on regeneration on hill country pasture in one region, for which some management implications are discussed.

10.5.2.1 Encouraging regeneration

A major advantage with managing natural stands is the saving of seed collection, and raising and planting of seedlings. A disadvantage is that regeneration is only going to occur on specific sites where site factors, while encouraging regeneration, do however, produce slower growth rates than better sites selected for plantations. This study indicates that the steep Northland pastoral sites are often difficult to maintain in pasture because they readily revert to the non-palatable seral woody species gorse and manuka as well as totara.

Natural regeneration requires seed trees left scattered over farmland and encouragement of diverse bird populations by protecting their habitat. Local bird populations can be enhanced by management of predators, eg., possums, mustelids and rodents (King 1984). This will indirectly improve chances of seed dispersal. Forest remnants will be enhanced when they are fenced to increase species diversity and where control of possums is undertaken Selective spraying to reduce gorse in favour of totara is another strategy that can be used during the establishment phase.

Shrubland reverting on hill country farmland in many regions, although not quantified, appears to be significant in many regions including parts of Northland, East Coast and the King Country and provides opportunities for management as a long-term indigenous timber resource. Where there is a lack of totara in reverting shrubland, common in some regions such as the East Coast of the North Island, establishing a seed source by planting will improve natural regeneration. Planted groups of seedlings on good sites in natural or cut gaps are likely to produce seed bearing trees within a decade. Although control of grazing animals may not be necessary for totara, fencing sites would encourage greater species diversity.

10.5.2.2 Management of developing stands

Where developing natural stands of totara are abundant, a good opportunity exists for developing a long-term timber resource. As this study was confined to three areas in one region, the area of farmland reverting to totara dominant forest is not known. Nor is the extent of totara regeneration in other regions throughout the country quantified. Although observation indicates widescale reversion of farmland in many regions, some including totara, a survey by region or on larger scale is required to determine its extent and the potential area in regenerating totara.

Long-term management of naturally established totara stands depends on the stem density of totara. Widely spaced trees may benefit from form pruning in early years to encourage single leaders. Two strategies for management of dense stands include leaving stands to undergo self-thinning, or to thin early to encourage better growth. Allowing intense intraspecific competition has the advantage of low input but the disadvantage of slower tree growth. Thinning of very dense young stands (10,000 or more stems ha^{-1}) within the first 30 years will be labour intensive. Delaying thinning until stands fall to less than 5000 stems ha^{-1} may be more desirable at around 40-50 years. Even so, stands may need to be thinned on an incremental basis over several years to avoid stand instability and development of coarse branches on residual trees.

10.6 PROPOSED MANAGEMENT REGIME AND ECONOMICS

10.6.1 Proposed scenario

A proposed regime for establishing and managing a plantation of totara and costs involved are presented in Table 10.2. The stand has only been taken up to a semi-mature stage of 80 years of age where volume predictions for plantation totara have been calculated in Chapter 8. Consequently, extraction costs and milling have not been incorporated in this preliminary exercise.

For this scenario, seedlings are planted at an initial stocking of 2500 stems ha^{-1} on a grassed open site. Mortality is not expected to be significant as has been found with the well-managed Tapapakanga stand described in Chapter 8 where mean survival was 90% 12 years after planting. Management involves up to five releasings over the first 5 years from grass (as recommended in Chapter 7) although the number of seedlings requiring releasing from competing regrowth decreases with time.

Table 10.2: Description of operations and estimates of costs for establishing and managing a plantation of totara for a stand up to age 80 years.

Operation	Years from planting	Stocking (stems ha^{-1})	Cost per unit	Costs $ ha^{-1}
Land cost	0	-	-	4000
Site preparation – spot spraying	0	2500	.26	650
Seedling cost	0	2500	2.5	6250
Planting	0	2500	.80	2000
Release 1	1	2500	.26	650
Release 2	2	1000	.26	260
Release 3	3	1000	.26	130
Release 4	4	2500	.26	130
Release 5	5	500	.26	130
Form pruning 1	5	500	.26	130
Form pruning 2	10	500	1.0	500
Thinning 1	15	1500	.55	440
Thinning 2	30	1000	.55	165
Annual management cost	-	-	-	50

Two form pruning operations are suggested to remove only the largest acute-angled branches and multiple leaders. The Tapapakanga provenance trial (Chapter 3) indicates that at least 50% of the trees have multiple leaders. Removal of these double leaders or large acute-angled branches, as discussed in Chapter 9, within 5 years of planting is regarded as prudent to improve stem form. Form pruning of saplings within 5 years of planting is easily achieved and many could be removed using secateurs, hence an estimated cost of only 26 cents per tree. A second form pruning at about the first thinning operation 15 years after planting and only on residual trees will be more expensive per tree requiring some low level climbing as average tree height will be about 5 m (Fig. 8.2).

Two thinning operations at 15 years and 30 years were also included. Allowing for a maximum of 10% mortality (i.e., 2250 stems ha^{-1} remaining) the first thinning is aimed to reduce stocking to 1500 stems ha^{-1} requiring removal of some 750 stems ha^{-1}. The second thinning aims to reduce stocking to 1000 stems ha^{-1} requiring thinning of a further 500 stems ha^{-1}.

Merchantable volume yield was estimated to be 75% of total stem volume based on the recovery of timber from log sections assessed in Chapter 9 from a planted stand and is similar to the 80% recovery rate suggested by Goulding (1995) for untended radiata pine stands. Based on growth rates of planted totara stands in Chapter 8, merchantable volume yield was estimated at 642 m^3ha^{-1} for a stocking of 1000 stems ha^{-1}. Timber grade recovery is based on recovery rates of a 89-year-old planted totara stand assessed in Chapter 9 and price relativity is based on kauri timber as used by Herbert *et al.* (1996) (Table 10.3).

Table 10.3: Grade price relativities and grade outcomes for planted totara stands. Grade recovery estimates are from Chapter 9.

Grade	Price relativity	Grade outturn (%)
Clear	1.0	2.9
Premium	1.0	18.4
Dressing	0.63	72.5
Building	0.68	6.2

10.6.2 Preliminary economic analysis

A preliminary economic analysis has been undertaken for the plantation scenario given in Table 10.2. Values used in the analysis were chosen for a base-case scenario to give conservative returns. Various underlying assumptions, costs and prices were based on similar economic evaluations of planted kauri undertaken by Herbert *et al.* (1996) and more recent evaluations of the same species (G. Horgan pers. comm.; I. Barton pers. comm.). Land value was set at \$4000 ha^{-1} based on dry stock fattening quality hill country but of tractor rather than hauler terrain (Herbert *et al.* 1996). Timber value was set at \$1000 per m^3 regarded as a conservative value used for roundwood kauri of which approximately 50% of the timber was assumed to be sapwood (I. Barton pers. comm.).

Discounted cash flow analysis was used to determine present net worth (PNW) for a discount rate of 3% and 10% (Fraser and Horgan 1995). The 3% discount rate would be typical of that used based on a Social Rate of Time Preference (or Societal Rate) which is relatively low and normally ranges from 2.5-4%. Rates based on Social Rate of Time Preference are often used for long rotation species (G. Horgan pers. comm.). The 10% discount rate was used by Herbert *et al.* (1996) for plantation kauri. For exotic forestry based on radiata pine, PNW is currently calculated using a real after tax discount rate of 7.5% (eg., Fletcher Challenge 2001).

At the 3% discount rate, the PNW for this scenario was \$6309 ha^{-1} and at 10% discount rate was \$-11,704 ha^{-1}. Internal rate of return (IRR) was 3.5%. Compared with the economic analysis of a planted kauri stand of Herbert *et al.* (1996) where the 80-year-old scenario has been calculated at a 10% real discount rate, the PNW is \$-9219 ha^{-1} with an IRR of 2.3%. The figures for PNW highlight the importance of the selected discount rate. It is only possible to get a positive PNW at relatively low discount rates. Any analysis of long rotation species consistently show a low IRR typically between 2-4% (G. Horgan pers. comm.).

Clearly, as discussed by Herbert *et al.* (1996) for kauri, returns from growing totara from planted stands are similarly low by commercial forestry standards in New Zealand. Some of the issues they raise for kauri are also relevant for totara where rates of return are low and rotations are long. With any realistic wood value it is difficult to envisage plantations of either species being commercially viable based on wood production alone. Clearly other non-timber benefits have to be considered as important factors in establishing plantations of totara or kauri. Herbert *et al.* (1996) considers non-timbers benefits of kauri plantations and suggests values for recreational use and carbon sequestration. These values and other non-timber benefits discussed earlier are also applicable to the planting and management of totara as they are for planting other indigenous timber tree species.

10.7 CONCLUSIONS

Totara clearly has significant potential for management as a specialty wood species. It is amongst the more widely distributed lowland conifer tree species in New Zealand. It tolerates a wide range of site and climatic conditions. This site tolerance and the ease with which it can be cultivated have led to totara being widely planted throughout the country for over a century. Genetic variability both within and between populations indicates considerable potential genetic gain in both growth and form.

The ecological characteristics of totara make it ideally suited to silviculture. It produces viable seed from an early age and seeds in good quantities most years. Totara seed germinates within a season and seedlings are hardy and fast growing. Under cultivation, totara seedlings are amongst the easiest to produce using standard nursery-raising techniques. Planted seedlings show high survival rates and it is one of the faster growing indigenous conifers on a range of sites where adequate after-planting care has been undertaken. Totara tolerates an extremely broad environmental range including poor soils, exposed sites and drought and yet it responds positively to fertility, shelter and warm sites with excellent growth rates.

Under natural processes, totara regenerates in dense even-aged stands on fresh surfaces following catastrophic site disturbance. Pastoral landscapes on steep slopes in hill country mimic catastrophic disturbance evident in natural conditions and provide open sites on which regeneration of totara occurs, provided a local seed source is present. It is relatively unpalatable and regenerates on lightly grazed steep slopes dominated by poor quality pasture species. Fencing is, therefore, not essential for regeneration and development of stands on these sites. Grazing may, in fact, be beneficial in keeping pasture swards low, allowing more light to near ground level, and preventing regeneration of palatable, faster-growing hardwood species. In addition, trampling on steep slopes in wet weather is likely to create bare surfaces amongst grass cover suited to germination of totara seedlings.

Under grazing, natural stands of totara often develop into a near monoculture on many Northland sites that can be left to develop naturally, albeit slowly. Within a century, dense sapling thickets grow into stands of semi-mature trees that have undergone intense natural thinning to less than 1000 stems ha^{-1}. Trees have a mean DBH of 30 cm, mean height up to 20 m, average clear lower boles 6 m long and volume mean annual increments of around 6 $m^3ha^{-1}year^{-1}$. Silvicultural tending offers some potential for improving stem form and growth rates where landowners are keen to intervene.

Planting offers the best opportunity for quickly developing a resource of totara for future generations providing an option for the supply of high quality wood. Growth rates are considerably faster in planted stands on good sites than in untended natural stands on less desirable hill slopes. Predicted yields from average planted stands are over four times that of natural stands on Northland hill country sites within 100 years of planting. While there are opportunities for managing natural stands on hill country pasture, the establishment of plantations provides scope for targeting more sheltered and fertile sites to maximise growth potential. The few plantations that have been established at about 1000 stems ha^{-1} on sheltered, fertile, lowland sites and that have had good maintenance indicate that an average DBH close to 40 cm and volume mean annual increment of 10 $m^3ha^{-1}year^{-1}$ can be achieved in 80 years. However, rotation length is likely to be influenced largely by the desire for timber with a high proportion of heartwood. Indications are that rotations well in excess of 100 years will be required to allow development of a sufficient proportion of heartwood.

REFERENCES

Ahn, J.K.; John, S.I.; Jhun, G.S.; Hong, S.H.; Park, M.H.; Han, S.D. 1986: Study of heartwood formation in relation to tree age, site factors, and growth in *Pinus densiflora. Research report of the Institute of Forest Genetics, Korea Republic 22*: 5-8.

Allan, H.H. 1961: *Flora of New Zealand. Vol. I.* Wellington, Government Printer. 1085p.

Allen, R.B. 1992: RECCE. An inventory method for describing New Zealand vegetation. *FRI Bulletin No. 181*. Forest Research Institute, Ministry of Forestry, Christchurch, New Zealand. 25p.

Allen, R.B.; Partridge, T.R.; Lee, W.G.; Efford, M. 1992: Ecology of *Kunzea ericoides* (A.Rich.) J. Thompson (kanuka) in east Otago, New Zealand. *New Zealand Journal of Botany 30*: 135-149.

Applequist, M.B. 1958: A simple pith locator for use with off-centre increment cores. *Journal of Forestry 56 (2)*: 141.

Bamber, R.K. 1987: Sapwood and heartwood. *Technical Publication No. 2* (revised). Forestry Commission of New South Wales. 7p.

Baur, G.N. 1964: *The ecological basis of rainforest management.* Forestry Commission of New South Wales. 499p.

Baylis, G.T.S.; McNabb, R.F.; Morrison, T.M. 1963: The mycorrhizal nodules of podocarps. *Transactions of the British Mycological Society 46*: 378-384.

Bell, R.E. 1958: Dendrochronology. *New Zealand Science Review 16(1-2)*: 13-17.

Benecke, U. 1996: Ecological silviculture – the application of age old methods. *In*: An alternative approach to forestry – time to review! Proceedings of New Zealand Institute of Forestry Conference, 29 April – 1 May, Invercargill. 64-73.

Benecke, U. 2000: Near natural sustainable forestry from an international perspective. *In* Silvester, W.; McGowan, R. (eds.): *Native trees for the future*. Proceedings of a forum held at The University of Waikato, Hamilton, 8-10 October 1999. The University of Waikato. 85-93.

Bergin, D.O. 2000: Current knowledge relevant to management of *Podocarpus totara* for timber. *New Zealand Journal of Botany* 38: 343-359.

Bergin, D.; Pardy, G. 1987: Growing totara. *New Zealand Tree Grower*, August,: 68-70.

Bergin, D.O.; Ecroyd, C.E. 1987: Totara provenance trial – seed collection and measurement. Forest Research Institute Project Record No. 1751. (Unpubl.). 19p.

Bergin, D.O.; Herbert, J.W. 1995: The potential of indigenous forestry in Northland. NZ FRI Project Record No. 4492.

Bergin, D.O.; Kimberley, M.O. 1990: Provenance variation in *Podocarpus totara* seedlings. Forest Research Institute Contract Report FEW 90/37. (Unpubl.)

Bergin, D.O.; Kimberley, M.O. 1992: Provenance variation in *Podocarpus totara*. *New Zealand Journal of Ecology 16*: 5-13.

Bergin, D.O.; Kimberley, M.O.; Marden, M. 1995: Protective value of regenerating tea tree stands on erosion-prone hill country, East Coast, North Island, New Zealand. *New Zealand Journal of Forestry Science 25* (1): 3-19.

Bergin, D.O.; Pardy, G.F.; Beveridge, A.E. 1988: Planting to restore or extend native forest remnants. *New Zealand Tree Grower*, May: 44-47.

Best, E. 1916: Maori storehouses and kindred structures. *Dominion Museum Bulletin 5.*

Best, E. 1942: *Forest lore of the Maori.* Dominion Museum Bulletin 14. Government Printer. Wellington. Reprinted 1977.

Beveridge, A.E. 1962: Growth of podocarp seedlings in Pureora Forest Nursery. *New Zealand Forestry Research Note 32.* New Zealand Forest Service, Forest Research Institute, Rotorua. 12p.

Beveridge, A.E. 1964: Dispersal and destruction of seed in central North Island podocarp forests. *Proceedings of the New Zealand Ecological Society 11*: 48-55.

Beveridge, A.E. 1973: Regeneration of podocarps in a central North Island forest. *New Zealand Journal of Forestry 18* (1): 23-35.

Beveridge, A.E. 1977: Native trees on the farm. *Farm Forestry 19* (3): 58-70.

Beveridge, A.E. 1979: Management of the central North Island forests. Sanderson Memorial Address. *Forest and Bird 13*(4): 25-33.

Beveridge, A.E.; Bergin, D.O. 2000: The role of planting native trees in the management of disturbed forest. *In* Silvester, W.; McGowan, R. (eds.): *Native trees for the future*. Proceedings of a forum held at The University of Waikato, Hamilton, 8-10 October 1999. The University of Waikato. 51-60.

Beveridge, A.E.; Bergin D.O.; Pardy, G.F. 1985: Planting podocarps in disturbed indigenous forests of the central North Island. *New Zealand Journal of Forestry 30* (1): 144-58.

Bhat, K.M.; Bhat, K.V.; Dhamodaran, T.K. 1988: Effect of tree age on heartwood proportion of *Eucalyptus grandis* grown in Kerala. *Indian Journal of Forestry 11*: 95-97.

Blaschke, P.M.; Trustrum, N.A.; DeRose, R.C. 1992: Ecosystem processes and sustainable land use in New Zealand steeplands. *Agriculture, Ecosystems and Environment 41*: 153-178.

Bond, G. 1967: Fixation of nitrogen by higher plants other than legumes. *Annual Review of Plant Physiology 18*: 107-126.

Brownsey, P.J.; Smith-Dodsworth, J.C. 1989: *New Zealand ferns and allied plants*. Auckland, Bateman. 168p.

Bull, P.C.; Gaze, P.D.; Robertson, C.J.R. 1978: *Bird distribution in New Zealand. A provisional atlas 1969-1976*. The Ornithological Society of New Zealand, Wellington. 254p.

Burdon, R.D.; Miller, J.T. 1992a: Genetic survey of *Pinus radiata*. 5: Between-trait and age-age correlations for growth rate, morphology, and disease resistance. *New Zealand Journal of Forestry Science 22*(2/3): 211-27.

Burdon, R.D.; Miller, J.T. 1992b: Introduced forest trees in New Zealand: recognition, role, and seed source. 12. Radiata pine *Pinus radiata* D.Don. *FRI Bulletin No. 124*. New Zealand Forest Research Institute. 59p.

Burke, W.D. 1974: Regeneration of podocarps on Mt Tarawera, Rotorua. *New Zealand Journal of Botany 12*: 219-26.

Burns, B.R. 2000: Managing planted native stands. What can we learn from the ecology of natural forests? *In* Silvester, W.; McGowan, R. (eds.): *Native trees for the future*. Proceedings of a forum held at The University of Waikato, Hamilton, 8-10 October 1999. The University of Waikato. 47-50.

Burns, B.R.; Smale, M.C.; Merrett, M.F. 1999: Dynamics of kahikatea forest remnants in middle North Island: implications for threatened and local plants. *Science for Conservation Series 113*. Department of Conservation, Wellington. 23p.

Burrell, J. 1965: Ecology of *Leptospermum* in Otago. *New Zealand Journal of Botany 3* (1): 3-16.

Burrows, C.J. 1994: Fruits, seeds, birds and the forests of Banks Peninsula. *New Zealand Natural Sciences 21*: 87-107.

Burstall, S.W.; Sale, E.V. 1984: Great trees of New Zealand. Wellington, A. H. & A. W. Reed. 288 p.

Callaham, R.Z.; Liddicoet, A.R. 1961: Altitudinal variation at 20 years in ponderosa and Jeffery Pines. *Journal of Forestry 59*: 814-820.

Cameron, R.J. 1954: Mosaic or cyclical regeneration of in North Island podocarp forests. *New Zealand Journal of Forestry 7*: 55-64.

Cameron, R.J. 1959: The management potential of the native forests of North Auckland. *New Zealand Journal of Forestry 8* (1): 46-56.

Campbell, D.J. 1984: The vascular flora of the DSIR study area lower Orongorongo Valley, Wellington, New Zealand. *New Zealand Journal of Botany 22*: 223-270.

Chambers, T.C.; Farrant, P.A. 1998: The *Blechnum procerum* ("capense") (Blechnaceae) complex in New Zealand. *New Zealand Journal of Botany 36*: 1-19.

Clifton, N.C. 1990: *New Zealand timbers. The complete guide to exotic and indigenous woods*. GP Publications Ltd, Wellington. 170p.

Cockayne, L. 1928: *The vegetation of New Zealand.* Second edition. Leipzig, Engelmann. 456p.

Conner, H.E.; Edgar, E. 1987: Name changes in the indigenous New Zealand flora, 1960-1986 and Nomina Nova IV, 1983-1986. *New Zealand Journal of Botany 25*: 115-170.

Dakin, A.J.; Mearns, E.B. 1975: Practical aspects of rooting and growth of rimu cuttings. *Proceedings International Plant Propagators Society 25*: 344-50

Daly, G.T. 1973: The grasslands of New Zealand. *In*: Langer, R.H.M. (*ed.*): *Pastures and pasture plants*. Wellington, A.H. and A.W. Reed. 1-39.

Davidson, J. 1987: *The prehistory of New Zealand.* Auckland. Longman Paul. 270 p.

Dawson. M.I. 2000: Index of chromosome numbers of indigenous New Zealand spermatophytes. *New Zealand Journal of Botany 38*: 47-150.

Dean, M. 2000: Propagating native plants for forests. *In* Silvester, W.; McGowan, R. (eds.): *Native trees for the future.* Proceedings of a forum held at The University of Waikato, Hamilton, 8-10 October 1999. The University of Waikato. 9-10.

Department of Lands 1909: *Forestry in New Zealand.* Department of Lands, Wellington. 118p.

Dermott, M. 1985: Woodworking with New Zealand timbers. Auckland, Reed Methuen. 135 p.

Duguid, F. 1990: Botany of northern Horowhenua lowlands, North Island, New Zealand. *New Zealand Journal of Botany 28*: 381-437.

Duguid, F.; Druce, A.P. 1966: Totara forest at Ohau. *Wellington Botanical Society Bulletin 33*: 20-21.

Duncan, R.P. 1989: An evaluation of errors in tree age estimates based on increment cores in kahikatea (*Dacrycarpus dacrydioides*). *New Zealand Natural Sciences 16*: 31-37.

Duncan, R.P. 1993: Flood disturbance and the coexistence of species in a lowland podocarp forest, south Westland, New Zealand. *Journal of Ecology 81*: 403-416.

Dunwiddie, P.W. 1979: Dendrochronology studies of indigenous New Zealand trees. *New Zealand Journal of Botany 17*: 251-266.

Ebbett, R.L. 1992: Ecological characterisation of dense lowland podocarp forest, Whirinaki Sanctuary. MEnvtSci thesis, University of Auckland., New Zealand. (Unpubl.).

Ebbett, R.L. 1998: The ecology of lowland totara in South Island, New Zealand: distribution, regeneration, and future survival in a fragmented landscape. PhD thesis. University of Canterbury, Christchurch, New Zealand. (Unpubl.).

Ebbett, R.L.; Ogden, J. 1998: Comparative seedling growth of five endemic New Zealand podocarp species under different light regimes. *New Zealand Journal of Botany 36*: 189-201.

Ecroyd, C.; Herbert, J.; Miller, J.; Horgan, G. 1993: Kauri. Potential for plantation forestry. *Growing Today*. August. 20-23.

Edgar, E; Conner, H.E. 2000: *Flora of New Zealand. Volume V. Gramineae.* Lincoln, Manaki Whenua Press, Landcare Research. 650p.

Edmonds, A.S. 1978: Pureora Forest – What next? The fate of the West Taupo indigenous forests. *Environment News*, May: 2-3.

Ellis, J.C. 1979: Tree volume equations for the major indigenous species in New Zealand. New Zealand Forest Service, *Forest Research Institute Technical Paper No. 67*: 64p.

Ellis, J.C.; Hayes, J.D. 1997: Field guide for sample plots in New Zealand forests. New Zealand Forest Research Institute, Rotorua. *FRI Bulletin No. 186*. 84p.

Enright, N.J.; Hill, R.S.; Veblen, T.T. 1995: The southern conifers - an introduction. *In*: Enright, N. J.; Hill, R. S. (eds). *Ecology of the Southern Conifers*. Melbourne, Melbourne University Press. Pp. 1-9.

Enright, N.J.; Ogden, J 1995: The southern conifers – a synthesis. *In*: Enright, N. J.; Hill, R. S. (eds). *Ecology of the Southern Conifers*. Melbourne, Melbourne University Press. Pp. 271-287.

Esler, A.E. 1967: The vegetation of Kapiti Island. *New Zealand Journal of Botany 5*: 394-399.

Esler, A.E. 1978: *Botany of the Manawatu District, New Zealand*. New Zealand Department of Scientific and Industrial Research, Information Series No. 127. Wellington, Government Printer. 206p.

Esler, A.E.; Astridge, S.J. 1974: Tea tree (*Leptospermum*) communities of the Waitakere Range, Auckland, New Zealand. *New Zealand Journal of Botany 12*: 485-501.

Fletcher Challenge 2001: *Financial and operating Report 2001*. Fletcher Challenge Forests Ltd. 80p.

Florence, R.G. 1996: *Ecology and silviculture of Eucalypt forests*. Collingwood, Australia. CSIRO Publishing. 413p.

Forest Research Institute. 1980a: Establishing nursery-raised native trees. Forest Research Institute. *What's New in Forest Research No. 86*: 4p.

Forest Research Institute, 1980b: Raising native trees. Forest Research Institute. *What's New in Forest Research No. 85*: 4p.

Forest Research Institute 1982: The natural durability of untreated timbers. *What's New in Forest Research 112*. 4p.

Forest Research Institute. 1984: Supplementary plantings in South Westland. Forest Research Institute. *What's New in Forest Research No. 123*: 4p.

Forest Research Institute. 1984: Whirinaki State Forest – A management study in dense podocarp forest. *What's New in Forest Research No. 130*: 4p.

Forest Research Institute 1990: *MicroMARVL. Pre-harvest inventory. User guide.* Version 2.1. FRI Software Series No. 7. New Zealand Forest Research Institute, Rotorua,

Forest Research Institute 1997: Native trees for production forestry. New Zealand Forest Research Institute. *What's New in Forest Research 243*. 4p.

Foweraker, C.E. 1929: The podocarp rain forests of Westland, New Zealand. No. 2: Kahikatea and totara forests and their relationship to silting. *Te Kura Ngahere 2(4)*: 6-12.

Fraser, T.; Horgan, G. 1995: An introduction to discounted cash-flow analysis in forestry. *In* Hammond, D, (ed). *1995 Forestry handbook.* New Zealand Institute of Forestry (Inc.), Christchurch, New Zealand. 142-146.

Fritts, H.C. 1976: *Tree-rings and climate.* London, Academic Press. 567p.

Garratt, G.A. 1924: Some New Zealand woods. *New Zealand State Forest Service Professional Paper 1.* Government Printer, Wellington. 56p.

Gibson, L.J. 1983: Second-crop kauri evaluation. Auckland Conservancy Section Report No. 10. New Zealand Forest Service. (Unpubl.). 35p.

Goulding, C.J. 1995: Measurement of trees. *In* Hammond, D, (ed). *1995 Forestry handbook.* New Zealand Institute of Forestry (Inc.), Christchurch, New Zealand. 104-106.

Goulding, C.J., Deadman M.W., and Lawrence, M.E. 1993: Assessing stem qualities and using dynamic programming to predict log-product volumes in inventory. Pp. 171-178. *In* Nyyssonen, A., Poso S. and Rautala J., (eds). Proceedings of Ilvessalo symposium on National Forest Inventories. August 1992, Helsinki. Finnish Forest Research Institute Research Paper 444.

Grant, D.A. 1967: Factors affecting the establishment of manuka (*Leptospermum scoparium*). *Proceedings of the New Zealand Weed and Pest Control Conference 20*: 129-34.

Guest, R. 1985: Establishment of nursery-raised indigenous seedlings in selectively-logged forest in Pureora Forest Park. *New Zealand Journal of Forestry 30* (1): 159-166.

Guinon, M.; Larsen, J.B.; Spethmann, W. 1982: Frost resistance and early growth of *Sequoiadendron giganteum* seedlings of different origins. *Silvae Genetica 31*: 173-178.

Guthrie-Smith, H. 1921: *Tutira: The story of a New Zealand sheep station.* Edinburgh, Wm Blackwood and Sons.

Halkett, J.C. 1983: *Kauri forest management review.* Kauri Management Unit, Auckland Conservancy, New Zealand Forest Service. 90p.

Halkett, J.C.; Sale, E.V. 1986: *The world of kauri.* Reed Methuen, Auckland. 256p.

Harris, J.M. 1961: The dimensional stability shrinkage intersection point and related properties of New Zealand timbers. *New Zealand Forest Research Institute Technical Paper 36.*

Hawkins, B.J.; Sweet, G.B. 1989a: The growth of three podocarp species under different nutrient regimes. *New Zealand Journal of Botany 27*: 305-310.

Hawkins, B.J.; Sweet, G.B. 1989b: Evolutionary interpretation of a high temperature growth response in five New Zealand forest tree species. *New Zealand Journal of Botany 27*: 101-107.

Hawkins, B.J.; Sweet, G.B; Greer, D.H.; Bergin, D.O. 1991: Genetic variation in the frost hardiness of *Podocarpus totara. New Zealand Journal of Botany 29*: 455-458.

Healy, A.J.; Edgar, E. 1980: *Flora of New Zealand. Volume III. Adventive cyperaceous, petalous and spathaceous monocotyledons.* Wellington, Government Printer. 220p.

Henderson, L.T.; Koppe, T.F.; Schoenike, R.E. 1979: Ten-year evaluation of a seed source study of eastern red cedar in South Carolina. *Tree Planter Notes 30*: 3-6.

Herbert, J. 1980: Structure and growth of dense podocarp forest at Tihoi, central North Island, and the impact of selective logging. *New Zealand Journal of Forestry 25*: 44-57.

Herbert, J.W. 1976: Raising seedlings from seed contained in forest duff. Forest Research Institute Indigenous Silviculture Report No. 15. (Unpubl.). 18p.

Herbert, J.W. 1986: Cyclic regeneration of podocarps at Tihoi. *In*: Veale, B. J.; Innes, J. G. (eds.): *Ecological Research in the Central North Island Volcanic Plateau Region*. Proceedings of a New Zealand Forest Service Workshop, Pureora, November 1985. Rotorua, Forest Research Institute.

Herbert, J.; Beveridge, A.E. 1977: A selective logging trial in dense podocarp forest in the central North Island. *New Zealand Journal of Forestry, 22 (1)*: 81-100.

Herbert, J.; Glass, B.; Kimberley, M. 1996: A preliminary stand productivity and economic case study of plantation growth kauri. *In*: *An alternative approach to forestry – time to review!* Proceedings of New Zealand Institute of Forestry Conference, 29 April – 1 May. Invercargill. 83-91.

Herman, R.K.; Lavender, D.P. 1968: Early growth of Douglas-fir from various altitudes and aspects in southern Oregon. *Silvae Genetica 17*: 143-151.

Hewitt, A.E. 1998: New Zealand soil classification. *Landcare Research Science Series No. 1*. 133p.

Hicks, D.L. 1991: Long-term impact of erosion on hill country farm production: a method for estimation. *DSIR Land Resources Technical Record 32*. 20p.

Hill, M.O. 1979a: *DECORANA – A FORTRAN program for detrended correspondence analysis and reciprocal averaging*. Cornell University, Ithaca, New York. 52p.

Hill, M.O. 1979b: *TWINSPAN – A FORTRAN program for arranging multivariate data in an ordered two-way table by classification of the individuals and attributes*. Cornell University, Ithaca, New York. 90p.

Hill, M.O.; Bunce, R.G.H.; Shaw, M.W. 1975: Indicator species analysis, a divisive polythetic method of classification and its application to a survey of native pinewoods in Scotland. *Journal of Ecology 63*: 597-613.

Hill, M.O.; Gauch, H.G. 1980: Detrended correspondence analysis: an improved ordination technique. *Vegetatio 42*: 47-58.

Hinds, H.V.; Reid, J.S. 1957: *Forest trees and timbers of New Zealand.* New Zealand Forest Service Bulletin 12. 221p.

Hocking, G.H. 1949. Totara plantation of known age. *New Zealand Journal of Forestry*. 438.

Holloway, J.T. 1954: Forest and climate in the South Island of New Zealand. *Transactions of the Royal Society of New Zealand 82*: 329-410.

Horgan, G.P. 2000: Economic issues in the planting of New Zealand native trees. *In* Silvester, W.; McGowan, R. (eds.): *Native trees for the future.* Proceedings of a forum held at The University of Waikato, Hamilton, 8-10 October 1999. The University of Waikato. 76-79.

Hosking, G.P. 1978: *Ambeodontus tristis* (Fabricius) Two-toothed longhorn. *Forest and timber insects in New Zealand 26.* Forest Research Institute.

Hughes, H.R. 1991: Enacting and implementing sustainable environmental policies. *In*: Allen, J.C.; Whyte, A.G.D. (eds.) School of Forestry, Australia and New Zealand Institutes of Forestry Conference: New directions in Forestry: costs and benefits of change. Christchurch. School of Forestry, University of Canterbury. Pp. 156-162.

Innes, K.P.; Kelly, D. 1992: Water potentials in native woody vegetation during and after a drought in Canterbury. *New Zealand Journal of Botany 30*: 81-94.

James, I.L.; Norton, D.A. 2001: Helicopter-based natural forest management for New Zealand's rimu (*Dacrydium cupressinum*, Podocarpaceae) forests. *Forest Ecology and Management, 5619*: 1-10.

Jane, F.W. 1970: *The structure of wood.* Second Edition. London, Black. 478p.

Katz, A. 1980: Growth of podocarp pole stands on former Maori-cleared sites in the Whirinaki River valley. Unpublished Forest Research Institute Production Forestry Division, Indigenous Forest Management Report 24.

King, C. 1984: *Immigrant killers. Introduced predators and the conservation of birds in New Zealand.* Auckland, Oxford University Press. 224p.

Kirk, T. 1874: Durability of New Zealand timbers. Government Printer, Wellington, New Zealand. Section T, P4.

Lambrechtsen, N.C. 1975: *What grass is that?* New Zealand Department of Scientific and Industrial Research, Information Series No. 87. Wellington, Government Printer. 136p.

Lawry, E.A. 1980: Timber preservation in New Zealand – specifications. Timber Preservation Authority, Amendment 4. PT4.

Leathwick, J.R. 1987: Waipapa Ecological Area: a study of vegetation pattern in a scientific reserve. *Forest Research Institute Bulletin 130.* 82p.

Ledgard, N.J.; Norton, D.A. 1988: Shoot growth in 2-3 year old *Nothofagus* seedlings. *New Zealand Journal of Ecology 11*: 105-108.

Ledgard, N.J.; Norton, D.A. 1988: Shoot growth in 2-3 year old *Nothofagus* seedlings. *New Zealand Journal of Ecology 11*: 105-108.

Lee, W.G.; Allen, R.B.; Johnson, P.N. 1986: Succession and dynamics of gorse (*Ulex europaeus* L.) communities in the Dunedin Ecological District South Island, New Zealand. *New Zealand Journal of Botany, 24*: 279-292.

Levy, E.B. 1970: *Grasslands of New Zealand.* Third edition. Wellington, Government Printer. 374p.

Littell, R.C.; Milliken, G.A.; Stroup, W.W.; Wolfinger, R.D. 1996: SAS system for mixed models. Chapter 12: 463-489. SAS Institute Inc., Cary NC.

Liu, C.J. 1986: Rectifying radii on off-centre increment cores. *Forest Science 32*: 1058-1061.

Lloyd, R.C. 1949: Cicada damage in an indigenous forest. *New Zealand Journal of Forestry 6 (1)*: 64-65.

Lloyd, R.C. 1963: Indigenous tree rings. *New Zealand Journal of Forestry 8*: 824-825.

Long, J.N.; Smith, F.W.; Scott, D.R.M. 1981: The role of Douglas-fir stem sapwood and heartwood in the mechanical and physiological support of crowns and development of stem form. *Canadian Journal of Forest Research 11*: 459-464.

Maclaren, J.P. 1993: Radiata pine grower's manual. *FRI Bulletin No. 184.* New Zealand Forest Research Institute. 140p.

Magnussen, S.; Keith, C.T. 1990: Genetic improvement of volume and wood properties of Jack pine: selection strategies. *Forestry Chronicle 66 (3)*: 281-286.

Margolis, H.A.; Gaynor, R.R.; Pothier, D. and Pineau, M. 1988: The adjustment of growth, sapwood area, heartwood area, and sapwood saturated permeability of balsam fir after different intensities of pruning. *Canadian Journal of Forest Research 18*(6): 723-727.

Mason, R. 1958: Foods of the Australian opossum (*Trichosurus vulpecula* Kerr) in New Zealand indigenous forest in the Orongorongo Valley, Wellington. *New Zealand Journal of Science 1*: 590-613.

Masters, S.E.; Holloway, J.T.; McKelvey, P.J. 1957: *The National Forest Survey of New Zealand, 1955. Volume 1. The indigenous forest resources of New Zealand.* Wellington. Government Printer.

Mathews, H.J. 1905: *Tree culture in New Zealand.* Wellington, Government Printer.

Matsui, T. 2000: The ecology and recent history of coastal *Podocarpus* forests in southern New Zealand. MSc thesis, University of Otago, New Zealand. (Unpubl.). 213p.

McConchie, D. 2000: Quality native timber from future managed stands. *In* Silvester, W.; McGowan, R. (eds.): *Native trees for the future*. Proceedings of a forum held at The University of Waikato, Hamilton, 8-10 October 1999. The University of Waikato. 15-19.

McEwen, W.M. 1982: Cone development and phenology of podocarp tree species. Forest Research Institute Production Forestry Division Project Record 43. (Unpubl.). 21p.

McEwen, W.M. 1978: The food of the New Zealand pigeon (*Hemiphaga novaeseelandiae*). *New Zealand Journal of Ecology 1*: 99-108.

McSweeney, G.D. 1982: Matai/totara flood plain forests in South Westland. *New Zealand Journal of Ecology 5*: 121-128.

Meylan, B.A.; Butterfield, B.G. 1978: *The structure of New Zealand woods*. DSIR Bulletin 222. New Zealand Department of Scientific and Industrial Research. Wellington. 250p.

Miller, J.T.; Knowles, F.B. 1992: Introduced forest trees in New Zealand: recognition, role, and seed source. 9. The cypresses (revised edition) *Cupressus* spp. *Chamaecyparis* spp. *FRI Bulletin No. 124*. New Zealand Forest Research Institute. 33p.

Miller, J.T.; Knowles, F.B. 1994: Introduced forest trees in New Zealand: recognition, role, and seed source. 14. Douglas-fir *Pseudotsuga menziesii* (Mirbel) Franco. *FRI Bulletin No. 124*. New Zealand Forest Research Institute. 38p.

Molloy, B.P.J.; Ferguson, J.D.; Fletcher, P.J. 1978: The allelopathic effect of kahikatea. A progress report. *New Zealand Journal of Ecology 1*: 183-4.

Molloy, B.P.J. 1975: Manuka and kanuka. *In* Knox, R. (ed). *New Zealand's Nature Heritage, 6* (89). Hamlyn. 2469-2471.

Moor, L.B.; Edgar, E. 1970: *Flora of New Zealand. Volume II. Indigenous tracheophyta*. Wellington, Government Printer. 345p.

Mueller-Dombois, D.; Ellenberg, H. 1974: *Aims and methods of vegetation ecology*. New York, John Wiley and Sons. 547p.

New Zealand Forest Service 1977: Management policy for New Zealand's Indigenous State Forests. New Zealand Forest Service, Wellington.

New Zealand Meteorological Service 1983: Summaries of climatological observations to 1980. *New Zealand Meteorological Service Miscellaneous Publication 177*. 172p.

New Zealand Meteorological Service 1985: Climatic map series 1:2,000,000. Part 6: Annual rainfall. *New Zealand Meteorological Service Miscellaneous Publication 175*.

New Zealand Native Restoration Trust 1992: *The living forests of New Zealand*. Auckland, Bateman and the New Zealand Forest Restoration Trust. 98-105.

Newsome, P.F.J. 1987: *The vegetation cover of New Zealand*. Water and Soil Miscellaneous Publication No. 112. Ministry of Works and Development, Wellington. 153p.

Newton, T. 2000: The Forest Amendment Act and its future. *In* Silvester, W.; McGowan, R. (eds.): *Native trees for the future*. Proceedings of a forum held at The University of Waikato, Hamilton, 8-10 October 1999. The University of Waikato. 72-73.

Norton, D.A. 1991: Seedling and sapling distribution in a coastal podocarp forest, Hokitika Ecological District, New Zealand. *New Zealand Journal of Botany 29*: 463-466.

Norton, D.A.; Ogden, J. 1987: Dendrochronology: A review with emphasis on New Zealand applications. *New Zealand Journal of Ecology 10*: 77-95.

Norton, D.A.; Palmer, J.G.; Ogden, J. 1987: Dendrochronology studies in New Zealand 1. An evaluation of tree age estimates based on increment cores. *New Zealand Journal of Botany 25*: 373-383.

Norton, D.A. 1985: A multivariate technique for estimating New Zealand temperature normals. *Weather and Climate 5*: 64-74.

Norton, D.A. 1998: Impacts of tree coring on indigenous trees. *Conservation Advisory Notes 186*. Department of Conservation, Wellington. 6p.

Nugent, G.; Fraser, K.W.; Sweetapple, P.J. 1997: Comparison or red deer and possum diets and impacts in podocarp-hardwood forest, Waihaha catchment, Pureora Conservation Park. *Science for Conservation 50*: 61p.

O'Loughlin, C. 2000: Historical perspectives of indigenous forests. *In* Silvester, W.; McGowan, R. (eds.): *Native trees for the future*. Proceedings of a forum held at The University of Waikato, Hamilton, 8-10 October 1999. The University of Waikato. 1-6.

Ogden, J. 1983: The scientific reserves of Auckland University II. Quantitative vegetation studies. *Tane, 29*: 163-180.

Ogden, J. 1985: An introduction to plant demography with special reference to New Zealand trees. *New Zealand Journal of Botany 23*: 751-772.

Ogden, J.; Stewart, G.H. 1995: Community dymamics of the New Zealand conifers. *In*: Enright, N.J.; Hill, R.S. *eds. Ecology of the southern conifers.* Melbourne, Melbourne University Press. 81-119.

Pardy, G.F.; Bergin, D.O. 1992: Performance of native conifers planted in the early 1960's. *New Zealand Tree Grower*, February: 2-5.

Pardy, G.F.; Bergin, D.O.; Kimberley, M.O. 1992: Survey of native tree plantations. *FRI Bulletin No. 175*, Forest Research Institute, Rotorua; 24p.

Parham, B.E.V. 1929: Report on the heartwood and sapwood of totara (*Podocarpus totara* D.Don). Canterbury University College. 17p. 9 plates.

Parham, B.E.V.; Healy, A.J. 1976: *Common weeds in New Zealand.* Wellington. Government Printer. 173p.

Park, J.C.; Leman, C.S.E. 1983: A sawing study method for evaluating timber from pruned logs. *FRI Bulletin 47*. New Zealand Forest Service, Forest Research Institute. 42p.

Patel, N.P. 1967: Wood anatomy of Podocarpaceae indigenous to New Zealand. *New Zealand Journal of Botany, 5*: 307-21.

Pazdrowski, W.E. 1988: Studies on the relation between annual ring width and the proportion of sapwood and heartwood in butt logs from mature Scots pine (*Pinus sylvestris*) stands. *Sylvan 132*: 105-113.

Perceval, W.B. 1895: New Zealand timbers and forest products. Government Printer, Wellington, New Zealand.

Perry, N. B.; Foster, L. M.; Jameson, P. E. 1995: Effects of podocarp extracts on lettuce seed germination and seedling growth. *New Zealand Journal of Botany 33*: 565-568.

Philipson, W.R.; Molloy, B.P.J. 1990: Seedling, shoot, and adult morphology of New Zealand conifers. The genera *Dacrycarpus*, *Podocarpus*, *Dacrydium*, and *Prumnopitys*. *New Zealand Journal of Botany 28*: 73-84.

Preest, D.S. 1963: An attempt to hasten the germination of matai and miro seed using concentrated sulphuric acid. *New Zealand Journal of Forestry, 8* (5): 826-8.

Preest, D.S. 1979: Seed storage of several New Zealand indigenous trees. Part 1 – Kauri (*Agathis australis*). *New Zealand Journal of Forestry Science, 9* (3): 337-43.

Purnell, R.C.V. 1988: Variation in wood properties of *Eucalyptus nitens* in a provenance trial on the eastern Transvaal highveld in South Africa. *South African Forestry Journal 144*: 10-22.

Rehfeldt, G.E. 1979: Ecological adaptions in Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) populations. I. North Idaho and North-east Washington. *Heredity 43*: 383-397.

Rehfeldt, G.E. 1982: Differentiation of *Larix occidentalis* populations from the Northern Rocky Mountains. *Silvae Genetica 31*: 13-19.

Rehfeldt, G.E. 1983: Ecological adaptions in Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) populations. III. Central Idaho. *Canadian Journal of Forest Research 13*: 626-632.

Rehfeldt, G.E.; Wykoff, W.R. 1981: Periodicity in shoot elongation among populations of *Pinus contorta* from the Northern Rocky Mountains. *Annals of Botany 48*: 371-377.

Richards, F.J. 1959: A flexible growth function for empirical use. *Journal of Experimental Botany 10*: 290-300.

Roche, M. 1990: *History of forestry*. New Zealand Forestry Corporation. Wellington, GP Publications. 466p.

Royal Commission on Forestry 1913: Report of the Royal Commission on Forestry together with minutes of proceedings and of evidence. C.-12.

SAS. 1990: SAS/STAT guide for personal computers, version 6 edition. Cary, North Carolina, SAS International Inc.

Schoenike, F.E. 1969: Early evaluation of a seed source study in eastern red cedar (*Juniperus virginiana*) in South Carolina. *Proceedings of the Tenth Southern Forest Tree Improvement Conference, Houston, Texas*: 165-174.

Schultze-Dewitz, G.; Gotze, H. 1987: Bark percent, heartwood formation and fibre length in ten Scots pine provenances. *Beitrage fur die Forstwirtschaft 21 (3)*: 111-114.

Schumacher, F.X. 1939. A new growth curve and its application to timber-yield studies. *Journal of forestry 37*. 819-820.

Sheath, G.W.; Carlson, W.T. 1998: Impact of cattle treading on hill land 1 – soil damage patterns and pasture status. *New Zealand Journal of Agricultural Research 41* (2): 271-278.

Silvester, W.; McGowan, R. (eds.) 2000: *Native trees for the future*. Proceedings of a forum held at The University of Waikato, 8-10 October 1999. The University of Waikato. 96p.

Silvester, W.B. 1964: Forest regeneration problems in the Hunua Range, Auckland. *Proceedings of the New Zealand Ecological Society 11*: 1-5.

Simpson, P. 1988: He totara wahi rua he kai na te ahi (A totara split in two is food for the fire: unity is strength). *The Landscape,* Autumn/Winter. Department of Conservation Scientific Paper 31. 7p.

Sinclair, K. 1959: *A history of New Zealand.* Harmonds-worth, England, Penguin Books. 320p.

Smale, M.C.; Bergin, D.O.; Gordon, A.D.; Pardy, G.F.; Steward, G.S. 1985: Selective logging of dense podocarp forest at Whirinaki, early effects. *New Zealand Journal of Forestry Science, 15(1)*: 36-58.

Smale, M.C.; Beveridge, A.E.; Pardy, G.F.; Steward, G.A. 1987: Selective logging in podocarp/tawa forest at Pureora and Whirinaki. *New Zealand Journal of Forestry Science 17(1)*: 29-50.

Smale, M.C.; Burns, B.R.; Smale, P.N.; Whaley, P.T. 1997: Dynamics of upland podocarp/broadleaved forest on Mamaku Plateau, central North Island, New Zealand. *Journal of the Royal Society of New Zealand 27(4)*: 513-532.

Smale, M.C.; Kimberley, M.O. 1993: Regeneration patterns in montane conifer/broadleaved forest on Mt Pureora, New Zealand. *New Zealand Journal of Forestry Science 23(2)*: 123-141.

Smale, M.C.; McLeod, M.; Smale, P.N. 1997: Vegetation and soil recovery on shallow landslide scars in Tertiary hill country, East Cape region, New Zealand. *New Zealand Journal of Ecology 21 (1)*: 31-41.

Smith, D.M. 1962: *The practice of silviculture*. New York. John Wiley & Sons. 578p.

Soil Bureau 1954: General survey of the soils of North Island, New Zealand. New Zealand Department of Scientific and Industrial Research. *Soil Bureau bulletin 5*. Government Printer. 286p.

Soil Bureau 1968: General survey of the soils of South Island, New Zealand. New Zealand Department of Scientific and Industrial Research. *Soil Bureau Bulletin 27*. Government Printer. 286p.

Soper, M.F. 1976: *New Zealand birds*. Christchurch, Whitcoulls. 251p.

Standards Association of New Zealand 1988: *New Zealand timber grading rules*. New Zealand Standard 3631. Standards Association of New Zealand. 112p.

Stewart, G.H.; White, J.C. 1995: Tree ring analysis in rimu (*Dacrydium cupressinum*): implications for studies of forest dynamics and sustained yield management. *New Zealand Forestry*, August 1995: 27-31.

Sutherland, C.F.; Cox, J.E.; Taylor, N.H.; Wright, A.C.S. 1979: Soil map of Kaitaia – Rawene area (Sheets O03/04/05). North Island, New Zealand. Scale 1:100,000. *New Zealand Soil Bureau Map 182*.

Sutherland, C.F.; Cox, J.E.; Taylor, N.H.; Wright, A.C.S. 1980: Soil map of Whangaroa – Kaikohe area (Sheets 04/05). North Island, New Zealand. Scale 1:100,000. *New Zealand Soil Bureau Map 183*.

Sutherland, C.F.; Cox, J.E.; Taylor, N.H.; Wright, A.C.S. 1981: Soil map of Hukerenui – Whangarei area (Sheets Q06/07, R06/07). North Island. Scale 1:100,000. *New Zealand Soil Bureau Map 187*.

Tree Grower, 1995: Creation of conservation management plan for native totara. *New Zealand Tree Grower*, February 1995. 34.

Troup, R.S. 1928: *Silvicultural systems*. Second edition. Oxford, Oxford University Press. 216p.

Tyrell, L.E.; Crow, T.R. 1994: Structural characteristics of old-growth hemlock-hardwood forests in relation to age. *Ecology 75(2)*: 370-386.

van Dorsser, J.C.; Bergin, D.O. 1987: Raising bare-rooted native seedlings at FRI Nursery. FRI Project Record No. 1749. Forest Research Institute. (Unpubl.). 12p.

Veblen, T.T. 1992: Regeneration dynamics. *In*: Glenn-Lewin, D.C.; Peet, R.K.; Veblen, T.T. (eds.) *Plant succession theory and practice*. London, Chapman and Hall. 152-187.

Wardle, J.A. 1984: *The New Zealand beeches. Ecology, utilisation and management*. New Zealand Forest Service. Christchurch, Caxton Press. 447p.

Wardle, P. 1963: The regeneration gap of New Zealand gymnosperms. *New Zealand Journal of Botany 1*: 301-315.

Wardle, P. 1972: *Podocarpus totara* var. *waihoensis* var. nov.: the result of introgressive hybridisation between *P. totara* and *P. acutifolius*. *New Zealand Journal of Botany 10*: 195-201.

Wardle, P. 1974: The totara. *In* Knox, R. (ed.). *New Zealand's Nature Heritage, 1*(13). Hong Kong, Hamlyn. 347-350.

Wardle, P. 1991: *Vegetation of New Zealand.* Cambridge University Press. Cambridge. 672p.

Webb, C.J.; Sykes, W.R.; Garnock-Jones, P.J. 1988: *Flora of New Zealand. Volume IV. Naturalised pteridophytes, gymnosperms, dicotyledons.* Wellington, Government Printer.

Webby, R.F.; Markham, K.R.; Molloy, B.P.J. 1987: The characterisation of New Zealand *Podocarpus* hybrids using flavenoid markers. *New Zealand Journal of Botany 25*: 355-366.

Weller, D.E. 1987: A reevaluation of the –3/2 power rule of plant self-thinning. *Ecological Monographs, 57* (1): 22-43.

Wells, J.A. 1972: Ecology of *Podocarpus hallii* in central Otago, New Zealand. *New Zealand Journal of Botany 10*: 399-426.

White, J. 1985: The thinning rule and its application to mixtures of plant populations. *In*: White, J. *ed. Studies on plant demography, a Festschrift for John L. Harper*. London, Academic Press. 291-309.

Whyte, A.G.D. 2000: Forestry in New Zealand undermined. *International Forestry Review 2(2)*: 126-129.

Wilcox, M.D.; Ledgard, N.J. 1983: Provenance variation in the New Zealand species of *Nothofagus*. *New Zealand Journal of Ecology 6*: 19-31.

Williams, C.; Savolainen, O. 1996: Inbreeding depression in conifers: Implications for breeding strategy. *Forest Science 42*:102-117.

Williams, J.G.K.; Kubelik, A.R.; Livak, K.J.; Rafalski, J.A.; Tingey, S.V. 1990: DNA polymorphisms amplified by arbitrary primers are useful as genetic markers. *Nucleic Acids Research 18(22)*: 6531-6535.

Wilson, H.D. 1982: *Stewart Island plants*. Christchurch, Field guide publications. 528p.

Wilson, J.B.; Lee, W.G. 1988: The -3/2 Law applied to some gorse communities, with consideration of line fitting. *New Zealand Journal of Botany 26*: 193-196.

Worbes, M. 1988: Variety in structure of annual growth zones in *Tabebuia barbata* (E. Mey) Sandw., Bigoniaceae, a tropical tree species from Central Amazonian inundation forests. *Dendrochronologia 6*: 71-89.

Wright, J.W. 1970: Genetics of eastern white pine. *USDA Forest Service Research Paper WO-9*: 1-16.

Yang, K.C.; Hazenberg, G. 1991: Sapwood and heartwood width relationship to tree age in *Pinus banksiana*. *Canadian Journal of Forest Research 21*: 521-525.

Yang, R.C., Kozak, A., Smith, J.H.G. 1978: The potential of Weibull-type functions as flexible growth curves. *Canadian Journal of Forest Research 8*: 424-431.

Yoda, K.; Kira, T.; Ogawa, H.; Hozumi, K. 1963: Self-thinning in over-crowded pure stands under cultivated and natural conditions (Intraspecific competition among higher plants XI). *Journal of the Institute of Polytechnics, Osaka City University, Series D 14*: 107-129.

Zabkiewicz, J.A. 1976: The ecology of gorse and its relevance to New Zealand forestry. *In*: The Use of Herbicides in Forestry in New Zealand. *New Zealand Forest Service, Forest Research Institute Symposium 18*: 63-68.

APPENDICES

Appendix 1.1: Definitions of abbreviations and conventions used throughout, other than log and wood definitions.

Abbreviation	Definition
a.s.l.	above sea level
ANOVA	Analysis of variance
BA	Basal area
DBH, D	Diameter at breast height, 1.4 m above ground level
DCA	Detrended correspondence analysis
FRI	Forest Research Institute
H	Height
ha	hectare
LSD	Least significant difference
MAI	Mean annual increment
N, n	Stem density
NZFS	New Zealand Forest Service
RCD	Root collar diameter, taken at near ground level
SE	Standard error
T	Mean age of stands
V	Volume

Appendix 1.2: Alphanumeric codes used for each plot established in planted and natural stands with a brief description of stand type, plot location and land tenure.

Stand type	Plot code	Stand type	Land tenure and/or plot location
Natural stands	DONE1	Pole stand	Donelley, Glenbervie,
	DONE2	Saplings	Donelley, Glenbervie
	DONE3	Saplings	Donelley, Glenbervie
	DONE4	Pole stand	Donelley, Glenbervie
	DONE5	Semi-mature	Donelley, Glenbervie
	DONE6	Semi-mature	Donelley, Glenbervie
	BRID1	Semi-mature	MacBride, Glenbervie
	BRID2	Pole stand	MacBride, Glenbervie
	BRID3	Sapling stand	MacBride, Glenbervie
	BRID4	Sapling stand	MacBride, Glenbervie
	REED1	Mature stand	Reed Memorial Reserve, Whangarei
	QUIN1	Pole stand	Quinlan, Kaeo
	QUIN2	Pole stand	Quinlan, Kaeo
	LANE1	Saplings/poles	Lane, Kaeo
	LANE2	Saplings/poles	Lane, Kaeo
	LANE3	Semi-mature	Lane, Kaeo
	COOP1	Saplings	Cooper, Awaroa
	COOP2	Saplings	Cooper, Awaroa
	COOP3	Saplings	Cooper, Awaroa
	COOP4	Pole stand	Cooper, Awaroa
	COOP7	Pole stand	Cooper, Awaroa
	OWEN1	Pole stand	Owen, Broadwood
	OWEN2	Pole stand	Owen, Broadwood
	MACK1	Semi-mature	MacKenzie, Awaroa
	MACK2	Semi-mature	MacKenzie, Awaroa
	MACK3	Seedlings	MacKenzie, Awaroa
	MACK4	Seedlings	MacKenzie, Awaroa
	MACK5	Seedlings/saplings	MacKenzie, Awaroa
	MACK6	Seedlings/saplings	MacKenzie, Awaroa
	MACK7	Pole stand	MacKenzie, Awaroa
	MACK8	Pole stand	MacKenzie, Awaroa
	MACK9	Pole stand	MacKenzie, Awaroa
Planted stands	TAPA	Plantation	Tapakanga Regional Park, Firth of Thames
	HOLT	Plantation	Holt's Forest Trust, Hawkes Bay
	KIANG	Underplanted	Kiangaroa Forest, central North Island
	KAMO2	Shelterbelt	Going, Kamo, Northland
	GLEN	Plantation	Glenbervie Forest, Northland
	HOLD	Plantation	Holdsworth, TeKaraka, East Coast
	PUKE1	Plantation	Pukekura Park, New Plymouth
	PUKE6	Plantation	Pukekura Park, New Plymouth
	PUKE7	Small grove	Pukekura Park, New Plymouth
	CORN	Small grove	Cornwall Park, Auckland
	PURAU	Plantation	Purau, Banks Peninsula
	PRIOR	Plantation	Prior Park, Hawkes Bay
	BROU1	Plantation	Brough, Puhipuhi, Northland
	BROU2	Plantation	Brough. Puhipuhi, Northland
	KAMO1	Shelterbelt	Kamo, Northland (older shelterbelt)

Appendix 3.1: Seed tree details and geographic and climatic information for each of the totara provenances planted out in the Tapapakanga trial in 1988.

No.	Provenance location	Number of seed trees	Seed tree form*	Habitat†	Latitude (S)	Longitude (E)	Altitude (m)	Mean summer temp (°C)#	Mean annual rainfall (mm)‡
1	Kaikohe	3	Intermediate	Farmland	35° 21'	173° 49'	240	15	2000
2	Waipoua	2	Good	Forest	35°39'	173° 33'	120	15	2000
3	Auckland	20	Poor	Groves	37° 05'	174° 56'	60	16	1400
4	Kauaeranga (low altitude)	3	Intermediate	Grove on farmland	37°08'	175° 37'	30	15	1400
5	Kauaeranga	3	Variable	Scrub and open site	37° 00'	175° 38'	140	13	2000
6	Waharoa	30	Poor	Groves on farmland	37° 39'	175° 39'	30	14	1400
7	Matamata	3	Poor	Farmland	37° 39'	175° 39'	30	14	1400
8	Mamaku	2	Poor	Farmland	38° 00'	175° 54'	270	11	2800
9	Opotiki	10	Good	Forest	38° 07'	177° 11'	70	14	1400
10	Gisborne	12	Grove	Farmland	38° 27'	177° 50'	60	14	1000
11	Pureora (Fletchers Road)	6	Small, good	Forest edge	38° 27'	175° 34'	560	11	2000
12	Pureora (North Block)	3	Good	Tall forest	38° 27'	175° 34'	560	11	2000
13	Pureora (Education Res)	5	Excellent	Tall forest	38° 27'	175° 34'	560	11	2000
14	Taumaranui	20	Good	Pole stand	38° 58'	175° 14'	240	13	1400
15	Hurakia	10	Good	Forest	38° 35'	175° 31'	490	11	2000
16	New Plymouth	15	Poor	Groves and open sites	39° 06'	174° 07'	100	13	1400
17	Whangamomona	25	Poor	Farmland	39° 06'	174° 46'	210	12	2000
18	Taihape	15	Poor	Farmland	39° 38'	175° 46'	490	11	1000
19	Hunterville	20	Poor	Farmland	39° 54'	175° 32'	240	11	1000
20	Hawkes Bay	8	Poor	Farmland	39° 46'	176° 29'	275	12	700
21	Pohangina	20	Good	Tall forest	40° 08'	175° 50'	150	11	1000
22	Otaki	30	Poor	Farmland	40° 47'	175° 10'	30	13	1000
23	Masterton	30	Poor	Farmland	40° 49'	175° 37'	210	13	1000
24	Ngaumu Forest	1	Poor	Farmland	41° 01'	175° 58'	370	13	1400
25	Featherston	30	Poor	Groves on farmland	41° 08'	175° 23'	40	13	1000
26	Nelson	2	Good	Forest remnant	41° 24'	173° 03'	160	13	1000
27	Nelson (Wai-iti)	3	Poor	Groves and open sites	41° 26'	172° 59'	180	13	1000
28	Pelorus River	3	Poor	Forest edge	41° 18'	173° 34'	30	11	2000
29	Kaikoura (north)	10	Poor	Low forest	42° 13'	173° 53'	5	11	1000
30	Kaikoura (good form)	20	Good	Tall forest	42° 16'	173° 41'	450	11	1400
31	Kaikoura (poor form)	20	Poor	Farmland	42° 17'	173° 41'	240	12	1000
32	Harihari (seedlot 76A)	6	Poor	Stand on farmland	43° 07'	170° 36'	52	10	4000
33	Harihari (seedlot 76B)	6	Poor	Forest and farmland	43° 07'	170° 36'	52	10	4000
34	Banks Peninsula	15	Good	Forest	43° 42'	172° 54'	60	11	1000
35	Peel Forest	7	Good	Forest	43° 54'	171° 14'	300	9	1000
36	Dean Forest	2	Good	Forest	45° 52'	167° 38'	120	9	1000

* Subjective description of stem form of seed trees obtained from seed collection forms.
† Description of habitat type where seed trees were located.
\# Mean summer temperature calculated using methods of Norton (1985).
‡ Mean annual rainfall from New Zealand Meteorological Service (1985).

Appendix 3.2: P values for the correlation matrix of provenance means for growth variables between seedlings assessed during the nursery phase (1986-88) and performance of trees 6 years (1994) and almost 11 years (1999) after planting.

	Height 1986 (nursery)	Height 1987 (nursery)	Height 1988 (nursery)	Height 1988 (trial)	Height at age 6 (trial)	Height at age 11 (trial)	Height increment, 1987-1988 (nursery)	Root collar diameter at age 11 (trial)
Height 1987 (nursery)	< 0.001							
Height 1988 (nursery)	< 0.001	< 0.001						
Height 1988 (trial)	< 0.001	< 0.001	< 0.001					
Height at age 6 (trial)	0.49	0.75	0.04	0.004				
Height at age 11 (trial)	0.45	0.88	0.14	0.304	< 0.001			
Height increment 1987-1988 (nursery)	0.81	0.37	< 0.001	< 0.001	< 0.001	< 0.001		
Root collar diameter at age 11 (trial)	0.51	0.61	0.06	0.006	< 0.001	< 0.001	< 0.001	
DBH at age 11 (trial)	0.89	0.25	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

Appendix 3.3: P values for the correlations of provenance means for stem form traits in the nursery (1988) and planting trial assessments 6 years (1994) and almost 11 years (1999) after planting.

	Nursery variables		Planting trial variables		
	Stem form 1988	Branching 1988	Stem form at age 6	Trees with double leaders at age 11	Number of leaders per tree at age 11
Branching 1988 (nursery)	< 0.001				
Stem form at age 6	0.08	0.12			
Trees with double leaders at age 11	0.04	0.006	< 0.001		
Number of leaders per tree at age 11	0.11	0.01	< 0.001	< 0.001	
Height to double leader at age 11	0.04	0.001	< 0.001	< 0.001	< 0.001

Appendix 3.4: P values for correlations between provenance mean height and diameter, and geographic and climatic parameters of provenances.

	Height at planting	Height at age 6	Height at age 11	Root collar diameter at age 11	DBH at age 11
Latitude	0.26	0.005	< 0.001	0.24	0.02
Altitude	0.75	0.75	0.44	0.15	0.37
Mean summer temperature	0.37	0.008	< 0.001	0.05	0.01
Total annual rainfall	0.31	0.80	0.92	0.35	0.67

Appendix 3.5: P values for correlations for provenance means between stem form characteristics (assessed in the nursery and the planting trial), and geographic and climatic parameters of provenances.

	Nursery variables		Planting trial variables			
	Stem form 1988	Branching 1988	Stem form at age 6	Trees with double leaders at age 11	Number of leaders per tree at age 11	Height to double leader at age 11
Latitude	0.11	0.10	0.003	0.04	0.008	0.002
Altitude	0.90	0.81	0.01	0.38	0.15	0.19
Mean summer temperature	0.58	0.26	0.22	0.52	0.26	0.14
Total annual rainfall	0.37	0.84	0.35	0.91	0.50	0.47

Appendix 4.1: Site and climatic data for each stand. For most stands, climatic data was taken from the nearest weather station statistics (New Zealand Meteorological Service 1983). Stands are arranged from youngest to oldest (refer to Table 4.4 for stand ages).

Locality	Type of Stand	Altitude (m)	Aspect (°)	Slope (°)	Annual Rainfall (mm)	Daily MeanTemp °C	No. of Ground Frosts/Year	Sunshine Hours†
Tapapakanga Regional Park, Firth of Thames*	Plantation	35	95	18	1296	14	3	2102
Holts Forest Trust, Hawkes Bay	Plantation	240	275	5	1756	11.9	62	-
Kiangaroa Forest, central North Island	Underplanted	544	-	0	1483	10.7	99.5	-
Kamo, Northland	Shelterbelt	40	-	0	1600	15.4	7.2	1925
Glenbervie Forest, Northland	Plantation	107	20	10	1934	13.7	42.1	1925
TeKaraka, East Coast	Plantation	80	135	20	1010	13.8	45.5	2172
Pukekura Park, New Plymouth	Plantation	49	220	10	1539	13.5	6.6	2114
Cornwall Park, Auckland	Small grove	45	-	0	1112	15.5	0	2102
Purau, Banks Peninsula	Plantation	20	270	15	666	11.6	88.7	1974
Prior Park, Hawkes Bay	Plantation	65	-	0	850	13.5	54	2245
Puhipuhi, Northland (2 stands)	Plantation	260	-	0	1950	14	15	2045
Kamo, Northland (older shelterbelt)	Shelterbelt	45	360	5	1600	15.4	7.2	1925

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

Appendix 5.1: List of herbaceous and fern species with codes for the regeneration survey, Kaeo, Northland.

	Species code	Botanical name	Common name
Grasses	AGRSTO	*Agrostis stolonifera*	creeping bent
	ANTODO	*Anthoxanthum odoratum*	sweet vernal
	DACGLO	*Dactylis glomerata*	cocksfoot
	FESARU	*Festuca arundinacea*	tall fescue
	HOLLAN	*Holcus lanatus*	Yorkshire fog
	LOLPER	*Lolium perenne*	perennial ryegrass
	OPLIMB	*Oplismenus imbecillus*	
	PASDIL	*Paspalum dilatatum*	paspalum
	PENCLA	*Pennisetum clandestinum*	kikuyu grass
	POAPRA	*Poa pratensis*	Kentucky bluegrass
	SPOAFR	*Sporobolus africanus*	ratstail
Legumes	LOTSUA	*Lotus suaveolens*	hairy lotus
	LOTPED	*Lotus pedunculatus*	
	TRIREP	*Trifolium repens*	white clover
Herbaceous species	AGERIP	*Ageratina riparia*	mist flower
	ANAARV	*Anagallis arvensis*	scarlet pimpernel
	BELPER	*Bellis perennis*	field daisy
	CENERY	*Centaurium erythraea*	centaury
	CENUNI	*Centella uniflora*	
	CHRLEU	*Chrysanthemum leucanthemum*	oxeye daisy
	CIRVUL	*Cirsium vulgare*	scotch thistle
	CONALB	*Conyza albida*	fleabane
	COTAUS	*Cotula australis*	
	DIGPUR	*Digitalis purpurea*	foxglove
	FRAVES	*Fragaria vesca*	strawberry
	FUMMUR	*Fumaria muralis*	scrambling fumitory
	GNACOA	*Gnaphalium coarctatum*	purple cudweed
	MENPUL	*Mentha pulegium*	pennyroyal
	PHYOCT	*Phytolacca octandra*	inkweed
	PLALAN	*Plantago lanceolata*	narrow-leaved plantain
	PLAMAJ	*Plantago major*	broad-leaved plantain
	PRUVUL	*Prunella vulgaris*	selfheal
	RANREP	*Ranunculus repens*	creeping buttercup
	RUMACE	*Rumex acetosella*	sheep's sorrel
	RUMOBT	*Rumex obtusifolius*	broad-leaved dock
	STEMED	*Stellaria media*	chickweed
	TAROFF	*Taraxacum officinale*	dandelion
Sedges/rushes	JUNBUF	*Juncus bufonius*	toad rush
	JUNGRE	*Juncus gregiflorus*	
	SCHPUN	*Scirpus pungens*	three square sedge
Ferns	ADISPP	*Adiantum cunninghamii*	maidenhair fern
	BLENOV	*Blechnum novae-zelandiae*	kiokio
	DICSQU	*Dicksonia squarrosa*	wheki
	DOOMED	*Doodia media*	
	PAESCA	*Paesia scaberula*	scented fern
	PTEAQU	*Pteridium esculentum*	bracken

Appendix 5.2: F and P values for site characteristics, regeneration of woody species and species richness of pasture species for each slope class, aspect class and TWINSPAN group.

	Mean slope of each plot (°)	Bare ground (%)	Proportion of major woody species (%)				Mean size class of totara*	Mean number of totara per plot	Pasture species richness (No. of species per plot)
			Totara	Gorse	Manuka/ kanuka	Kahikatea			
Slope class	$F_{3,343} = 1109.96$ $p < 0.0001$	$F_{3,343} = 20.13$ $p < 0.0001$	$F_{3,343} = 96.41$ $p < 0.0001$	$F_{3,343} = 20.99$ $p < 0.0001$	$F_{3,343} = 4.10$ $p = 0.0071$	$F_{3,343} = 11.96$ $p < 0.0001$	$F_{2,78} = 0.31$ $p = 0.7316$	$F_{3,343} = 58.79$ $p < 0.0001$	$F_{3,343} = 24.38$ $p < 0.0001$
Aspect class	$F_{2,345} = 16.33$ $p < 0.0001$	$F_{2,345} = 5.03$ $p = 0.0070$	$F_{2,345} = 4.13$ $p = 0.0169$	$F_{2,345} = 8.48$ $p = 0.0003$	$F_{2,345} = 3.85$ $p = 0.0222$	$F_{2,345} = 0.61$ $p = 0.5465$	$F_{1,80} = 2.49$ $p = 0.1182$	$F_{2,345} = 2.38$ $p = 0.0944$	$F_{2,345} = 8.73$ $p = 0.0002$
TWINSPAN Group	$F_{3,343} = 95.34$ $p < 0.0001$	$F_{3,343} = 17.29$ $p < 0.0001$	$F_{3,343} = 31.13$ $p < 0.0001$	$F_{3,343} = 38.06$ $p < 0.0001$	$F_{3,343} = 13.28$ $p < 0.0001$	$F_{3,343} = 24.96$ $p < 0.0001$	$F_{2,78} = 1.73$ $p = 0.1843$	$F_{3,343} = 23.76$ $p < 0.0001$	$F_{3,343} = 41.44$ $p < 0.0001$

Appendix 5.3: Two-way TWINSPAN table classification of plots with cover abundance of grass, herbaceous and fern species on farmland, Kaeo, Northland. Separation of TWINSPAN groups taken to the second level are indicated by arrows with slope, percentage groundcover and proportion of plots with totara present in each group indicated.

No.	Species	Plot cover abundance values
		[illegible]
4	PAESCA	[illegible]
19	CIRVUL	[illegible]
17	PENCLA	[illegible]
20	DIGPUR	[illegible]
26	COTAUS	[illegible]
26	COTAUS	[illegible]
31	PHYOCT	[illegible]
2	AGERIP	[illegible]
8	DOOMED	[illegible]
9	CONALB	[illegible]
24	BLENOV	[illegible]
25	FRAVES	[illegible]
33	DICSQU	[illegible]
34	STEMED	[illegible]
35	SCHPUN	[illegible]
37	ADISPP	[illegible]
1	JUNGRE	[illegible]
7	LOTSUA	[illegible]
42	GNACOA	[illegible]
18	TAROFF	[illegible]
43	RUMACE	[illegible]
15	PASDIL	[illegible]
41	CENUNI	[illegible]
45	CENERY	[illegible]
38	PTEAQU	[illegible]
40	JUNBUF	[illegible]
49	LICHEN	[illegible]
27	MYRAUS	[illegible]
44	FESARU	[illegible]
46	MOSS	[illegible]
12	ANTODO	[illegible]
47	LOTPED	[illegible]
3	HOLLAN	[illegible]
6	PRUVUL	[illegible]
36	SPOAFR	[illegible]
14	DACGLO	[illegible]
22	PLALAN	[illegible]
10	MENPUL	[illegible]
28	AGRSTO	[illegible]
30	OPLIMB	[illegible]
32	CHRLEU	[illegible]
48	BELPER	[illegible]
11	LOLPER	[illegible]
13	RANREP	[illegible]
16	TRIREP	[illegible]
5	ANAARV	[illegible]
21	FUMMUR	[illegible]
23	RUMOBT	[illegible]
29	PLAMAJ	[illegible]
39	POAPRA	[illegible]
		[illegible]

↑ ↑ ↑

TWINSPAN group 1	TWINSPAN group 2	TWINSPAN group 3	TWINSPAN group 4
Average slope 29°	Average slope 25°	Average slope 16°	Average slope 9°
Bare ground 16.5%	Bare ground 19.7%	Bare ground 6.7%	Bare ground 3.8%
Plots with totara 60%	Plots with totara 34%	Plots with totara 8%	Plots with totara 0%

Appendix 6.1: Site and climatic characteristics for each sampling site in the main study areas in Northland. Climatic data was taken from the nearest weather station statistics (New Zealand Meteorological Service 1983).

Study area	Annual rainfall (mm)	Daily mean temperature (°C)	No. of ground frosts /year	Sunshine hours[†]	Sampling site				
					Identifier code	Altitude (m)	Grid reference	Longitude (E)	Latitude (S)
Glenbervie	1934	13.7	42.1	-	DONE	140	Q06 349 130	174° 22'	35° 41'
					BRID	140	Q06 412 108	174° 26'	35° 42'
					REED	80	Q06 320 109	174° 20'	35° 42'
Kaeo	1682	15.1	24.9	2004	QUIN	140	P04 790 760	173° 45'	35° 07'
					LANE	25	P04 835 752	173° 48'	35° 07'
Herekino	1506	15.1	8.5	-	COOP	40	O06 366 589	173° 16'	36° 16'
					OWEN	60	O06547 597	173° 29'	36° 16'
					MACK	50	O06 357 597	173° 16'	36° 16'

† Sunshine hours not recorded at all stations.

Appendix 6.2: Stand and site descriptions for each plot established in natural stands.

Study area	Plot code	*Stand description*	Altitude (m)	Aspect (°)	Slope (°)
Glenbervie	DONE1	Dense pole stand	150	90	23
	DONE2	Dense thicket of saplings	140	165	27
	DONE3	Dense thicket of saplings	130	160	30
	DONE4	Dense pole stand	150	90	25
	DONE5	Semi-mature totara stand, felled by landowner	140	120	14
	DONE6	Semi-mature totara in mixture with hardwoods trees	120	330	18
	BRID1	Semi-mature dense totara stand	130	230	25
	BRID2	Pole stand	140	235	32
	BRID3	Sapling stand within scattered manuka/kanuka	145	240	29
	BRID4	Sapling stand within scattered manuka/kanuka	145	240	27
	REED1	Mature dense totara stand	80	180	25
Kaeo	QUIN1	Pole stand with tree fern and native hardwoods	135	150	30
	QUIN2	Pole stand with tree fern and native hardwoods	145	160	15
	LANE1	Dense saplings and small poles	25	90	30
	LANE2	Dense saplings and small poles	30	120	38
	LANE3	Semi-mature stand in mixture with poles	20	70	26
Herekino	COOP1	Totara saplings within mixed shrub hardwoods	30	150	18
	COOP2	Totara saplings within mixed shrub hardwoods	35	170	16
	COOP3	Totara saplings within mixed shrub hardwoods	35	170	16
	COOP4	Dense totara pole stand	45	260	8
	COOP7	Dense totara pole stand	40	172	28
	OWEN1	Totara poles in mixture of manuka and shrub hardwoods	60	315	12
	OWEN2	Totara poles in mixture of manuka and shrub hardwoods	55	300	10
	MACK1	Semi-mature totara stand with occasional kanuka	65	200	13
	MACK2	Semi-mature totara stand with occasional kanuka	70	240	28
	MACK3	Seedlings under light canopy of mainly kanuka	40	215	36
	MACK4	Seedlings under light canopy of mainly kanuka	40	210	40
	MACK5	Seedlings and saplings under kanuka	45	15	27
	MACK6	Seedlings and saplings under kanuka	45	340	32
	MACK7	Stand of small poles with kanuka and other species	50	30	24
	MACK8	Poles within stand of kanuka and hardwoods	50	25	31
	MACK9	Poles within stand of kanuka and hardwoods	45	20	28

Appendix 6.3: Sampling plot types and sizes and quantities of increment cores and cross-sectional discs taken for each plot. Cores were categorised into one of five categories of a growth ring distinctiveness score# based on ring clarity. Those cores categorised as having a distinctiveness score of 4 or 5 were used for estimating stand age.

Study area	Plot code	Sampling technique*	Plot area (ha)	Date of sampling	No. of cores sampled	Number of distinct† cores used for estimating stand age	No. of discs sampled
Glenbervie	DONE1	Recce	0.004	July 1996	13	13	4
	DONE2	Recce	0.004	July 1996	5	5	2
	DONE3	Recce	0.004	July 1996	7	7	1
	DONE4	Recce	0.004	July 1996	0	0	0
	DONE5	PSP	0.041	February 1996	0	0	19
	DONE6	PSP	0.041	May 1998	21	18	0
	BRID1	PSP	0.041	September 1999	13	13	0
	BRID2	PSP	0.008	September 1999	11	11	0
	BRID3	Recce	0.004	September 1999	0	0	3
	BRID4	Recce	0.004	September 1999	0	0	3
	REED1	PSP	0.041	May 1998	0	0	0
Kaeo	QUIN1	PSP	0.008	October 1999	2	2	0
	QUIN2	PSP	0.008	October 1999	5	5	0
	LANE1	Recce	0.001	August 1996	0	0	12
	LANE2	Recce	0.001	August 1996	0	0	12
	LANE3	PSP	0.008	August 1996	21	21	6
	LANE4	Recce	0.001	April 1998	0	0	0
Herekino	COOP1	Recce	0.004	July 1996	7	0	14
	COOP2	Recce	0.001	July 1996	5	0	5
	COOP3	Recce	0.001	July 1996	5	0	3
	COOP4	PSP	0.008	August 1998	0	0	4
	COOP7	PSP	0.003	August 1998	0	0	4
	OWEN1	Recce	0.004	September 1996	2	2	0
	OWEN2	Recce	0.004	September 1996	3	3	4
	MACK1	PSP	0.041	August 2000	20	16	0
	MACK2	PSP	0.041	August 2000	19	14	0
	MACK3	Recce	0.004	August 2000	0	0	7
	MACK4	Recce	0.004	August 2000	0	0	9
	MACK5	Recce	0.004	August 2000	0	0	14
	MACK6	Recce	0.004	August 2000	0	0	13
	MACK7	Recce	0.004	August 2000	2	2	9
	MACK8	Recce	0.004	August 2000	4	4	5
	MACK9	Recce	0.004	August 2000	5	5	9

* Sample plot type: Recce – temporary rectangular reconnaissance plot; PSP – circular Permanent Sample Plot.

\# Growth ring distinctness score: 1 = indistinct, 2 = slightly distinct, 3 = moderately distinct, 4 = distinct, 5 = very distinct.

† Includes only those cores with a growth ring distinctness score of 4 or 5.

Appendix 6.4: Percentage species composition of trees and shrubs in the canopy or sub-canopy within each plot established in naturally regenerating totara-dominant stands. Plot age is estimated age based on cores sampled across all totara stems.

Plot code	Mack6	Mack5	Lane1	Quin1	Owen2	Mack3	Mack4	Lane2	Owen1	Brid3	Mack7	Brid4	Coop1	Done2	Coop2	Done3	Done4	Coop4	Coop3	Quin2	Coop7	Mack8	Mack9	Lane3	Done1	Done6	Mack2	Brid2	Mack1	Done5	Brid1	Reed1
Plot age (years)	**23**	**24**	**28**	**30**	**31**	**32**	**32**	**33**	**33**	**39**	**39**	**42**	**42**	**44**	**45**	**45**	**45**	**45**	**47**	**52**	**56**	**65**	**66**	**73**	**75**	**84**	**90**	**90**	**99**	**126**	**129**	**140**
Podocarpus totara	79	85	91	62	21	51	20	96	28	39	96	37	75	100	70	100	100	100	64	63	92	92	75	84	100	71	93	82	92	100	62	82
Kunzea ericoides	2	15	0	21	0	18	16	0	0	56	0	56	1	0	0	0	0	0	0	0	0	6	3	11	0	0	3	0	5	0	0	0
Leptospermum scoparium	18	0	0	1	57	28	46	0	56	0	3	0	2	0	7	0	0	0	7	0	3	0	0	0	0	0	0	0	0	0	0	0
Coprosma rhamnoides	0	0	0	0	2	3	18	0	0	0	1	0	8	0	17	0	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0
Leucopogon fasciculatus	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pseudopanax crassifolius	0	0	0	0	0	0	0	0	0	0	0	7	2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	2
Phyllocladus trichomanoides	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	10	4	0	0	0	0	0	0	0	14
Weinmannia sylvicola	0	0	0	1	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	1	0	2	3	2	0	0	3	0	0	0	0	2
Geniostoma rupestre var. *crassum*	0	0	0	1	3	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Myrsine australis	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	3	0	0	3	0	0	0	0	0	0	0	0	0
Coprosma hybrid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Melicytus ramiflorus	0	0	0	0	3	0	0	0	0	0	0	0	0	0	3	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0
Rubus australis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0
Rhopalostylis sapida	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23	0	0	0	0	0	0
Dysoxylum spectabile	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	27	0
Hedycarya arborea	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
Dacrydium cupressinum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
Prumnopitys ferruginea	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0
Ulex europaeus	0	0	5	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dacrycarpus dacrydioides	0	0	5	9	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	3	0	0	0
Schefflera digitata	0	0	0	0	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0
Dicksonia squarrosa	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	3	0	0	0	0	0	0	0	0	0	0	0
Cyathea dealbata	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0
Pittosporum tenuifolium	0	0	0	0	11	0	0	0	12	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0
Cyathea medullaris	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	0	0	0	0	0	0	0	0	0	0	0	0

Appendix 7.1: Early performance of planted totara based on stands and trials established for up to 50 years.

Region	Site	Stand age (years)	Sample	Survival (%)	Mean DBH (cm)	DBH MAI (mm)	DBH range (cm)	Mean height (m)	Height MAI (cm)	Height range (m)
CNI	Pureora	6	18	100				1.4	24	
Auckland	Totara Park	10	7		4.2	4.2	3.2-4.8	4.1	41	3.1-5.2
Auckland	Tapapakanga	10	200	89	8.6	8.6	5.7-10.1	5.5	55	4.7-6.5
Waikato	TeUku	11	3		4.7	4.2	3.2-5.9	3.4	31	3.2-3.5
Hawkes Bay	Havelock Nth	11	1		9.0	8.2		4.7	43	
Waikato	Rototuna	14	1		10.3	7.4		5.2	37	
BOP	Rotoehu	15	89	76				1.0	7	
CNI	Pureora	15	23	92				1.6	11	
CNI	Pureora	15	25	100				1.5	10	
CNI	Pureora	15	9	36				1.3	9	
CNI	Pureora	15	19	76				1.4	9	
Hawkes Bay	Gwavas	17	96	71				1.9	11	
Westland	Ianthe	20	19	18	2.9	1.5		2.6	13	
Auckland	Cornwall Park	21	4	75				7.4	35	6.9-8.5
Canterbury	Riccarton	21	6		11.3	5.4	8.1-15.8	7.8	37	6.1-11.8
Waikato	Raglan	22	8		11.5	5.2	6.5-16.7	6.4	29	4.8-7.2
CNI	Pureora	22	23		11.0	5.0	7.3-21.6	5.4	25	4.4-6.7
Hawkes Bay	Puketitiri	22	15		11.7	5.3	6.6-15.2	6.8	31	5.2-8.4
Southland	Slopedown	22	42					2.2	10	
Northland	Russell	23	181	34				1.6	7	
Hawkes Bay	Holts Forest	23	30	95	11.2	4.9	7.8-14.5	6.3	27	5-7.2
Hawkes Bay	Havelock Nth	24	2		20.2	8.4	19.4-21.1	8.2	34	8-8.4
Auckland	Woodhill	25	73	87	4.5	1.8		3.3	13	
Auckland	Woodhill	25	31	92	4.2	1.7		2.7	11	
Auckland	Woodhill	25	95	92	2.8	1.1		2.7	11	
Auckland	Woodhill	25	113	87	4.5	1.8		3.3	13	
CNI	Kaingaroa	25	140	58	7.4	2.9		5.9	24	
Hawkes Bay	Napier	25	2		11.2	4.5		7.0	28	
Manawatu	Palmerston Nth	25	3		17.2	6.9	13-20.3	10.6	42	9.8-11.9
CNI	Mamaku HCG	26	150	64	9.4	3.6		6.5	25	
CNI	Mamaku TCG	26	138	44	9.8	3.8		6.3	24	
CNI	Mamaku TCL	26	111	67	9.8	3.8		5.6	22	
Waikato	Walton	31	2		23.8	7.7	31-35	12.8	41	11.3-14.3
Taranaki	Pukekura	31	6		29.8	9.6	24.9-43.2	11.8	38	10.7-12.8
Manawatu	Palmerston Nth	31	9		20.0	6.5	14.5-23.5	8.7	28	8-9.2
Otago	Dunedin	31	1		17.1	5.5		9.0	29	
Northland	Kamo	32	14	95	32.5	10.2	21-45	14.4	45	13.7-15.2
Hawkes Bay	Havelock Nth	32	2		20.7	6.5		11.0	34	
Canterbury	LeBons Bay	34	2		17.5	5.1	13.4-21.6	7.9	23	7.6-8.2
Canterbury	Waimate	34	4		18.1	5.3	15.8-19.1	9.5	28	7.6-11
Northland	Glenbervie	35	17	80	24.9	7.1	17.1-38.5	10.4	30	9.8-10.8
Hawkes Bay	Hastings	35	31	90	21.2	6.1	11-35.0	6.7	19	5.3-8.4
Northland	Glenbervie	37	10	80	31.2	8.4	24.5-44.4	13.7	37	12-15.5
BOP	Ohiwa	38	3		52.4	13.8	50.6-55.0	16.7	44	15.2-17.7
East Coast	TeKaraka	39	30		16.8	4.3	11.0-22	10.6	27	9.1-12.8
CNI	Pureora	40	21		16.1	4.0	10.3-23.5	10.2	26	8-11.0
Hawkes Bay	Holts Forest	41	2		30.1	7.3	28.0-37	15.9	39	15.2-16.5
Hawkes Bay	Holts Forest	50	13	80	36.6	7.3	24.0-49	18.2	36	14.3-21.3
Taranaki	Pukekura	50	15	85	32.0	6.4	20.9-45.5	17.2	34	15.9-18
Taranaki	Pukekura	50	6		49.5	9.9	35.9-58.8	17.1	34	16.2-17.7
Taranaki	Hawera	50	5		39.8	8.0	27.7-58	15.1	30	12.5-17.7

* Site preparation at this site in Mamaku involved hand clearing of groups (HCG), tractor clearing of groups (TCG) and tractor cleared lanes (TCL).

Appendix 7.2: Early performance of planted rimu based on stands and trials established for up to 50 years.

Region	Site	Stand age (years)	Sample	Survival (%)	Mean DBH (cm)	DBH MAI (mm)	DBH range (cm)	Mean height (m)	Height MAI (cm)	Height range (m)
CNI	Pureora, Heli trial	6	37	89				2.2	37	
CNI	Pureora, Heli trial	6	111	80				1.1	18	
CNI	Guest paper	6	99	98				1.7	28	
Hawkes Bay	Holts Forest	6	31	95	2.8	4.7	2.0-4	2.9	48	2.4-3.6
Hawkes Bay	Parkers, Havelock	6	2		2.5	4.2		2.8	47	
Waikato	Silcock, TeUku	8	4		4.5	5.6	3.3-5.4	3.2	40	2.6-3.3
Auckland	Wilson,Papakura	9	2		2.2	2.4		3.2	36	2.5-3.9
Auckland	Totara Park	10	1		2.0	2.0		2.5	25	
CNI	Horohoro	11	143					2.5	22	
Taranaki	Patua	11	4		8.5	7.7	6.9-10.4	5.5	50	5.2-5.8
Taranaki	Pukerangiora Pa	13	8		10.2	7.8	7-13.1	5.5	42	4.9-6.6
BOP	Rotoehu	15	45	69				0.7	5	
Hawkes Bay	Gwavas	17	85	69				2.1	12	
CNI	Pureora Pikiariki	20	8		12.2	6.1	6.8-14.6	5.7	29	4.1-7.2
Westland	Ianthe	20	185	29	2.7	1.3		2.4	12	
Waikato	Bryant, Raglan	21	11		10.9	5.2	8.2-14	7.0	33	5.2-8.9
Taranaki	Pukekura	22	7		20.5	9.3	13.7-27.5	9.0	41	6.4-11.1
Southland	Slopedown	22	46					1.4	6	
Hawkes Bay	Holts Forest	23	30	90	8.0	3.5	3.5-12	5.5	24	4.1-6.8
Northland	Russell	24	318	81				1.7	7	
CNI	Kaingaroa	25	140	62	6.9	2.8		5.0	20	
Hawkes Bay	Wills,TePohue	25	2		8.2	3.3	7.0-10	5.4	22	
Manawatu	Greenwood, P.Nth	25	3		8.4	3.4	6.6-11.6	8.1	32	7.2-9.4
Manawatu	Farquhar, P.Nth	25	3		20.2	8.1	17.2-20.1	10.1	40	8.2-11.3
Auckland	Woodhill	26	162	64	6.8	2.6		5.9	23	
Auckland	Woodhill	26	43	86	2.8	1.1		2.7	10	
CNI	Mamaku HCG	26	105	53	7.4	2.8		6.6	25	
CNI	Mamaku TCG	26	158	70	6.8	2.6		5.9	23	
CNI	Mamaku TCL	26	166	68	8.3	3.2		6.0	23	
Dunedin	Neill	31	3		14.1	4.5	12.8-16.1	8.8	28	8.5-9.1
Hawkes Bay	Parkers, Havelock	33	1		9.6	2.9		6.7	20	
BOP	Reeve, Ohiwa	38	3		29.2	7.7	27.3-30.3	14.9	39	13.4-16.6
Auckland	Cornwall Park	39	36		31.8	8.2	21.2-41.5	14.4	37	10.7-15.8
Hawkes Bay	Holts Forest	41	10		21.6	5.3	16.0-28	14.3	35	12.2-15.9
BOP	Reeve,Waiotahi	44	3		28.3	6.4	25.0-33	13.3	30	13.1-13.4
Hawkes Bay	Holts Forest	50	5	80	26.1	5.2	21.0-32	16.8	34	
Taranaki	Pukekura	50	15	80	27.9	5.6	21.2-32.3	17.9	36	17.7-18.3
Taranaki	Pukekura	50	1		47.5	9.5		16.8	34	
Taranaki	Naumai,Hawera	50	7		30.1	6.0	20.3-44.8	13.9	28	12.8-15.2

* Site preparation at this site in Mamaku involved hand clearing of groups (HCG), tractor clearing of groups (TCG) and tractor cleared lanes (TCL).

Appendix 7.3: Early performance of planted kahikatea based on stands and trials established for up to 50 years.

Region	Site	Stand age (years)	Sample	Survival (%)	Mean DBH (cm)	DBH MAI (mm)	DBH range (cm)	Mean height (m)	Height MAI (cm)	Height range (m)
Hawkes Bay	Holts Forest	5	29					2.8	56	2-3.9
CNI	Guest paper	6	42	96				1.9	31	
Waikato	Silcock, TeUku	11	8		5.6	5.1	4.2-7	4.4	40	4.1-4.9
CNI	Horohoro	11	172	97				3.3	30	
Hawkes Bay	Holts Forest	11	26	90	7.2	6.5	4-12.5	5.9	54	4.2-7.7
Taranaki	Pukerangiora Pa	13	5		8.2	6.3	6.9-9.6	6.0	46	5.7-6.2
Waikato	Singleton, Rototuna	14	2		7.8	5.6		5.9	42	5.8-5.9
BOP	Rotoehu	15	5	13				0.7	5	
Canterbury	Leech,Rangiora	16	2		12.8	8.0	11.3-14.4	8.0	50	7.8-8.2
Hawkes Bay	Gwavas	17	87	75				2.1	12	
Hawkes Bay	Holts Forest	18	20	80	18.0	10.0	12-22.9	11.8	66	10.4-13.4
CNI	Pureora Pikiariki	20	10		10.9	5.5	8.1-14.2	6.9	35	5.4-7.5
Westland	Ianthe	20	114	72	2.8	1.4		1.9	10	
Auckland	Cornwall Park	21	19	70	21.8	10.4	15-30.3	10.3	49	8.2-12
Waikato	Bryant, Raglan	21	3		15.2	7.2	10.9-17.8	8.1	39	6.5-9
Canterbury	Riccarton	21	19		8.4	4.0	4.9-12.5	6.7	32	5.2-7.9
CNI	Pureora Nth Blk	22	9		6.6	3.0	4.2-10.6	6.4	29	5.6-7.5
Manawatu	Sutherlands Bush	22	30		6.4	2.9	3.5-9.5	5.6	25	3.9-7
Hawkes Bay	Cunningham	23	1					4.2	18	
Auckland	Russell	24	223	72				2.8	12	
Auckland	Russell	24	77	64				2.8	12	
CNI	Kaingaroa	25	91	50	4.0	1.6		4.2	17	
Manawatu	Farquhar, P.Nth	25	3		21.9	8.8	18.6-25.1	12.9	52	11.6-14
Auckland	Woodhill	26	35	54	1.9	0.7		2.5	10	
Auckland	Woodhill	26	30	52	1.0	0.4		1.1	4	
CNI	Mamaku HCG*	26	34	54	6.0	2.3		5.1	20	
CNI	Mamaku TCG*	26	145	81	6.2	2.4		6.6	26	
CNI	Mamaku TCL*	26	61	85	6.5	2.5		6.4	25	
CNI	Kaingaroa	26	91	50	4.0	1.5		4.2	16	
Canterbury	Leech,Rangiora	26	3		14.2	5.5	10.3-17.7	9.9	38	9.3-10.7
Manawatu	Greenwood, P.Nth	30	1		13.3	4.4		9.3	31	
Manawatu	Opiki	30	282	43	16.5	5.5		9.6	32	
Canterbury	Riccarton	30	10		15.8	5.3	11.9-20.3	14.1	47	12-15.7
Dunedin	Neill	31	5		17.6	5.7		13.7	44	
Canterbury	Meyer, Waimate	34	1		14.0	4.1		10.1	30	
Hawkes Bay	Holts Forest	47	3	90	37.6	8.0	28.0-50	19.7	42	18.6-20.7
Taranaki	Pukekura	48	15	80	40.4	8.4	19-47.0	17.3	36	15.9-18.6
Taranaki	Pukekura	50	2		42.8	8.6	38.6-47	15.5	31	14-17.1
Taranaki	Naumai,Hawera	50	6		40.7	8.1	28.8-47.5	17.2	34	17.1-17.4

* Site preparation at this site in Mamaku involved hand clearing of groups (HCG), tractor clearing of groups (TCG) and tractor cleared lanes (TCL).

Appendix 7.4: Early performance of planted kauri based on stands and trials established for up to 50 years.

Region	Site	Stand age (years)	Sample	Survival (%)	Mean DBH (cm)	DBH MAI (mm)	DBH range (cm)	Mean height (m)	Height MAI (cm)	Height range (m)
Northland	Glenbervie	4	7	80				1.5	38	1.3-1.7
Hawkes Bay	Parkers, Havelock Nth	8	1		3.5	4.4		3.2	40	
Auckland	Totara Park	10	1		1.7	1.7		2.2	22	
Auckland	Kirks	10	8	80	3.9	3.9		5.0	50	
Taranaki	Patua	11	4		6.1	5.5	4.4-7.5	5.0	45	4.2-6.6
Northland	Glenbervie	12	11	80	5.1	4.3	3-7.1	4.0	33	2.7-5.1
Taranaki	Pukerangiora Pa	13	8		10.5	8.1	7.4-12	6.4	49	5.2-8
Waikato	Singleton, Rototuna	14	1		5.9	4.2		4.2	30	
Hawkes Bay	Cunningham	14	1					3.3	23	
Waikato	Bryant, Raglan	21	6		8.1	3.9	4.9-10.8	6.9	33	5.5-8.2
Taranaki	Pukekura	22	15	90	25.0	11.4	14.3-34.2	11.5	52	7.5-13.3
Hawkes Bay	Holts Forest	23	30	95	11.5	5.0	7.0-18	6.5	28	4.5-8.5
Hawkes Bay	Parkers, Havelock Nth	24	1		9.9	4.1		7.3	30	
Manawatu	Greenwood, P.Nth	24	2		5.3	2.2	4.4-6.2	4.9	20	4.6-5.2
Hawkes Bay	Hartrees	25	11		11.3	4.5	6.4-17.3	11.4	46	9.0-13
Manawatu	Farquhar, P.Nth	25	1		7.0	2.8		6.4	26	
Waikato	Gudex	26	20		23.2	8.9	18.6-29	11.8	45	10.7-13.4
Canterbury	Leech,Rangiora	26	1		7.3	2.8		5.0	19	
Hawkes Bay	Wills,TePohue	29	31		18.5	6.4	12.0-25	11.2	39	10.0-12
Auckland	Kirks	31	40	100	28.7	9.3	15.4-39.4	14.6	47	12.2-17.5
Hawkes Bay	Holts Forest	31	10	95	19.9	6.4	16.0-24	14.3	46	12.2-15.5
Taranaki	Pukekura	31	9		27.0	8.7	22.0-31	12.7	41	11.7-13.9
Dunedin	Neill	31	29		18.7	6.0	11.3-24.8	13.0	42	11.3-24.8
Northland	Glenbervie	32	14	90	26.3	8.2	17.6-29.2	12.6	39	8.7-14.5
Taranaki	Jury	36	1		52.6	14.6		19.8	55	
Northland	Glenbervie	37	15	90	24.8	6.7	18.1-30.4	16.7	45	14.3-18.6
BOP	Reeve, Ohiwa	38	1		38.3	10.1		14.9	39	
Auckland	Cornwall Park	39	14	70	35.1	9.0	26.5-42.9	12.8	33	11.3-14.6
East Coast	Williams,TePuia	40	11		18.2	4.5	12.0-26	15.7	39	13.0-19
Hawkes Bay	Holts Forest	43	2		34.9	8.1	32.0-38	20.4	47	20.1-20.7
Taranaki	Rahotu	43	5		22.1	5.1		16.4	38	
Northland	Mair Pk, Whangarei	44	38		30.9	7.0	19-40.7	19.9	45	13.4-23.8
Taranaki	Brookland	50	15	90	29.0	5.8	22.7-35.2	19.1	38	16.8-21.4
Taranaki	Pukekura	50	15	90	36.7	7.3	28.2-40.5	18.7	37	17.7-19.2
Taranaki	Fred Cowling	50	50	95	25.5	5.1	17.7-33.6	15.1	30	14.6-15.9
Taranaki	Naumai,Hawera	50	44		33.3	6.7	16.6-41.3	16.3	33	14.9-17.7

Appendix 7.5: Early performance of planted tanekaha based on stands and trials established for up to 50 years.

Region	Site	Stand age (years)	Sample	Survival (%)	Mean DBH (cm)	DBH MAI (mm)	DBH range (cm)	Mean height (m)	Height MAI (cm)	Height range (m)
Waikato	Silcock, TeUku	8	1					3.5	44	
Auckland	Wilson, Papakura	9	1		2.7	3.0		3.0	33	
BOP	Rotoehu	15	16	21				0.5	3	
CNI	Pureora, Fletchers 4/60	20	19	76				2.3	11	
CNI	Pureora, Fletchers 4/60	20	20	84				1.09	5	
CNI	Pureora, Fletchers 4/60	20	24	96				2.1	11	
CNI	Pureora, Fletchers 4/60	20	20	80				4.1	21	
Waikato	Bryant, Raglan	21	10		8.4	4.0	4.8-13.4	6.7	32	5.2-8.4
Northland	Russell	24	49	46				1.4	6	
Manawatu	Greenwood, P.Nth	24	1		6.9	2.9		6.5	27	
Auckland	Woodhill	25	80	80	4.1	1.6		4.4	18	
Auckland	Woodhill	25	72	72	6.6	2.6		6.3	25	
Hawkes Bay	Wills,TePohue	25	11	80	16.3	6.5	13.0-20	9.1	36	8.0-11
Auckland	Woodhill	26	68	72	6.6	2.5		6.3	24	
Auckland	Woodhill	26	77	80	4.1	1.6		4.4	17	
CNI	Mamaku HCG*	26	27	42	3.6	1.4		4.9	19	
Waikato	Willis, Walton	31	1		14.2	4.6				
Taranaki	Pukekura	31	1		28.7	9.3		14.0	45	
Auckland	Cornwall Park	39	6		21.1	5.4	18.5-24.9	11.6	30	10.1-14.3
CNI	Pureora	40	10		11.4	2.9	6.9-15.1	11.5	29	10-12.5
Hawkes Bay	Holts Forest	41	10		13.2	3.2	8.0-19	10.5	26	8.7-11.9
Hawkes Bay	Holts Forest	50	2		25.3	5.1	23.0-28	14.5	29	14-14.9
Taranaki	Pukekura	50	8		24.8	5.0	19.1-28.8	11.0	22	10.4-11.6

* Site preparation at this site in Mamaku involved hand clearing of groups (HCG).

Appendix 7.6: Early performance of planted matai based on stands and trials established for up to 50 years.

Region	Site	Stand age (years)	Sample	Survival (%)	Mean DBH (cm)	DBH MAI (mm)	DBH range (cm)	Mean height (m)	Height MAI (cm)	Height range (m)
Hawkes Bay	Cunningham	23	1					2.0	9	
Northland	Russell	24	131	54				1.1	5	
Manawatu	Farquhar, P.Nth	25	2		10.8	4.3	10-11.7	7.2	29	6.1-8.2
Auckland	Woodhill	26	120	60				2.8	11	
Auckland	Woodhill	26	7	14				1.3	5	
CNI	Mamaku HCG	26	26	56				1.97	8	
Manawatu	Greenwood, P.Nth	30	2		5.4	1.8	5.3-5.5	4.7	16	4.6-4.8
Hawkes Bay	Holts Forest	41	1		17.6	4.3		11.6	28	
Taranaki	Pukekura	50	16		16.0	3.2	12.3-20	9.9	20	9.6-10.4

Appendix 7.7: Early performance of planted miro based on stands and trials established for up to 50 years.

Region	Site	Stand age (years)	Sample	Survival (%)	Mean DBH (cm)	DBH MAI (mm)	DBH range (cm)	Mean height (m)	Height MAI (cm)	Height range (m)
Taranaki	Pukekura	22	2		9.9	4.5	8.8-11.1	4.6	21	4.6-4.7
Manawatu	Greenwood, P.Nth	24	1		5.1	2.1		5.4	23	
Manawatu	Greenwood, P.Nth	28	1		10.9	3.9		8.0	29	
BOP	Reeve, Ohiwa	38	1		29.5	7.8		10.7	28	
Taranaki	Naumai,Hawera	50	1		25.5	5.1		10.4	21	

Appendix 9.1: Definition of terms used to assess log and timber characteristics including defects used to grade sawn boards (mostly based on Standards Association of New Zealand 1988).

Name	Description
board	The inner planks of a sawn log
butt	End of the butt log closest to the ground before felling
butt log	Base log or portion of stem of a tree closest to ground
check	A separation of the fibres along the grain forming a fissure, but not extending through the piece
decay	Decomposition of wood by fungi
flitch	Longitudinal section of timber sawn from a log; both surfaces have been sawn
grain	The general direction of the fibres or wood elements
heartwood	The inner layers of the log, which in the growing tree, have ceased to contain living cells; heartwood is generally darker in colour than sapwood
knot	A section of a branch which is embedded in the wood of the tree trunk or of a larger branch
LED	Large end diameter of a log
live sawing	Sawing pattern of log where entire log is sawn into longitudinal lengths of timber from one side to the other without rotation of the log; refer to Figure 9.1
occluded knot	A discontinuous knot normally formed as a result of pruning and subsequent clearwood growth around the end of the branch stud
pin knot	A sound intergrown knot not exceeding 15 mm in diameter
resin streak	Fibre that is saturated with resin
sapwood	The living outer layers of the wood of a tree; sapwood is generally lighter in colour than heartwood
SED	small end diameter of a log
slab	The outer edges of a sawn log
split	A lengthwise separation of wood fibres extending through a piece of timber from one surface to another
sweep	A curvature from the plane for a log in the direction of the length; similar to bow
taper	Description of a decreasing log diameter with increasing height to form a cone shape

Appendix 9.2: Assessment of sapwood/heartwood content from visual assessment of cross-sectional discs taken from within a natural stand (N), within a plantation (P) and edge trees from the same plantation (PE). Estimated mean age of the natural stand was 101 years based on ring counts. The plantation was 90 years old.

Stand	Disc No.	Diameter of disc (cm)	No. of growth rings*	Heart wood zone clarity#	Mean length of transects (cm)	Mean length of sapwood (cm)	Mean length of heartwood (cm)	Basal area of heartwood (cm^2)	Basal area of sapwood (cm^2)	Total basal area (cm^2)	Proportion of heartwood (%)
N	35	15.0	96.0	2	8.5	4.1	4.4	61	168	229	27
N	24a	20.6	101.5	2	9.6	9.6	0	0	290	290	0
N	24	21.9	93.0	2	14.6	6.5	8.1	205	464	669	31
N	44	25.1	94.3	2	10.9	6.8	4.0	51	321	372	14
N	47	25.9	118.0	1	12.9	8.4	4.5	63	458	521	12
N	e	28.9	87.0	2	12.5	9.4	3.1	30	462	492	6
N	4	30.7	98.0	1	13.7	9.9	3.8	45	545	590	8
N	3	31.4	85.5	2	15.2	7.1	8.1	206	517	723	29
N	45	35.0	104.5	2	16.0	9.7	6.3	124	681	805	15
N	b	38.8	74.0	1	16.0	8.3	7.7	184	616	800	23
N	c	41.9	82.0	1	16.9	1.9	15.0	704	193	896	79
N	7	42.5	114.0	1	18.4	9.3	9.2	264	805	1068	25
N	42	52.0	95.0	1	15.8	5.6	10.2	325	456	781	42
N	10	58.0	108.5	1	22.1	7.6	14.6	668	873	1540	43
N	d	58.5	118.0	2	17.7	5.4	12.3	477	507	985	49
N	12	70.0	127.5	1	15.5	6.3	9.2	268	489	758	35
N	a	70.5	123.0	1	34.4	13.4	20.6	1334	2300	3633	37
P	2	10.5	58.5	1	5.6	2.6	3.0	28	70	99	29
P	1	10.7	66.0	1	5.0	1.1	4.0	49	30	79	62
P	17	12.6	69.5	2	6.4	6.4	0	0	129	129	0
P	3	13.2	76.5	1	6.5	2.6	3.9	48	85	133	36
P	11	13.9	76.5	2	6.6	1.3	5.3	88	48	136	64
P	4	14.4	71.5	2	7.2	2.7	4.5	64	99	163	39
P	5	15.2	62.5	2	7.6	7.6	0	0	182	182	0
P	16	15.6	73.0	2	6.7	2.3	4.4	61	80	141	43
P	9	15.7	92.0	2	7.4	4.7	2.7	23	151	174	13
P	14	16.5	81.0	1	7.9	1.9	5.0	111	82	194	58
P	7	20.5	82.5	2	10.1	0	6.0	113	208	321	35
P	13	21.2	75.0	1	9.8	2.4	7.4	171	131	302	57
P	12	21.8	85.5	2	10.4	3.4	6.9	151	188	339	44
PE	18	15.6	82.5	2	7.3	2.2	5.1	82	86	168	49
PE	20	24.4	92.0	2	10.9	5.7	5.3	87	288	375	23
PE	19	28.5	114.0	1	12.9	4.6	8.4	220	306	526	42
PE	21	30.3	100.0	2	14.2	6.8	7.4	171	458	629	27
PE	8	31.5	137.0	1	13.0	5.9	7.1	158	374	532	30
PE	23	35.4	115.0	1	17.4	5.1	12.3	472	477	949	50
PE	24	38.0	112.5	1	18.6	7.4	11.2	393	697	1090	36
PE	25	39.2	102.5	1	18.6	9.0	9.6	291	799	1090	27
PE	22	40.6	114.0	2	19.7	11.9	7.8	193	1030	1223	16
PE	27	44.0	124.5	1	20.5	7.8	12.7	507	808	1314	39
PE	26	45.9	146.5	1	21.6	11.5	10.1	321	1144	1465	22
PE	28	52.1	117.5	2	24.6	14.4	10.2	327	1577	1904	17

* Mean ring count along two transects on each disc

\# Clarity of heartwood zone categories: 1 = well defined sapwood/heartwood boundary; 2 = partially distinct boundary; 3 = indistinct boundary (discs not included in table)