COMPARISON OF DEVELOPMENT OF RADIATA PINE (*Pinus radiata* D. DON) CLONES IN MONOCLONAL AND CLONAL MIXTURE PLOTS

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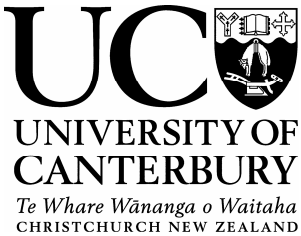

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LIST OF SYMBOLS / ABBREVIATIONS

SYMBOLS / ABBREVIATIONS	Full Form
α, β, γ	Parameters of models
μ	mean
ρ	Wood density
GF	Growth and form
LI	Long internodes
GLD	Ground-line diameter
DBH	Diameter at breast height over bark
TSI	Transplant stress index
RYI	Relative Yield index
MTH	Mean top height
GLM	General linear model
SAS	Statistical analysis system
CI	Competition Index
DI	Diameter Increment
CV	Coefficient of variation
PC1, PC2, PC3	Principal component 1, 2 and 3 respectively
V	Velocity
E_d	Dynamic modulus of elasticity
NZFS	New Zealand Forest Services
3-PG	Physiological principles predicting growth
pFS	Foliage stem ratio
NIWA	National institute of water and atmospheric research

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ABSTRACT

The development of radiata pine (*Pinus radiata* D. Don.) clones was compared in monoclonal and clonal mixture plots planted in an experiment established at Dalethorpe, Canterbury, New Zealand with ten radiata pine clones in September 1993. Clones were deployed in a randomised complete block plot design with three replications. Each replication contained ten treatments of monoclonal plots and one in which all the clones were intimately mixed in equal proportions.

Clones significantly differed in initial morphologies, survival and stem slenderness. Sturdiness and initial heights were found to be the best predictors of initial survivals. The study revealed that mode of deployment did not affect overall productivity, but individual clones exhibited significantly different productivities between modes of deployment. All clones contributed similarly to overall productivity in the monoclonal mode of deployment, whereas the contribution of clones in the clonal mixture mode of deployment was disproportionate. A minority of the clones contributed a majority of overall productivity in the clonal mixture mode of deployment.

The inclusion of competition index as an independent variable in a distance-dependent individual tree diameter increment model explained a significant amount of variability in diameter growth. The use of an inverse-squared distance to neighbouring plants in the competition index provided a slightly superior fit to the data compared to one that employed a simple inverse of distance. Addition of genotype information in the competition index further improved the fit of the model. Clones experienced different levels of competition in monoclonal and clonal mixture modes of deployment. Competition in monoclonal plots remained uniform over time, whereas some clones experienced greater competition in clonal mixture plots which led to greater variability in their tree sizes. This study indicated that single tree plot progeny test selections and early selections may miss out some good genotypes that can grow rapidly if deployed monoclonally.

Stand level modelling revealed that clones differed significantly in modeled yield patterns and model asymptotes. Clones formed two distinct groups having significantly different yield models. The study also demonstrated that models developed from an initial few years' data were biased indicators of their relative future performances.

Evaluation of effectiveness of the 3-PG hybrid model using parameter values obtained from destructive sampling and species-specific values from different studies revealed that it is possible to calibrate this model for simulating the productivity of clones, and predictions from this model might inform clonal selections at different sites under differing climatic conditions. Destructive sampling at age 5 years revealed that clones significantly differed in foliage and stem biomass. The differences in productivities of clones were mainly due to differences in biomass partitioning and specific leaf areas.

Clones significantly differed in dynamic wood stiffness, stem-slenderness, branch diameter, branch index and branch angle at an initial stocking of 1250 stems/ha. Mode of deployment affected stem slenderness, which is sometimes related to stiffness. Although dynamic stiffness was correlated with stem slenderness and stem slenderness exhibited a significant influence on stiffness, clones did not exhibit statistically significant differences in dynamic stiffness. Increasing initial stocking from 833 stems/ha to 2500 stems/ha resulted in a 56 % decrease in branch diameter and a 17 % increase in branch angle.

Trees in the monoclonal mode of deployment exhibited greater uniformity with respect to tree size, stem-slenderness, and competition experienced by clones compared to those in the clonal mixture mode of deployment. Susceptibility of one clone to Woolly aphid suggested that greater risks were associated with large scale deployment of susceptible clones in a monoclonal mode of deployment.

This study also indicated that if the plants were to be deployed in a monoclonal mode then block plot selections would have greater potential to enhance productivity.

CHAPTER 1

INTRODUCTION

1.1 Background

The forestry scene in New Zealand changed a lot with the introduction of radiata pine in the 1850s from its native California (North America). Radiata pine (*Pinus radiata* D.Don) has adapted to local conditions well, and Clonal forestry has given a new thrust to radiata pine's expansion in the country. At present the country has 23% of its geographical area under native trees and 7% (1.8 m ha) under plantation forests. Radiata pine comprises about 89% of plantation forests and for the rest, 6% is under Douglas fir (*Pseudotsuga menzieisii*) and 5% is under other exotic softwoods and hardwoods (NZIF 2005/2006).

The main advantages of clonal forestry are more uniform crops, deployment of desired traits, more control over wood properties, and greater genetic gains (Libby and Rauter, 1984; Carson, 1986; Burdon, 1989; Carson and Burdon, 1989; Lindgren, 1993; Sorensson and Shelbourne, 2005). These advantages may lead to rapid acceptance of clonal forestry as a superior option to family forestry in New Zealand and several companies have invested in clonal selection. Planting well planned and long term demonstration plots may promote the acceptance of clonal forestry by the general public, foresters, conservationists and industry people (Stelzer, 1997).

New Zealand's planted forests now provide more than 98 percent of New Zealand's annual 21 million m^3 wood harvest (NZIF, 2005/2006). More than half of this is exported, and wood is now one of New Zealand's major exports. New Zealand's forest industry supplies 1.1% of the world's and 8.8% of Asia Pacific's forest products trade from just 0.05% of the world's forest area and an annual harvest area equivalent to 0.0009% of global forest cover (NZIF, 2005/2006). This fast expansion is also raising new issues like decreasing genetic diversity and biodiversity, risks of insect pests and disease attack and more expectations that scientists will produce fast growing breeds or clones.

Clonal forestry has expanded very quickly in other parts of the world in recent years and at present there are over three million hectares of clonal plantations in the world (Kellison, 2004). But to enhance benefits of clonal forestry it is necessary to identify better clones with respect to growth potentials, wood properties and resistance to insect pest and diseases using effective selection methods to achieve maximum gains from selections.

Clonal forestry also has some technical and plantation management issues (Aimers-Halliday *et al*. 1997; Aimers-Halliday *et al*. 2003; Burdon and Aimers-Halliday, 2003; El-Kassaby and Moss, 2004) which still require research. Some of these issues related to clonal forestry are discussed below.

1.1.1 Maturation

Maturation is the progression of change from embryonic to mature state, due to ontogenetic ageing (Sweet, 1973; Greenwood, 1995; Aimers-Halliday *et al.* 2003). The negative effects of maturation are: decrease in rooting ability, and early loss of vigor (slow rate of diameter growth) of cuttings taken from older trees. This loss of early vigor has been called a physiological ageing or maturation problem (Horgan and Holland, 1989; Menzies and Aimers-Halliday, 1997). The positive effect of maturation is improved stem form.

Cuttings from older trees have less ability to root and grow fast (Libby *et al*. 1972; Sweet, 1973; Greenwood, 1995; Aimers-Halliday *et al*. 2003). Methods like serial propagation of stock and hedging can overcome this problem (Libby *et al*. 1972; St Clair *et al.* 1985; Aimers-Halliday *et al.* 2003). The success of cryo-perservation and somatic embryogenesis techniques have made clonal forestry of radiata pine feasible (Aimers-Halliday *et al.* 2003; Carson *et al*. 2004), but still costs of production of clonal material by these techniques are approximately five times more than seedling production (Sorensson and Shelbourne, 2005). There is a need to develop cost-effective clonal propagation, juvenility maintenance and multiplication techniques that work for most genotypes and give large numbers of uniform plants per clone, with minimal ageing after clonal testing (Aimers-Halliday *et al*. 1997; Menzies and Aimers-Halliday, 1997; Horgan *et al*. 1997).

1.1.2 Quality of planting stock

Good quality of planting stock is essential for rapid initial growth and survival (Ritchie, 1984; Bernier *et al*. 1995). The quality of planting stock is defined as "fitness for purpose", which for a seedling is its ability to survive and then grow rapidly when planted in the field (Duryea, 1984; Ritchie, 1984). The quality of planting stock is often assessed by morphological measurements such as shoot height, stem diameter (South *et al.* 2001), and shoot-root ratio or physiological characteristics such as root growth potential, root starch levels, root water potential, drought hardiness and frost hardiness. Sometimes combinations of morphological and physiological measurements are used (Duryea, 1984; Menzies, 1988). Initial growth and survival affect the yield of stands at rotation age (Mason, 2006). Various morphological predictors have been standardized for radiata pine seedlings and cuttings for New Zealand conditions (Menzies, 1988; Menzies, *et al.* 2001). There is a need to maintain juvenility of progeny test materials and the need for large scale, rapid propagation of planting stock has increased the use of micro-propagation techniques (Aimers-Halliday *et al*. 1997; Menzies and Aimers-Halliday, 1997). The increased use of micro-propagated planting materials has emphasized the need to develop standards for micro-propagated stock for different site conditions. However, these techniques may not work for all clones, plant quality may be poor, and costs are also high for micro-propagated planting stock (Aimers-Halliday and Burdon, 2003). Propagation failure of some good clones may result in low genetic gain, reduced effective selection intensity and genetic diversity in commercial plantations (Aimers-Halliday and Burdon, 2003). In order to produce uniform planting stock of different clones nursery management such as under-cutting and wrenching and top pruning may have to be tailored to each clone.

1.1.3 Selection of better clones

New Zealand breeders have developed some improved breeds: GF (growth and form), LI (long-internodes), DR (resistant to Dothistroma needle blight), and HD (increased wood density) for deployment in plantations (MacLaren, 1993; Vincent, 1997). Different stakeholders in the forest industry have different desires. Plantation growers are interested in short rotation clones whereas the wood processing industry is more concerned about uniform products with better wood qualities for higher returns. To optimize benefits from

clonal forestry there is need to select clones with respect to fast growth rate, better form, better wood qualities, resistance to insect-pest and diseases and combinations of these traits.

1.1.4 Timing of selection

If clones are selected early at the testing stage then they can be deployed on time and concerns of maturation can also be dealt with. However, in some studies clones that performed very well in the early years were not the best performers over and extended period of testing. Low (1989) studied the interaction of *Cyclaneusma* needle cast with early selection in *Pinus radiata* and reported changes in stem diameter growth rankings of some families between the ages of 5 and 18 years. Debell and Harrington (1997) have reported interchanges of ranks of total live woody yield at age 3 years between spacings in monoclonal plots of *Populus* clones. Zsuffa (1975) has reported interchanges of ranks in mean heights among *Populus* clones between ages 1 and 6 years and Ares (2002) in scaled volume ((diameter at breast height)^2 x total height) among *Populus* clones between ages 3 and 10 years in clonal mixture plots. Menzies and Carson (1989) suggested that for early screening to be effective there should be moderate to high correlation between some early attributes and later clonal performance. Clones can be evaluated at an early stage for traits such as initial survival, resistance to diseases, frost tolerance, branching habits and windfirmness (Menzies and Carson, 1989). Selections for traits such as volume (m^3/ha) and wood quality may be done by analyzing correlations between traits such as height, diameter, stem dry mass, acoustic velocity and mature traits such as volume and stiffness. Therefore there is need to devise early testing techniques that involve selection of clones based on some early characteristics as the indicators of future mature characteristics.

1.1.5 Clonal testing

Clonal testing is important to identify superior clones. Many aspects of clonal testing still require research. These include the range and number of sites needed for testing and optimal field test design (Aimers-Halliday *et al*. 1997). The important issue is whether clones should be selected on the basis of their performance in single tree plots (clonal mixture progeny test plots) or in clonal block plots. At present in New Zealand selections are being done in single tree plots (White, 2001) because they are efficient, statistically

robust, and low in cost (Libby and Cockerham, 1980; Libby, 1987b). However, some researchers compared the effectiveness of block plot, single tree plot or row plot progeny test designs and concluded that screening in single tree plots or row plots after the on-set on inter-tree competition would be impractical due to inter-genotypic competition effects if the selected genotypes were going to be deployed in monoclonal blocks in operational plantations (Franklin, 1989; Foster 1989; Foster *et al*. 1998; Stagner *et al*. 2007). Foresters are concerned with stand growth and productivity. Genotype, environment, survival, competition, management practices, and their interactions affect stand productivity. Single tree plots lack information on unit-area productivity and competition related mortality (Johnsson, 1974; Libby, 1987b; Staudhammer *et al*. 2006). Libby (1987a) had recommended initial testing in single tree plots when the numbers of entries are large, and testing of promising clones in block plots to evaluate clones for per unit area productivity at higher levels of selection programs. Clones are genetically uniform and may have less stability in their performance across different sites than full-sib and half-sib families that provide buffering against genotype x environment interactions (St Clair and Kleinschmit, 1986). Therefore, other factors such as number of test sites, size of the test, number of clones and number of replications per test site that influence the precision of selection need to be considered when choosing field test designs (van Buijtenen, 1983). The ultimate choice of method of selection would depend on trade offs between selection gains, cost of testing and the choice of mode of deployment. These aspects require further research to improve the effectiveness of clonal testing procedures for different modes of deployment in commercial plantations.

1.1.6 Clonal Deployment

A major issue of clonal forestry is whether the clones should be deployed in monoclonal or clonal mixture stands (Aimers-Halliday, 1997; Tuskan, 1998; Ritchie, 1996; El-Kassaby and Moss, 2004). There are still differing views among researchers regarding modes of clonal deployment. Some advocate monoclonal deployment and some prefer the clonal mixture mode of deployment. The clonal mixture mode of deployment is considered to be a better option to minimize risks of insect-pests and disease infestation (Zobel and Talbert, 1984). Zobel (1993) reported that growers of clonal eucalyptus plantations favor monoclonal blocks for their uniform growth and wood properties. Libby (1987a, 1987b) advocated that a mosaic of monoclonal stands is the best strategy to minimize risks of

insect-pests and disease infestation, to increase uniformity of wood and facilitate management. Some studies and reviews have compared the productivity of monoculture and polyculture of species of different genera (Bristow *et al.* 2006; Forrester *et al*. 2004; 2006, Debell *et al.* 1997; Parotta, 1999; Piotto *et al.* 2004; and Petit and Montagnini, 2006) and reported intermediate to greater productivity of mixtures than monocultures of species. There is a paucity of studies comparing productivity of clones of a species in different modes of deployment, particularly among conifers. The main issue that needs to be addressed through research studies is whether a set of well-adapted clones can perform better in clonal mixture than in monoclonal blocks, through complementary exploitation of the resources of the environment (Burdon and Aimers-Halliday, 2003). Therefore, there is need to settle this controversy through research comparing productivities of various modes of deployment.

1.1.7 Growth and yield models

To get desired output from plantations, the managers always look for those growth and yield models which can accurately predict future states of their plantations. Various growth and yield models, from mensuration-based to process-based, are available. Mensuration-based models only predict the future state of the stand based on previous performance of a species or forest type in similar conditions (Kimmins *et al*., 1990; Vanclay, 1994) and the disadvantage is they do not represent detailed phenomena like photosynthesis, light interception, biomass allocation, and competition, and climate changes or environmental stresses that affect the growth of trees and stands may not be represented (Kimmins *et al*., 1990; Mohren and Burkhart, 1994). Process-based models take into account changes in growing conditions, but these models have not been used much by foresters because of the number of sub-models involved, compounding of errors associated with sub-models, and large numbers of parameter values that may not be readily available to forest managers (Mohren and Burkhart, 1994; Landsberg and Gower, 1997; Sands *et al.,* 2000; Landsberg, 2003). Therefore the emphasis has shifted to develop “hybrid” models that can combine positive features of both mensuration-based and process-based models in predicting the behaviours of species in different growing conditions. Increasing use of clones and influences of genotype x environment interactions on productivities of plantations necessitate the use of effective models to predict the likely behaviour of clones growing in differing conditions. So there is need to develop and test the effectiveness of hybrid models

for their accuracy in prediction of growth and productivity of genotypes for different site conditions.

1.1.8 Risk analysis

The main risks to clonal forestry with radiata pine include reduced genetic diversity, technical difficulties of clonal propagation and storage, inadequate evaluation of clonal material and risk of insect-pest and diseases infestation (Burdon and Aimers-Halliday, 2003). Use of few clones in plantations is considered to be a major risk of insect-pest and disease infestation (Lindgren, 1993; Aimers-Halliday, 1997; Roberts and Bishir, 1997; Bishir and Roberts, 1999). Therefore there is need to determine the number of clones required and their mode of deployment to keep risks of insect-pest and disease infestation within tolerable levels by maintaining adequate genetic diversity in clonal plantations. Some researchers have presented estimates of safe number of clones in clonal mixtures (Burdon, 2001; Libby, 1987b; Huhn, 1987; Roberts and Bishir 1997) and they believe 15-30 clones are sufficient to maintain genetic diversity to minimize biological risks and maximize genetic gains (Park, 2006). Another important issue in addition to number of clones is the relative number of copies of each clone in a plantation (Lindgren, 1993; Burdon and Aimers-Halliday, 2003).

The risks of failure of some clones during propagation and clonal storage may result in wastage of resources invested in selection and testing of clones, loss of genetic gain and loss of genetic diversity in production population. Inadequate evaluation which includes short duration of clonal tests, lack of buffering against genotype x environment interaction may result in change in clonal rankings (Aimers-Halliday and Burdon, 2003). Differential maturation of planting stock may result in greater variability in stands and also lower the commercial acceptability of planting stock.

1.1.9 Cost-Benefit analysis

There is need to compare the costs and benefits of using cuttings or micro-propagated planting stock with the use of seedlings to evaluate the benefits of clonal forestry compared to family forestry (O'Regan, M. and Sar, L., 1989). Cost of planting stock could be a decisive factor in choosing alternative options for large-scale deployment (Arnold, 1990).

The cuttings of radiata pine cost more than twice the cost of seedlings (Smith, 1989; Arnold, 1990; Menzies *et al*. 1991; Menzies *et al*. 2001; ANU Department of Forestry, 1998) and micro-propagated stock cost about five times the cost of seedlings (Sorensson and Shelbourne, 2005). The use of cuttings or micro-propagated stock has the advantage of increasing genetic gains from capture of non-additive genetic variance and greater uniformity of crops. The additional benefits of improved stem form and disease resistance can be achieved by using cuttings of physiological age 3-4 years without a serious decrease in growth (Menzies and Klomp, 1988; Menzies *et al*. 1989). The use of juvenile rooted cuttings with a physiological ages of 3-4 years has been recommended for planting on topple prone sites (Trewin, 2003; Aimers-Halliday *et al.* 2003). The economics of planting seedlings of radiata pine was compared with that of cuttings, and evaluation at harvest age of 36 years showed that trees from cuttings produced higher quality wood and generated 14 % higher profit compared to seedling trees (ANU Forestry Market Report, 1998). There is also a need to compare the costs of production and management associated with different modes of clonal deployment and their benefits.

Considering all these issues, a clonal experiment was established at Dalethorpe, Canterbury, New Zealand in Sept. 1993 with ten radiata pine clones to help find solutions to these challenges of clonal forestry. This study was designed to address following questions.

Which morphological predictors of stock quality would be effective in explaining differential initial growth and survival of clones?
Do productivities and risks differ between monoclonal and clonal mixture plots?
Do clones behave differently in monoclonal and clonal mixture plots?
Is it possible to enhance uniformity using clones?
Is it possible to identify strongly competitive clones that cause reductions in growth of their neighbours?
How effective would a distance-dependent individual tree model be as tool for clonal selection when the genotypes of the neighboring trees are known?
How does competition index vary with mode of deployment?
What factors will determine choice of mode of deployment?
How effectively can traditional mensurational models predict future productivities of clones?

How effective it would be to use biomass allocation in hybrid models for prediction of future growth rates of clones?

Does mode of deployment influence stem form and stem-wood stiffness?

1.2 Objectives of the study

- ❖ To test alternative modes of deployment (monoclonal versus clonal mixture deployment).
    - Evaluate the impact of alternative measures of planting stock quality on growth and survival of clones
    - Evaluate relative performances of clones in monoclonal and clonal mixture plots.
    - Compare rankings of clones in monoclonal and clonal mixture plots at a variety of ages when clones might be selected.
    - Analyze the effects of competition on performances of clones.
    - Evaluate the effects of mode of deployment on stem form and stem-wood stiffness.

- ❖ To evaluate the effectiveness of modelling approaches for clonal selection, management, and for explaining clonal differences in growth rates.
    - Evaluate the relative effectiveness of mensurational and hybrid modelling for prediction of future yields of clones.
    - Evaluate the effectiveness of different times of clonal selection.
    - To develop distance-dependent individual model as tool for clonal selection when the genotypes of the neighbouring trees are known.

The chapters are organised into papers that have been or will be submitted for publication, and so they contain some necessary repetition describing the layout of the experiment.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Clonal forestry "the establishment of plantations using tested clones" offers the main advantages of efficient capture of non-additive genetic gains, greater crop uniformity, shorter plant production times, control of pedigree, flexibility of deployment, multiplication of valuable crosses and better exploitation of genotype x environment interactions, compared to family forestry (Carson and Burdon, 1989; Carson, 1986; Libby and Rauter, 1984; Sorensson and Shelbourne, 2005). Adoption of clonal forestry in New Zealand with radiata pine has been limited, in spite of its potential to enhance productivity, by some technical problems such as lack of suitable methods of clonal propagation, maturation and maintenance of juvenility (Aimers-Halliday *et al.* 2003; Aimers-Halliday and Burdon, 2003). Recently, developments of organogenesis and embryogenesis for propagation, and maintenance of juvenility by cryo-perservation have made clonal forestry feasible (Aimers-Halliday *et al.* 2003; Carson *et al*., 2004), but still there are some problems which need to be addressed so that we can benefit from using tested clones in plantations. There is a need to standardize some silvicultural regimes for different site conditions, to test various modes of deployment with respect to productivity, uniformity and risks, and to develop effective models for predicting the future states of clonal stands.

In this chapter important issues of clonal forestry that relate to the studies reported in this thesis will be reviewed.

2.2 Maturation and quality of planting stock

Maturation

In New Zealand bare-root planting stock is most commonly used (Menzies *et al*., 2001). Vegetative propagation methods have been developed for radiata pine in New Zealand to allow the multiplication of scarce genetic material, particularly control-pollinated seed, and allow a larger area to be planted with this stock (Menzies and Aimers-Halliday 1997).

Vegetative propagation allows genetic gains from the use of non-additive genetic variance and greater uniformity (Libby *et al*. 1972; Zobel, 1992; Menzies *et al*. 2001) but there are concerns about plant quality of rooted cutting compared with seedlings with respect to root system quality, physiological age (maturation), and their field performance (Sweet, 1973; Menzies *et al.* 2001). Cuttings and tissue culture plantlets develop adventitious roots around the shoot base following callus formation, and the number of roots and distribution of roots can vary (Menzies *et al*. 2001). In some species propagules tend to grow like the branches from which they came, a phenomenon called plagiotropism which adversely affects tree form and quality and also results in reduced early vigor (Sweet, 1973; Zobel, 1992; Menzies and Aimers-Halliday 1997; Menzies *et al*. 2001).

Reduced early vigor, but improved stem form of rooted cuttings taken from older trees are signs of physiological ageing (Menzies and Klomp, 1988; Amiers-Halliday *et al*. 2003). In New Zealand and Australia, the terms “physiological ageing” and “maturation” are often used synonymously, with “physiological age” used to define the particular development state (Aimers-Halliday *et al*. 2003).

Maturation is defined as the progression of change from embryonic through juvenile, adolescent and mature states, due to ontogenetic ageing (Sweet, 1973; Greenwood, 1995; Aimers-Halliday *et al.* 2003; Aimers-Halliday and Burdon, 2003). Maturation adds risks to implementation of clonal forestry programs in two ways. Firstly, vegetative propagation as cuttings becomes difficult with increasing age of donor plants (Menzies and Klomp, 1988). The second way in which maturation causes risks to clonal forestry is from decreased diameter growth rates (Menzies and Klomp, 1988; Libby and Ahuja, 1993; Amiers-

Halliday *et al*. 2003) and poor field performance compared to juvenile plants that may likely cause changes in clonal rankings (Aimers-Halliday,and Burdon 2003).

Embryonic or juvenile maturation states are generally preferred for most forestry purposes (Aimers-Halliday and Burdon, 2003) to minimize the risks associated with maturation. There is an optimal age of 3 to 4 years with the advantage of improved stem form and little loss of initial growth (Menzies *et al*. 1989; Menzies and Aimers-Halliday 1997; Aimers-Halliday *et al*. 2003). The use of juvenile rooted cuttings with a physiological age of 3-4 years has been recommended for planting on topple prone sites (Aimers-Halliday *et al.* 2003) and also confers a degree of disease resistance (Power and Dodd, 1984; Zagory and Libby 1985; Frampton and Foster, 1993; Power *et al*. 1994). In New Zealand hedging and serial propagation are used to maintain juvenility and over come the problem of maturation in radiata pine. The success of cryo-perservation and somatic embryogenesis techniques have made clonal forestry of radiata pine feasible (Aimers-Halliday *et al.* 2003; Carson *et al*. 2004), but still costs of production of clonal material by these techniques are approximately five times more than seedling production (Sorensson and Shelbourne, 2005). There is a need to develop cost effective clonal propagation, juvenility maintenance and multiplication techniques that works for most genotypes and gives large numbers of uniform plants per clone, with minimal ageing, after clonal testing (Aimers-Halliday *et al*. 1997; Menzies and Aimers-Halliday, 1997; Horgan *et al*. 1997).

Quality of planting stock

The productivity of plantations depends upon a number of factors including genotype, quality of planting stock, competition, survival, management practices adopted, soil fertility, climate and their interactions.

Initial survival and initial growth rate are measures of initial plantation performance (Duryea, 1984). The performance of planting stock depends upon site conditions, which emphasizes the need to match stock quality to particular sites. Poor quality planting stock results in lower survival and slow initial growth due to transplant stress. Seedlings take a long time to reach merchantable size, which results in a loss of value and volume yield (Menzies *et al.,* 2005). Different quality criteria have been used to assess the quality of

planting stock. Several morphological and physiological indicators are in use to describe quality of planting stock.

2.2.1 Morphological indicators of planting stock quality

Morphological indicators are the visible attributes of planting stock (Duryea, 1984) such as stem height, stem diameter, root system, shoot: root ratio, and root-fibrosity.

Plant height: Tall plants are more difficult to plant and may have greater shoot: root ratios than short plants. Minimum standards for height vary by species and age class (Thompson, 1985). For radiata pine plants at time of transplanting height range of 30-40 cm is considered ideal (Menzies, 1988). The New Zealand Forest Research Institute recommended a height range of 25-30 cm for bare-root radiata pine cuttings (Faulds and Dibley, 1989). Tuttle *et al.* (1987) reported that initial height of loblolly pine seedlings (1+0) was inversely related to total seedling height growth during the first two seasons, and a "Transplant Stress Index" (TSI) defined as the slope of a linear relationship between initial seedling height and subsequent height growth has been proposed as an indicator of moisture stress following planting (South and Zwolinski, 1997). The negative slope indicates the plants are experiencing planting check. However, South and Mason (1993) reported that taller seedlings of Sitka spruce at planting were also taller after 6 years of growth. South *et al.* (2001) found that planting larger seedlings of average diameter of 8.5 mm and 50 cm tall of Loblolly pine increased the survival slightly on one site and increased fourth year volume production with intensive management.

Stem diameter: Diameter of seedlings is considered to be the best single predictor of field survival (Thompson, 1985). Greater stem diameter is reputedly associated with greater proportion of roots produced (Menzies *et al.* 2005). Diameters of 6 mm and 8-10 mm have been recommended for radiata pine seedlings and bare-root cuttings respectively for New Zealand conditions (Faulds and Dibley, 1989). Anstey (1971) reported that radiata pine field growth and survival were greater with greater initial diameter. South *et al*. (1985) reported that survival of loblolly pine seedlings of root-collar diameter greater than 4.7 mm was significantly greater than seedlings of initial root-collar diameter of less than 1.6 mm and volume production at age 13 years was 17.5 percent greater than seedlings of initial root-collar diameter of 3.2-4.7 mm. Mason *et al*. (1996) reported that seedling ground-line

diameter (GLD) was best correlated with tree performance of radiata pine seedlings at one site while GLD squared x height was most significant at another. Mason (2001) included GLD as a predictor of survival and growth of radiata pine in a juvenile growth model, and GLD was found to be most influential when environmental conditions were harsh.

Shoot: root ratio: The shoot: root ratio is important from water balance of planting stock. Shoot represents transpirational area and root the water absorption capacity of planting stock (Thompson, 1985). A shoot: root ratio of 3:1 is considered ideal for most species (O'Reilly *et al.* 2002). For dry soil conditions a low shoot: root ratio (1.5 to 2.5) is viewed as desirable for bare-root stock (Thompson, 1985; Bernier *et al.* 1995) to ensure high survival.

Root fibrosity: Seedlings with large root systems are considered good for rapid growth and survival. Root weight is often correlated to seedling diameter (Ritchie, 1984). A greater proportion of roots reduces shoot: root ratio which is helpful to maintain water balance of planting stock. A more fibrous root system has a greater surface area for absorption of water and nutrients which is very important for initial growth and survival of planting stock (Thompson, 1985; Deans *et al*. 1990). Deans *et al.* (1990) reported that root growth potential (RGP) of 2+1 transplants of *Picea sitchensis* was related to their number of fine root apices and removal of fine roots resulted in lower RGPs of seedlings, and concluded that root fibrosity promotes root regeneration after out-planting.

Sturdiness: Sturdiness, the ratio between height and GLD, indicates the balance between height and diameter. Due to positive correlations between height and foliage biomass, and diameter and root biomass, sturdiness represents the water balance of planting stock. To offset transpirational losses a certain amount of transpiring foliage needs a certain amount of roots to absorb soil water. A low height: diameter ratio means that roots are abundant compared to foliage for uptake of water to offset transpirational losses from the foliage, and a seedling therefore has high water stress avoidance potential. In general sturdiness of 50 is considered ideal for most of the species (Trewin, 2000) and 40-60 for radiata pine in New Zealand depending upon site conditions (Menzies, 1988).

2.2.2 Physiological indicators of planting stock quality

Physiological indicators are non-visible attributes of a seedling such as root growth potential (RGP), amount of food reserves and frost resistance.

Root growth potential (RGP): The ability of the root system to produce and elongate roots when placed into an environment favorable for root growth (Ritchie, 1985; Simpson and Ritchie, 1997; Davis *et al.* 2005; Gazal *et al*. 2004) is known as root growth potential. High RGP reputedly enables a seedling to establish rapidly after planting. Researchers differ about the effectiveness of RGP as the predictor of initial growth and survival. Those who doubt the effectiveness of RGP argue that: 1) Actual site conditions differ from the optimal conditions maintained during test. 2) RGP describes seedling performance potential, rather than performance (Simpson and Ritchie, 1997; Davis *et al.* 2005). However, numerous studies have reported RGP as an accurate predictor of growth and survival. Larsen *et al.* (1986) reported enhanced survival of seedlings of loblolly pine during first year after out-planting that had greater RGP (measured as number of new roots ≥ 0.5 cm emerged in greenhouse test). Hallgren and Tauer (1989) reported a strong correlation (r=0.58) between RGP and survival of shortleaf pine seedlings. Feret and Richard (1985) reported a high correlation of RGP with survival and first two years height growth of Loblolly pine seedlings. Gazal *et al.* (2004) studied the root growth potential and seedling morphological attributes of Narra (*Pterocarpus indicus* Willd.) seedlings after 7, 14 and 21 days of transplanting. Twenty seedlings were measured destructively at each test interval. RGP of each seedling measured by counting the number of new roots and measuring their lengths. They reported that shoot biomass, root biomass, total biomass, height, root collar diameter and quality index were significantly correlated with RGP (number and length of new roots) except root: shoot ratio. RGP of 4-5 on a 0-5 visual scale (after 28 days at 20 ^{o}C) has been recommended for bare-root radiata pine seedlings for New Zealand conditions (Menzies, 1988).

Food reserves: Plants need a supply of food for their maintenance and growth. From the time of lifting till placement in the field, plants use carbohydrate reserves. Hellmers (1963) studied physiological changes in stored seedlings of Jeffrey pine and attributed the decrease in field survival of stored seedlings to disappearance of starch in stored seedlings.

Undercutting and wrenching helps to increase carbohydrate levels (van Dorsser and Rook, 1972).

Frost hardiness: Frost or cold hardiness is defined as the lowest temperature below the freezing point to which a seedling can be exposed without being damaged (Glerum, 1985). In New Zealand frost tolerance levels of -12 ^{o}C for winter and -6 ^{o}C for summer are considered ideal for bare-root radiata pine seedlings (Menzies, 1988). Menzies and Holden (1981) evaluated the frost tolerance of *Pinus radiata* in New Zealand and reported that individual seedlings exhibited a range of frost tolerance. Menzies *et al.* (1981) evaluated seasonal changes in frost tolerance of *Pinus radiata* seedlings raised in different nurseries and reported that stock produced at the higher altitude nurseries were more tolerant and could tolerate 3^{o}C lower temperatures compared to seedlings produced in low altitude nurseries. Karen *et al*. (1986) evaluated the effectiveness of four cold hardiness tests on three western conifers and reported that a freeze induced electrolyte leakage test and a differential thermal analysis test were effective for estimating cold hardiness. The results from a freeze induced electrolyte leakage test and differential thermal analysis test were available in 2 days and 1 hour respectively.

The main drawback of physiological indicators is that they are time consuming and expensive to measure and often mean that measured trees are destroyed. Morphological indicators are often used because they are easy to employ.

2.2.3 Nursery management techniques

Top pruning: Top pruning is practiced by most of the nursery managers in Southern United States and Australia to improve the root-weight ratio (ratio of dry weight of the root system and the dry weight of the total seedling) of both bare-root seedlings and rooted cuttings (South, 2000). Top pruning is done to enhance field survival of planting stock by maintaining the balance between roots and shoots at planting.

Under-cutting and wrenching: Root morphology is manipulated through under-cutting and wrenching. In under-cutting, the roots of the plants are severed at a depth of about 8 cm when the plants are about 20 cm high. Under-cutting is done 10-12 weeks before the plants are required for planting out. After under-cutting, a thicker blade, tilted at an angle

approximately 45 degrees is drawn under the plants, partly lifting the plants in the soil, thereby aerating the seedbed (van Dorsser and Rook, 1972). Under-cutting enhances lateral root growth and wrenching checks the shoot growth of plants. Under-cutting and wrenching decreases shoot: root ratio (van Dorsser and Rook, 1972). These operations increase root proportion and root fibrosity which are important for maintaining the plant water balance necessary for rapid establishment. Rook (1971) reported root: shoot ratios of 0.16, 0.26 and 0.44 of radiata pine seedlings that were unwrenched, wrenched once and wrenched fortnightly respectively during a 5 month period. He reported greater survival of seedlings that were wrenched fortnightly for 5 months compared to seedlings wrenched once and those not wrenched.

2.3 Clonal deployment

In order to maximize gains and minimize risks, two basic decisions need to be made regarding the number of clones to be deployed and the mode of their deployment (Burdon, 2001; Burdon and Aimers-Halliday 2003; Tuskan, 1998; Ritchie, 1996; El-Kassaby and Moss, 2004).

Number of clones to be deployed

Safety of clonal plantations is becoming a major concern with increasing acceptance of clonal forestry (Libby, 1987b). Decisions regarding the number of clones to be deployed at a site or region need to be made to counter biological and future market risks associated with clonal forestry. Some estimates on the safe number of clones in clonal mixtures have been presented (Burdon, 2001; Libby, 1987b; Roberts and Bishir 1997) and many researchers suggest that 15-30 unrelated clones of a species are adequate to balance gains of clonal forestry against its the risks (Park, 2002). Another important issue in addition to number of clones is the relative numbers of copies of each clone in a plantation (Lindgren, 1993; Burdon and Aimers-Halliday, 2003). Lindgren (1993) suggested that the following general considerations would determine the number of clones and number of copies of each clone to be deployed in a clonal mixture plantation:

a) The rotation age of the species: lower numbers can be used if the species is shorter-lived.
b) The fraction of the initial plants remaining at harvest: lower numbers can be used if the majority remains.
c) The intensity of the system: lower numbers can be accepted if the system is intense.
d) Whether the clones considered are well known and high-ranking: the more well known a clone is, the more exclusive its use is acceptable.

Choice of mode of deployment

There have been mainly two approaches to clonal deployment in forestry: monoclonal and clonal mixture deployment (Libby, 1987a, 1987b; Lindgren, 1993; Zsuffa *et al.* 1993; Debell and Harrington, 1993; Ritchie, 1996).

- *Monoclonal deployment or Mosaics of Monoclonal Stands (MOMS)*: Clones are deployed in monoclonal stands (all neighbouring trees in such stands are genetically identical), but these stands are inter-mixed with many other stands containing different clones (Libby, 1987a, 1987b). A genetically diverse mosaic pattern can be achieved by deploying many clones of same or different species, different age classes (Lindgren, 1993). This approach could also be beneficial when the foresters are interested to grow different clones for different end uses.
- *Clonal mixture deployment or Widespread Intimately Mixed Plantations (WIMPs)*: Clones are inter mixed (randomized) in one stand (Libby, 1987a, 1987b). This approach is considered to minimize the risks mainly from insect pest and diseases, but greater variability in tree size or wood quality as a result of inter-genotypic competition might make it difficult for wood processors to maintain consistent product quality at low cost.

Several other modes of deployment such as row-to-row and tree-to-tree clonal mixtures (Zsuffa *et al.* 1993); mixtures of clones and seedlings (Park, 2002) have been used, but monoclonal and clonal mixture modes of deployment have been widely adopted (Dawson and McCraken, 1995; Debell and Harrington, 1997; Benbrahim *et al*. 2000). Scientists still differ on whether to grow monoclonal stands or clonal mixture stands. The factors such as productivity, crop uniformity, risks, and operational efficiencies in tending, harvest, log

segregation and subsequent processing and marketing might influence decisions about mode of deployment. Zobel (1993) reported that growers of clonal eucalyptus plantations favor monoclonal blocks for their uniform growth and wood properties.

The main issue that needs to be addressed through research studies is whether a set of well-adapted clones can perform better in clonal mixture than in monoclonal blocks, through complementary exploitation of the resources of the environment (Burdon and Aimers-Halliday, 2003). Various studies and reviews have compared the productivity of monoculture and polyculture of species of different genera (Bristow *et al.* 2006; Forrester *et al*. 2004; 2006, Debell *et al.* 1997; Parotta, 1999; Piotto *et al.* 2004; and Petit and Montagnini, 2006) and reported intermediate to greater productivity of mixtures compared to monocultures of species. A few studies have been conducted mainly in short rotation hardwood species to compare the productivity of mainly two modes of deployment (i.e. monoclonal and clonal mixtures). One study in long duration species relevant to radiata pine has been reported by Zhou *et al.* (1998). They compared the productivity of clones of conifer species Chinese fir (*Cunningahamia lanceolata* (Lamb) Hook) in monoclonal block plantations with single row plantations relative to seedling check plantations. These studies have yielded mixed results (Table 2.1).

Table 2.1: Summary of results of the studies that compared the productivity of monoclonal and clonal mixture plots.

Researchers	Species	Age (years)	Productivity Monoclonal vs. Clonal mixture
Markovic and Herpka (1986)	*Populus*	4	Slightly higher volume, mean height and mean diameter growth in clonal mixture plots.
Dawson and McCraken (1995)	*Salix*	3	Greater biomass yield in clonal mixture plots compared to either the mean yield of component clones or individual yield of any component grown monoclonally
Debell and Harrington (1997)	*Populus*	3	Similar biomass (stem+branches) productivity
Benbrahim *et al*. 2000	*Populus*	8	Similar biomass (stem+branches) productivity
Zhou *et al.* (1998)	Chinese fir (*Cunninghamia lanceolata* (Lamb) Hook.)	9	27-30 % greater volume per hectare of monoclonal blocks of clones compared to single row plots over seedling check plots.

Biological and market risks are important factors that might influence choice of mode of deployment. Clonal mixture mode of deployment is useful option where there is a known serious disease or pest problem and mosaic of monoclonal blocks is useful option to address market risks (Burdon and Aimers-Halliday, 2003).

In New Zealand monoclonal deployment is more common than clonal mixture deployment. In this thesis two modes of deployment are compared, these modes of deployment are hereafter described simply as deployment of clonal mixtures and monoclonal stands.

2.4 Clonal screening

Timing of screening

Screening of clones is important for successful clonal forestry (Menzies and Carson, 1989). Stem diameter (DBH), stem straightness, branch cluster frequency, needle retention, malformation traits have been used for selection of clones in New Zealand (Jayawickrama and Carson, 2000). In New Zealand the standard age of selection is eight years (White 2001; Jayawickrama, 2000), although selections within seedling progeny tests have also been made between four to ten years (King and Burdon, 1991).

Menzies and Carson (1989) suggested that for early screening to be effective there should be moderate to high correlation between early attributes and later clonal performance. Early selection is essential to cull undesirable clones during the clonal screening, and minimize the cost of maintaining the juvenility and measuring the tested clones. Some selection traits such as growth rate (height and diameter), branching habit, disease resistance, wind-firmness, and frost tolerance have greater potential for early selection (Menzies and Carson, 1989). However, Low (1989) studied the interaction of *Cyclaneusma* needle cast with early selection in *Pinus radiata* and reported changes in stem diameter growth rankings of some families between the ages of 5 and 18 years. In this study he found that the trees which were dominant at age 5 years were relegated to well below average by age 15 years. Debell and Harrington (1997) reported interchanges of ranks between spacings in monoclonal plots of *Populus* clones. Zsuffa (1975) and Ares (2002) also reported interchanges of ranks in clonal mixture plots. Dungey (2004) evaluated the

effectiveness of early selection for growth and form traits by analyzing the correlations of early growth (1-3 years) data with field measurements at age 8 years. He reported low to moderate (0.29-0.65) correlations between early ages (1-3 years) at farm sites (highly fertile sites with intensive site preparation, intensive weed control, and close spacing) and measurements at the field site (normal progeny test sites) at age 8 years. This farm-field experiment design was undertaken based on hypothesis that highly fertilised "farm" sites may be more effective in showing early genetic differences than normal progeny testing 'field" sites in the forest (Dungey, 2004).

Screening method

In New Zealand multi-trait and multi-site indices have been in use for selections in breeding programs (White, 2001; Dungey, 2004). Various combinations of traits including DBH, straightness, malformation, wood density, branch cluster frequency have been in use in multi-trait indices and economic weights are also assigned to each trait depending upon breeding goals. The selections are carried out in single tree progeny tests and all entries are ranked based on scoring of each entry at multi-site, multiple trait selection indices (Wilcox *et al.* 1976; Burdon, 1979; Shelbourne and Low, 1980; White, 2001).

The most common objectives of progeny tests in breeding programs are: a) to produce a base population for advanced generation selection; b) to provide information for evaluating parents ; c) to estimate genetic parameters; and d) to estimate realised gain directly (Johnson, 1974; McKinley, 1983).

In breeding programs the first step is to select superior parents from the breeding population based on progeny tests and then to produce full-sib families from selected parents for selection of best genotypes (clones) from best families through clonal trials for deployment in commercial plantations (Aimers-Halliday *et al*. 1997).

Clonal testing is an essential part of clonal forestry, but there are some issues of clonal testing that still need research. These include the range and number of sites needed for testing and optimal clonal field-tests design (Aimers-Halliday *et al*. 1997; Aimers-Halliday and Burdon, 2003). Number of trees per clone and number of replications per site are also important decisions that influence the precision of selection (van Buijtenen, 1983; Aimers-

Halliday and Burdon, 2003).Various genetic test designs, including single tree plots, row plots, and block plots, have been recommended for forest trees (Foster, 1989). Single tree plots are usually used for selections because they are statistically more efficient than block plots and less expensive (Libby and Cockerham, 1980; Libby, 1987b). There are some issues associated with the use of single tree plot test design:

- Inter-genotypic competition might suppress some initially slower growing genotypes in single tree plots. So selections made in such conditions could miss out genotypes that may perform well in monoclonal plantings and may overestimate differences between clones (Franklin, 1989; Foster 1989; Carson *et al*. 1999a; Foster *et al*. 1998; Stanger *et al*. 2007).
- Foresters are concerned with stand level growth and productivity. Genotype, environment, survival, competition, management practices, and their interactions affect stand productivity. Single tree plots lack information on unit-area productivity and competition related mortality (Johnsson, 1974; Libby, 1987b; Staudhammer *et al*. 2006).

Breeders recognise the pros and cons of single tree plot and block plot (BP) screening methods (Table 2.2) and regard land requirement of block plot method the most serious.

Table 2.2: Key advantages and disadvantages of single-tree-plot (STP) and monoclonal block-plots (BP) for use in screening trials.

Factors	STP	BP
Land area required	Less	More
Growth bias from inter-clonal competition	More	Less
Monoclonal stand productivity and growth pattern analysis	No	Yes

Therefore, when the number of clones to be tested is large the reasonable strategy is to first test a large number of clones using single tree plots (Libby and Cockerham, 1980) and then at later stage a small number of promising clones can be tested (Libby, 1987b). Libby (1987a) suggested four step approach to testing of clones:

Level I. *Initial screening*: Screening of large number of genotypes in single tree plots.

Level II. *Candidacy testing:* Use of 2-6 ramets of each genotype to identify genotype x environment interactions and selecting better clones for further testing or deployment in plantations as clonal mixtures.
Level III. *Clonal performance testing*: This step involves testing stability over contrasting sites using 2-6 ramets of each clone at different sites to evaluate each clone's appropriate range of sites for deployment (Level IIIa), and to evaluate per unit area productivity of clones using large contiguous plots of each clone (Level IIIb). The number of clones tested in this level will be moderately small (< 200).
Level IV. *Compatibility testing*: Clones selected at level III can then be tested in sequenced mixtures to identify compatible sets of clones that would make complementary demands on their environments at same time and would enhance overall per unit area productivity. This level of testing is recommended at advanced stage of selection programs when number of clones to be tested will be small (20-50).

In New Zealand block plots trials have been established and used to predict realised gains in yield of genetically improved *Pinus radiata* breeds over unimproved stands (Carson *et al*. 1999a) and to examine the interaction of silviculture and genetic improvement in *Pinus radiata* (Carson *et al*. 1999b). Cleland (1985) and Johnson *et al*. (1992) have reported the comparisons of genotypes in block plot trials comparing volume per unit area for commercial seedlots of improved and unimproved origin of radiata pine. There appear to be no reports of comparisons of single tree plots with block plots for estimating genetic gain in New Zealand.

2.5 Wood Properties

Wood quality can be divided into characteristics that are externally visible on a tree such as straightness and lack of forking; branch size and branch distribution, and those that are not visible such as stiffness, strength and stability (Maclaren, 2002). Externally visible characteristics such as stem straightness; branch size, number of whorls and internode length influences wood appearance, wood recovery, and internal wood properties. A tree with long-length clears produced by pruning has high value, and those with small branches and long internodes give high-value shop grades from unpruned logs (Shelbourne *et al.* 1997). A long internode branching habit is desirable for production of appearance grade lumber from unpruned logs (Carson and Inglis, 1988; Grace and Carson, 1993), and for

greater yield of knot-free lumber in the unpruned part of the stem for a variety of products (Jayawichrama *et al.* 1997).

There are certain disadvantages associated with a long-internode habit. Trees with long-internode grown on fertile sites at wide spacing tend to have larger branch diameters than multimodal trees and are more susceptible to breakage in areas with strong winds. Internode length is under strong genetic control; therefore selection for long-internode length and deployment at appropriate sites would enhance wood recovery and also reduce the cost of pruning.

Stiffness, strength and stability during drying are the main wood properties that determine the quality of structural timber (Punches, 2004; Huang *et al.* 2003). Plantation-grown *Pinus radiata* timber has relatively poor stiffness and stability compared to other internationally traded structural lumber species (Walford, 1991; Cave and Walker, 1994). Wood density, microfibril angle, slope of grain, knots and extractives are the wood characteristics that influence these wood properties (Harries, 1989; Sorensson, *et al*. 1997; Evans and Kibblewhite, 2002; Gartner, 2005). Stiffness is considered to be the most important wood property for structural timber of radiata pine. Wood density was the first wood characteristic that was included in the New Zealand breeding program, because it showed strong correlations with stiffness and strength (Walford, 1985).

The core of a log generally has inferior wood properties. The average increase in *Pinus radiata* wood density over the first 30 years is between 30% to 50%, depending upon the geographic region (Huang *et al*. 2003). Wood density was almost linearly related to wood strength and stiffness according to Tsehaye *et al*. (1995). On this basis alone one might predict a 30-50% increase in longitudinal stiffness and strength over a 30 year rotation. Cave and Walker (1994); Tsehaye *et al*. (1995); and Evans and Kibblewhite (2002) reported, however, that density alone is not good predictor of stiffness in the core of a log, and emphasised the need to reduce microfibril angle to improve stiffness.

The density of radiata pine increases from pith to bark and microfibril angle decreases outwards from the pith. In radiata pine two characteristics of corewood, low density and large microfibril angle together reduce the axial stiffness relative to that of outerwood (Huang *et al*. 2003).

Spiral grain is another important wood characteristic that influences wood quality. Spiral grain in radiata pine often reaches its maximum value (5-10^{o}) by the second or third annual growth rings from the pith and thereafter, tends to decrease and nearly straight angle after tenth growth ring (Harris, 1989). Twist in sawn lumber and reduction in strength are the main problems associated with excessive spirality (Sorensson *et al*. 1997; Harris, 1989). Considering both high heritability and high variability of spiral grain reported between trees (Harris, 1989) this trait was included as standard selection criterion in New Zealand breeding programme (Sorensson *et al*. 1997; Shelbourne *et al*. 1997).

Recently emphasis of breeders has shifted from wood density improvement to make selection for wood performance more direct i.e. testing stiffness rather than density, testing twist rather than spirality of radiata pine (Sorensson, 2002; Jayawickrama, 2000).

2.5.1 Genetic control of wood properties

Various studies of different *Pinus radiata* genetic material concluded that wood properties are under moderate to high genetic control. In clonal trials use of between four and six ramets per site has been recommended to estimate clonal mean heritability of wood properties (Gezan *et al.* 2006). The precision of measurement increases with increase in number of ramets per clone used. Russell and Libby (1986) have recommended the use of two to six ramets per clone per site for clonal testing and estimating genetic parameters. Shelbourne (1997) have reported clonal mean heritability of longitudinal stiffness of 0.98 based on five ramets per clone. Dungey *et al.* (2006) reported high to moderate genetic control of microfibril angle, density and stiffness, in corewood and outerwood respectively.

2.5.2 Influence of silvicultural practices on wood properties

Silvicultural practices tend to act indirectly on wood quality through their effects on the growing environment of the tree's crown and roots (Zobel and van Buijtenen, 1989; Punches, 2004). Trees compete for light, nutrients and water, and silvicultural practices mainly regulate competition for these resources. Competition between trees could be regulated by manipulating stocking, controlling non-crop competititors, fertilization and irrigation. Initial stocking has been reported to influence stiffness of 11 year old radiata pine clones (Lasserre *et al*., 2004). Morphology of genotypes determines the ability to

capture light, nutrients and moisture, and one of the factors responsible for growth differences. Mason (2006) reported significant influences of genotype, slenderness and pruned height on stiffness in a study conducted to analyse the effect of weed control on wood stiffness.

Genotype, site conditions such as latitude, altitude, slope, windiness, and soil fertility, and silvicultural practices including thinning, pruning, irrigation, fertilization, and weed control influence growth rate. Growth rate partly affects wood characteristics that determine the quality of timber (Macdonald and Hubert, 2002; Punches, 2004; Gartner, 2005). The initial and subsequent stocking of the stand control branch diameter and thus knot size in the unpruned parts of the tree, and so affect strength and stiffness of resulting structural lumber (Shelbourne, 1997).

2.5.3 Non-destructive techniques of measuring stiffness of timber, lumber and standing tress

Non-destructive evaluation of materials is a science of identifying physical and mechanical properties of a piece of material without altering its end-use capabilities (Ross and Pellerin, 1994). Transverse vibration and longitudinal stress wave (acoustics) are the non-destructive evaluation techniques used to assess the modulus of elasticity (MOE) of structural lumber (Ross and Pellerin, 1994; Wang *et al.,* 2001a. Longitudinal stress wave is most commonly used to evaluate wood properties (Wang *et al.,* 2001b). Two ways of using acoustics in forest operations are the resonance and time of flight methods. Resonance based tools have an edge over time of flight tools in terms of ease of use but their application is limited to cut logs or lumber, because acoustic waves travel back-and-forth, therefore two cut ends are essential (Chauhan and Walker, 2006). With the resonance vibration method, one end of the log of length L is struck with a hammer to induce disturbance. The disturbance generates a set of compressions and dilatational that travels backwards and forwards between the two cut faces of the log producing a wave. The frequencies of oscillations and the stress wave velocities are related by:

$$V_n = 2L\, f_n \qquad (2)$$

Where V_n and f_n are the velocity and frequency of the n^{th} harmonic in the wave respectively and L is the length of log.

Measuring stiffness of standing trees might be of great benefit to forest managers who could then segregate young trees when deciding which trees to cull during thinning operations and make decisions on log allocation to structural, utility, cut-stock mills or for pulpwood (Tsehaya and Walker, 1995). Foresters however generally use acoustic resonance tools (Joe *et al.* 2004) to segregate logs after harvest and do not routinely measure standing tree acoustic time of flight. Many instruments have been developed based on the resonance techniques and on the transit-time techniques. Several non-destructive acoustic based testing tools developed to measure stiffness in standing trees have been used: Fakkopp (Chauhan *et al.* 2005), Director ST-300TM (Carter *et al.* 2005), and TreeTap (Lasserre *et al.* 2004, Grabianowski *et al.* 2005, Mason, 2006). Use of these tools has enabled researchers to study impacts of management practices on wood properties. These tools are based on the following fundamental relationship between stress wave velocity and dynamic MOE,

$$MOE=\rho V^2 \quad (3)$$

Where ρ is the density of wood and V is the measured velocity of sound. Non-destructively wood density is usually measured using increment cores taken at breast height (Lindstrom *et al.* 2004). The relationship between clearwood MOE and density can be expressed in the general form (4):

$$MOE= k\rho^n \quad (4)$$

Where k is a constant and n is an exponent that defines the shape of the curve which varies from 0.8 to 0.9 for softwoods (Tsehaye *et al*. 1995; Huang *et al*. 2003). According to this relationship stiffness increases almost linearly with density. In practice, the density of wood varies slightly across a site (Hays and Chen, 2003). In radiata pine the green density is so dominated by water that regardless of the basic density the wet density is always close to 1000 kg/m^3, whereas within a forest the diversity of wood stiffness can be as much as a factor of four (Harris and Andrew, 1999). Therefore stress wave velocity is the main variable used to estimate the dynamic MOE of timber, lumber and standing trees when

assessments are made using stress wave based techniques, and these methods appear to hold good for all materials. The equation assumes that the velocity measured from standing trees can be used as surrogate for resonance velocity because strong linear relationships (r^2 = 0.71-0.93) have been reported between acoustic velocity measured in trees and acoustic velocity measured in logs (Carter *et al* 2005; Wang *et al*. 2007). Wang *et al.* (2001b) have also reported correlation coefficient of 0.63 and 0.78 between MOE_d (dynamic modulus of elasticity) of trees and MOE_s (static modulus of elasticity) of the small, clear specimens cut from the trees in western hemlock (*Tsuga heterophylla*) and Sitka spruce (*Picea sitchensis*) respectively. Lindstrom *et al.* (2002) have reported a strong relationships (r^2 = 0.96) between MOE_d of butt logs and MOE_s of internodal bolts taken from butt logs of radiata pine clones. Wang *et al*. (2001a) have reported the correlation coefficients of 0.87 and 0.77 between stress wave MOE versus static MOE in jack pine (*Pinus banksiana* Lamb.) and red pine (*Pinus resinosa* Ait.) respectively.

2.6 Modelling approaches

Presently there are three forest growth and yield modelling approaches:

- Mensuration-based growth and yield modelling
- Physiological modelling
- Hybrid modelling

2.6.1 Mensuration-based Growth and Yield Modelling

Growth is the total increase in dimensions of one or more individuals in a forest stand over a given period of time (e. g. volume growth in m^3 ha^{-1} y^{-1}), and yield refers to accumulated growth at the end of a certain periods (e. g. total volume in cubic meters per hectare at harvest) (Vanclay, 1994; MFR, 2006). A model is an abstraction, or a simplified representation, of some aspect of reality (Vanclay, 1994). Growth and yield prediction models are abstract or simplified representations of forests used primarily to estimate the future growth and yield of forest stands (MFR, 2006). These models are fitted to data describing forest growth on a particular site assuming similar site conditions in future (Kimmins *et al.,* 1990; Vanclay, 1994). These models are preferred by foresters due to their simplicity, and they can be tested rigorously through residual analysis. The draw back

of these models is that they are not useful for prediction of productivity of differing clones, nor of sites with differing site conditions or subject to climate change.

One of the key requirements to optimise benefits of clonal forestry is the development of growth and yield models that can predict future productivities of clonal stands and represent reasonably well the changes in growth patterns of stands with minimum bias. In family forestry genetic effects have been incorporated in growth and yield models to estimate yield and genetic gain of genetically improved seedlots (Carson *et al.* 1999a; Adams *et al.* 2006). Carson *et al.* (1999a) used genetic gain multipliers to predict the future productivities of improved seedlots of radiata pine compared to unimproved seedlots and reported that applying genetic gain multipliers to basic growth-and-yield models was adequate. Adams *et al*. (2006) reported that inclusion of genetic functions of relative survival, relative diameter, relative height and stem profile in growth-and-yield models reduced the bias in volume prediction of nine different families.

Use of genetic gain multipliers to predict the productivities of monoclonal stands might not be useful because genetic gain multipliers have been developed using measurements taken in stands of improved seedlots and unimproved seedlot, so are more applicable to family forestry. The stands of different seedlots also represent clonal mixture stands, and growth patterns of genotypes in monoclonal stands might differ from clonal mixture stands. Therefore, careful analysis of age-age correlations by using traditional yield modelling to extrapolate clonal growth rates might be more useful.

Traditional growth and yield models are classified into two major groups. The models which need stand level information (volume/ha and stand average diameter) called *whole stand models*. The models which require a sum of individual tree information (tree height, tree diameter and crown lengths) to produce the estimates of yield are called *individual tree models*. Individual tree level models have been sub grouped as *distance-dependent* or *distance-independent* individual tree models (Munro, 1974). There is third class of models called size class models which produces a histogram of stem diameters. These models are compromise between whole stand models and individual-tree models (Vanclay, 1994).

2.6.2 Physiological modelling

Physiological models attempt to model the processes of growth, taking as input the light, temperature and soil nutrient levels, and modelling photosynthesis, respiration and the allocation of photosynthates to roots, stems and leaves. These are also called "mechanistic models". These models can be more flexible than mensurational growth and yield models, and can be used to make predictions for changing climate conditions. The complexity of these models, due to many submodels involved, leads to less accuracy in prediction and these models require many parameter values that are generally not readily available to forest managers (Korzukhin *et al.* 1996; Landsberg and Gower, 1997; Sands *et al.* 2000; Mäkelä *et al*., 2000). In the past a number of physiological models have been developed, among these FOREST-BGC (Running and Coughan, 1988; Running and Gower, 1991) is one of the best known and most widely used, while others are BIOMASS (McMurtrie *et al.,* 1990), MAESTRO (Wang and Jarvis, 1990), TREGROW (Weinstein *et al*. 1991).

2.6.3 Hybrid Modelling

A forester requires models that are simple to operate, require few parameter values and that can be useful for making predictions with changes in edaphic and climatic conditions. This led to development of new modelling approaches called "Hybrid modelling" which combine the positive features of both mensuration-based and process-based models. The 3-PG (physiological processes predicting growth) hybrid model (Landsberg and Waring, 1997) and ProMod hybrid model (Battaglia and Sands, 1999) were recently developed hybrid models. The 3-PG hybrid model was developed to bridge the gap between conventional, menstruation-based growth and yield models, and process-based carbon balance models.

Overview of 3-PG

The 3-PG model is a monthly time step model and produces, at monthly time steps, updated values of basal area/ha, stand volume and biomass in foliage, roots, and stems within a stand. This model uses "Beers Law" to estimate absorbed photosynthetically active radiation (APAR) given any amount of radiation and LAI as in equation (5).

$$APAR = (1 - e^{-kL}) PAR \quad (5)$$

The model then calculates the proportion of absorbed photosynthetically active radiation converted to GPP (gross primary productivity) as in equation (6).

$$GPP = \alpha_c APAR \min(f_\theta \; f_D) f_T \; f_F \; f_S \quad (6)$$

Where α_c is quantum efficiency, and is determined by environmental factors (growth modifiers). The value of these modifiers varies from 0 to 1. In equation (6): f_θ is the soil water modifier (0-1), f_D is the vapour pressure deficit modifier (0-1), f_T is the temperature modifier (0-1), f_F is the frost modifier (0-1), and f_S is the senility modifier (0-1).

Then NPP (net primary productivity) is calculated as fixed proportion of GPP.

$$NPP = Y \; GPP \quad (7)$$

Y is constant proportion (0.47) in 3-PG.

The model then partitions NPP in to foliage, stem and roots. The partitioning to roots is influenced by soil nutrition and available soil water, partitioning to foliage and stem is based on the observed allometric relationships (8 and 9) between foliage or stem biomass and DBH (Landsberg and Waring, 1997).

$$WS = a_s DBH^{n_s} \quad (8)$$

$$WF = a_F DBH^{n_F} \quad (9)$$

Where W_S and W_F are stem and foliage mass respectively, and a_s and a_f are coefficients and n_s and n_f are powers.

Species specific values of litter-fall and root-turnover are used to determine net biomass of foliage and roots. The 3-PG model then uses well established mathematical formulae to determine the variables basal area/ha, LAI, stand volume, stem number (calculated using -

3/2 self-thinning law) and MAI (mean annual increment) from the biomass pools of roots, foliage and stems.

The 3-PG model was employed in the study described here in order to determine whether or not different carbon allocation patterns might allow the model to simulate differential growth rates of clones.

2.7 Competition

Every living organism has some basic requirements for its survival. Plant communities need nutrients, water, carbon dioxide and sunlight for their survival. A deviation from potential growth takes place when one of these elements becomes limited. Trees growing with competing vegetation have to share available resources. The overall demand of members of a community and availability of resources cause them to interact with each other to compete for light, water, and/or nutrients. Individual plant characteristics, climatic and soil factors determine the zone of influence of plant for acquiring the nutrients and water for growth during initial years of establishment. As the plants grow in size this zone of influence also increases. At some stage the size of the zone of influence of the plants growing in neighbourhood of each other intersects and with enhanced requirement for the basic elements for growth they start modifying the environment around each other. Thus they start exploiting the zone of influence of each other for their survival and optimum growth at the expense of each other's resources. This phenomenon has been termed as "Interference" (Harper, 1961; Weiner, 1984) and "Competition" (Cannell and Grace, 1993). Harper (1961) has defined competition as "those hardships caused by the proximity of neighbours" and Cannell and Grace (1993) described competition as "the process by which proximal plants modify each other's environment".

The intensity of competition depends upon available resources (site factors or environment), density, competing species (genetic factors) and their interactions. The competition between the trees of the same species and between trees of different species has been termed as "intra-specific competition" and "inter-specific competition" respectively (Shainsky *et al*. 1992; Liu and Burkhart 1994; Park *et al.* 2003; Bristow *et al*. 2006).

Competition within a plantation may be asymmetric or symmetric. Asymmetric competition occurs when a small number of large individuals utilize a disproportionately large share of the available resources and result in reduction of smaller neighbours, and in symmetric competition the growth of each plant is in proportion to its size (Park *et al.* 2003). The competition within species mixtures is asymmetric because of differences in growth patterns and morphologies of different species and this results in greater size inequalities. The competition in single species plantations is generally more symmetric and results in less variability in size. Sakai *et al*. (1968) compared intra-clonal and inter-genotypic competition in *Cryptomeria japonica* D. Don forests and reported lower intra-clonal competition compared to inter-genotypic competition, suggesting that the same competition within monoclonal stands may be more symmetric than that in mixed clonal stands. This idea will be tested in the study described in this thesis.

Stand density influences the extent of competition among trees in a stand which influences final productivity. Pretzsch (2003) studied the influence of density on productivity of pure and mixed stands of Norway spruce (*Picea abies* [L.] Karst.) and common beech (*Fagus sylvatica* L.) and reported that in pure stands maximum growth was obtained only at medium stand density, whereas in mixed stands growth was almost unchanged over a range of low, medium and high stand densities.

The study described here examined the extent of competition symmetry in mono-clonal and mixed clonal stands, and used modelling techniques to test whether or not knowledge of genotype might improve models that represent competition between individual trees in clonal stands. It is therefore relevant to review literature relating to competition and how it is represented within models.

2.7.1 Competitive Behaviour and models of competition

In the early years of establishment or before canopy closure competition is mainly for nutrients and soil moisture. Competition for light increases as the canopy becomes more closed. In plant to plant interactions, there are three main components (size of the plants interacting, distance between them and number of neighbours) that affect the growth of either of the plant. A likely outcome after interaction between them is differentiation in the sizes of competitors (Figure 2.1).

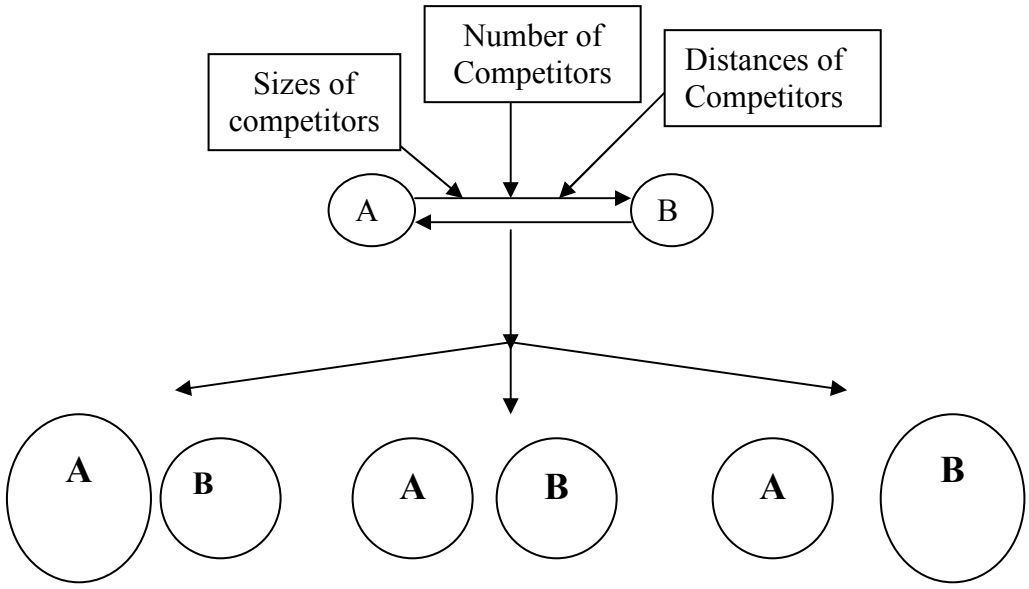


Figure 2.1: Model of competitive interaction among plant communities. Small circles A and B at the top in this model represent two trees or plants of almost equal sizes interacting and the sizes of circles at bottom represent the sizes of the trees or plants after interaction. Sizes of competitors, number of competitors and distances between competitors are the factors that affect competitive interaction.

2.7.2 Measures of competition

From a modelling point of view there is a need to quantify effects of competition when plants grow in communities. The effect or intensity of competition depends upon whether the competition is "intra-specific" or "inter-specific". Plant to plant interaction may result in reduction of growth of weak competitive plants. So the extent of this growth reduction is of main concern for the modellers to incorporate in their models for the realistic predictions of stand productivity, which is of real interest to the forest managers for making silvicultural, management and economic decisions for their estates.

A competition index characterizes the degree to which the growing space of an individual plant is shared by other plants (Deluis *et al.* 1997). It is difficult to define a zone of influence for use in a competition index for individual trees that includes all competitors and sources of competition for scarce resources.

Two major classes of competition indices have been developed: distance-independent and distance-dependent (Munro, 1974).

Distance-independent indices don't require spatial data whereas the distance-dependent indices use spatial data to simulate individual trees or their component parts (crowns, branches, etc.). Single tree spatial models use information about the distances and sizes of neighboring trees. The distance-dependent competition indices described in the literature can be divided into three groups:

1) Size-ratio

Size ratio indices calculate sums of ratios of subject tree dimensions to competitor tree dimensions. These ratios are often weighted by distances of the subject tree to its competitors. The most common tree dimensions used are diameter at breast height (DBH), total height, and basal area (the sum of individual tree cross-sectional areas). Hegyi's (1974) competition index is the most widely used size-ratio index which is calculated as in function (1).

$$CI = \Sigma\left(\frac{DBH\,j}{DBH_i} * \frac{1}{d}\right) \qquad (1)$$

Where CI is overall competition index of i^{th} subject tree, DBH_j is diameter at breast height of j^{th} competitor, DBH_i is diameter at breast height of subject tree and d is distance between j^{th} competitor and i^{th} subject tree. Size-ratio indices are useful for situations where there is uncertainty about the radius of the influence zone.

2) Crown or influence-zone overlap

Crown or influence-zone overlap indices evaluate competition from the amount of influence-zone overlap between competing trees. The influence-zone of a tree is defined as an area over which the tree obtains or competes for site factors (Opie, 1968). The following are some competition indices which belong to this category.

- Stabler's index (1951) is the sum of linear overlaps within competition circles.
- Newham's index (1966) used an angular measure, expressed as that proportion of the circumference of the competition circles that is overlapped by the circles of competitors.

- Opie (1968) and Gerrard (1969) evaluated competition effect directly from the area of influence-zone overlap relative to the total influence-zone of the subject tree.

But the limitation of these models is that size differentiation between subject tree and its competitors was assumed to have no effect on competitive interactions.

3) Growing space or area potentially available indices

Growing space or area potentially available indices map the potentially area available to each tree, which is usually calculated by bisecting perpendicularly the distance between each tree and its neighbours, often using a weight according to tree size. The intersections of the bisectors form the corner points of the tree polygon. Moore *et al.* (1973) used tree basal areas to determine the location of the perpendicular bisectors.

A number of studies have compared various competition indices and their modifications (Daniels *et al* 1986; Tome and Burkhart, 1989) and reported variable results. Bigging and Dobbertin (1992) reported improvement in many of the traditional competition indices when crown parameters were incorporated in measurement of competition for ponderosa pine and Douglas fir.

In New Zealand Tennent (1975) used competition quotient based on area overlap indices and reported that competition quotient as useful concept for analysis of competition experienced by individual trees. Tennent, (1982) developed distance-dependent individual tree growth model for *Pinus radiata* and evaluated the effectiveness of several competition indices and reported that Gerrard's (1969) and Hegyi's, (1974) competition indices performed equally well in diameter, basal area and height increment models. Richardson *et al.* (1999) have evaluated various competition indices of interspecific plant competition between *Pinus radiata* and either buddleia (*Buddleija davidii* Francher) or broom (*Cytisus scoparius* L.), two important forest weed species in New Zealand. The best competition index combined measures of weed height relative to tree height, proximity of the weed to the tree, and weeds abundance, and was negatively correlated with an index of light availability.

2.8 Risks

Risk may be defined as the product of the probability of an adverse outcome and its severity or seriousness (Burdon and Aimers-Halliday, 2003). Every long term investment should be evaluated for risks because of long interval between investment and returns. In plantation forestry risks could be classified as biotic (from insect pests and diseases and wild animals) and abiotic (from environmental factors, future markets, poor management) that could lead to premature death, or slower-than-usual growth (Gadgil *et al*. 1995; Somerville, 1995). Burdon (2001) classified risks into biological (fungal diseases, insect damage, animal damage, and including climatic damage) and market risks (uncertainties of future markets). The risks of clonal forestry can be grouped under the following risk categories:

- Risks of reduced genetic diversity (biotic , market and climatic risks)
- Risks of clonal propagation, storage and low gains from breeding (technical risks)
- Risks of public acceptance and regulation (social and political risks).

Risks of reduced genetic diversity

Use of few species in plantations for timber production is perceived as a risk due to lack of diversity (Walsh, 1995). Many ecologists agree with the traditional diversity-stability hypothesis which states that more diverse communities will be more stable than less diverse ones. Goodman (1975) reviewed the development of this hypothesis and concluded that there is no simple relationship between diversity and stability in ecological systems and need more research in this area. Chou (1983); Sweet and Burdon, (1983) also questioned the theoretical basis of this hypothesis because of lack of clear evidence that outbreak of disease in pure stands can be ascribed to lack of species diversity.

Clonal forestry, which has many potential advantages for increased genetic gains and crop uniformity (Libby and Rauter, 1984; Carson, 1986; Burdon, 1989; Carson and Burdon, 1989; Lindgren, 1993; Kube and Carson, 2004; Sorensson and shelbourne, 2005), has been perceived to enhance the intensity of monocultures due to use of just a few good genotypes in plantations. Radiata pine has proved remarkably well suited to New Zealand conditions.

The dominant monoculture of radiata pine is considered vulnerable to risks stemming from reduced genetic diversity through large-scale clonal propagation and deployment (Burdon and Aimers-Halliday, 2003). A major risk to clonal plantations is considered as their vulnerability to insect-pest and diseases infestation. Minor incidences of *Sirex* attack and *Dothistroma* highlight the significance of biotic risks to monocultures of radiata pine (Gadgil *et al.* 1995; Walsh, 1995). Sharpe *et al.* (1986) reported that approximately 50,000 diseases are known to attack tree species. In New Zealand overall fungal diseases constitute a hazard that needs to be addressed (Gadgil *et al.* 1995; Ridley *et al*. 2005). There are uncertainties about what disease will arrive and how they would behave on arrival (Burdon and Aimers-Halliday, 2003). Use of few susceptible clones on large scale may intensify this problem.

Foresters in New Zealand have been warning of the dangers of large monocultural forests (Walsh, 1995). Opinions among the scientific community and foresters still differ about risks. Monoclonal plantings are considered more vulnerable to risks (Carson and Carson, 1989; Burdon, 1982; Zobel, 1992). Some researchers believe it is much easier to manage risks in monoclonal plantations. In their view mixed clonal plantations make it difficult to manage risks because if some severe insect-pest or disease attacks one or two clones in the mixture, the trees of that clone cannot be effectively salvaged by thinning and replanting. However, if grown in blocks, the clonal block that is damaged can be harvested early and replanted with some other resistant clone (Zobel, 1993). Lindgren (1993) argues that if a clone is planted over a large enough area and time, it may become more susceptible as the parasite adapts. If a clone is only a small part of the niche to which a parasite becomes adapted, the parasite will confront many genotypes and is unlikely to become specially adapted to a particular clone and a mix of clones can, depending on the biology of the pathogen, confer some epidemiological protection against disease (Burdon, 2001). The minimum number of clones deployed to a region must be larger than that used in a single plantation. A single event could eradicate a single clone. If a sufficient numbers of clones are used, that event may be less likely to lead to a regional disaster.

Although clonal forestry has a narrow genetic base, careful management of clone numbers and the way they are deployed can minimize pest and disease problems. Roberts and Bishir (1997) have suggested that use of 30-40 unrelated clones will generally provide security against catastrophic failure. Libby (1982; 1987b) suggested that mixtures of 7-30 unrelated

clones will be as safe as similar mixtures of large number of clones. Burdon (2001) suggested a mixture of 20 unrelated clones would be sufficient to manage risks. Many scientists agree that planting 15-30 clones mixed in plantations should be sufficient for protection yet still confer the benefits of clonal forestry, according to Park (2002).

Burdon, (1982) and Zobel *et al.* (1987) emphasised that problems arise when species, particularly exotics, are ill suited to a site. Silvicultural practices such as harvesting, site and species practices, thinning and pruning damage make stands prone to risks of insect pest and disease infestation (Gadgil *et al*. 1995; Chou, 1983).

Burdon (2001) suggested three risk management measures:

a) Risk avoidance: risk avoidance entails passive measures that involve tradeoffs between expected rate of return and level of risks, and active measures that involve breeding for disease resistance.
b) Risk spread: this approach involves diversifying species deployed. This measure entails that the probability of simultaneous eventuation of the risks for all the species is lower than for the risks associated with any one species.
c) Response preparation: this approach involves long term strategies to take corrective action after an eventuality.

Market risks of clonal forestry comprise the sale-ability of planting stock, risks due to propagation failure and unwanted intraclonal variation (Aimers-Halliday and Burdon 2003; Burdon and Aimers-Halliday 2003). Use of very small numbers of clones can intensify the risks of demand for particular traits or wood qualities.

Climatic damage can be more predictable than certain biotic risks (Aimers-Halliday and Burdon, 2003). Throughout the life of a stand of trees, there is exposure to physical damage, primarily from climatic factors such as wind, snow, frost and fire. These risks can be addressed by deployment of resistant site-specific species or genotypes, and adopting suitable mode of deployment (monoclonal or clonal mixture).

Wind is the main physical risk factor to New Zealand's softwood plantations (Somerville, 1995). The wind damage includes stem leader breakage, wind-throw, toppling and butt log

malformation largely resulting from severe lean. On topple prone sites deployment of physiologically aged cuttings or planting stock that have balanced root system can mitigate this problem (Aimers-Halliday and Burdon, 2003).

High snow loadings can also lead to topple and stem and branch breakage. Choice of species, for instance Douglas-fir that is considered to be more wind stable and tolerate to snow loading than radiata, the deployment of such species on risk prone sites might mitigate the risks of financial losses (Somerville, 1995).

Frost is another important climatic risk factor. Most New Zealand sites experience frosts from late autumn through early spring. Deployment of resistant planting stock, keeping the site weed free and planting at the end of winter when seedlings are harder and the most severe frosts are over can help to manage risks from frost damage (Somerville, 1995).

Risks of clonal propagation, storage, inadequate evaluation and low gains from breeding

These risks include failure in part of a population in propagation and clonal storage systems that would result in wastage of resources invested in selection and testing of clones, loss of genetic gain and loss of genetic diversity in production population, risks associated with unwanted variation within clones due to somaclonal variation and differential maturation effects which will compromise commercial acceptability of planting stock, risks of inadequate evaluation which include short duration of clonal tests, lack of buffering against genotype x environment interaction that may result in change in clonal rankings (Aimers-Halliday and Burdon, 2003). Kube and Carson (2004) identified the following risks factors relevant to clonal forestry:

- Incorrect choice of species or provenances for breeding population development may result failure of breeding programs.
- Developing incorrect definitions of breeding goals without considering the appropriate traits to be improved and demand for future products and markets may result in lower economic returns.
- Inappropriate mating designs may result in loss of time, resources and slow capture of genetic gains.

- Gains from breeding programs are calculated from estimates of heritability, genetic variance, genetic correlations both among traits and between juvenile and mature trait expression, and genotype x environment interaction. Incorrect estimates of these parameters may result in biased estimates of gains.
- Human error in mislabeling of breeding material, degradation of tags and vandalism may result in unwanted error in clonal selection trials (Aimers-Halliday, 2003).

Risks of public acceptance and regulation

Risks may arise from public perceptions of what is environmentally sound or ethically acceptable, they involve issues such as rights and wrongs of species monocultures, clonal forestry or genetic engineering (Burdon, 2001; Aimers-Halliday and Burdon, 2003; Kube and Carson, 2004). Public concern about clonal forestry originates from the mistrust concerning Man's attempts in manipulating nature by planting clones instead of planting seedlings or natural regeneration (Stelzer and Goldfarb, 1997). Restrictive government legislation for clonal deployment is a related, important risk. The governments of some European countries have enforced the use of clonal mixtures and have specified minimum numbers of clones to be used in conifer plantations (Muhs, 1993). Such strict restrictions might limit the acceptance and further development of clonal forestry resulting in lower genetic gains. In order to promote the acceptance of clonal forestry it is required to publicize and demonstrate the benefits of clonal forestry to general public, foresters, conservationists and industry people by planting of well planned and long term demonstration plots (Stelzer, 1997).

2.9 Summary of literature review

This review of relevant literature has highlighted some key issues that are very important for plantation forestry in general and clonal forestry of radiata pine in particular.

- A need for development of standards of morphological or physiological indicators of quality of micro-propagated planting stock of radiata pine for different site conditions.

- Evaluation of clonal selection methods, such as contrasting the effectiveness of single tree plot versus block plots may improve clonal screening programmes.
- There is also a need for evaluation of various modes of clonal deployment particularly in long rotation species to provide managers information regarding productivity, uniformity and risks of each mode of deployment to help them make decisions about the mode of deployment for their plantations.
- The monoclonal mode of deployment requires the development of stand level models for clonal plantations and evaluation of effectiveness of mensuration-based or process-based models in predicting long term productivity of monoclonal stands.
- There is a need to evaluate effectiveness of competition indices in distance-dependent growth models and development of competition indices that can be helpful to evaluate the influence of genotypes on growth or productivity of other genotypes to identify the strong competitors.
- There is also a requirement to evaluate effects of monoclonal and clonal mixture modes of deployment on risks of insect-pest and disease infestation and wind or snow damage.

Most of these issues are related to mode of clonal deployment, and the study reported here was designed to compare the development of clones in two modes of deployments *i.e*. monoclonal and clonal mixture.

2.10 Design of the experiment

An experiment was established in order to meet the objectives outlined in Chapter 1.

The experiment was established with radiata pine on a site at Dalethorpe (latitude 42^{o}-45'S, longitude 171^{o}-55'E, elevation 520 m above sea level.), 70 km west of Christchurch, Canterbury, New Zealand in September 1993. The soil at the site was a well-developed silt-loam (NZ Soil Bureau, 1968). Mean annual precipitation was 1058 mm from 1993-2006 (NIWA, 2006). Precipitation was distributed fairly evenly throughout the year although a marked dry period can occur during February and March (McCracken, 1980).

In this experiment ten clones were deployed in two ways (monoclonal, clonal mixture) in a randomized complete block design with three replications. Each replication (block) had eleven treatments (ten monoclone plus one clonal mixture). In clonal mixture plots equal numbers of trees of all the clones were randomized. All plots were of rectangular shape (16 x 20 m), and contained 40 trees (5 x 8) except for one clonal mixture plot (64 x 20 m) that was larger (5 x 32 trees). Trees were spaced at 2 m within rows, and rows were spaced at 4 m (1250 stems/ha). The total area of the experiment was 1.15 hectares. No pruning or thinning treatments were applied to the experiment from 0-6 years. At age 7 years all trees were pruned to a height of 2.5 m. A common silivicultural regime in Canterbury is an initial stocking of 1250 stems per hectare thinned to 600 stems per hectare at ages 6-7 years (MAF, 2005; SPBL, 2006). Thinning was not carried out in this experiment and a stocking of 1250 stems/ha was maintained unless mortality reduced it.

Ten clones (1-10) were planted in this experiment. Clones 3, 7 and 10 were propagated from different seeds of same cross. Clones 1 & 9 and clones 6 & 8 were also propagated from different seeds of each of two crosses. Clones 2, 4 and 5 were from three different crosses. Clones deployed in this experiment therefore represented six different families. The exact pedigrees of the clones were not revealed by the organization that provided the clones for this experiment, although they were said to have growth and form ratings between 25 and 30 (Sorensson, personal communication). Clones were propagated by organogenesis from controlled pollinated mature seeds that were surface sterilised and germinated into sterile tissue cultures. After propagation they were hardened off in a nursery in the North Island at the Fletcher Challenge Forests Ltd. Biotechnology Centre, TeTeko, with an undercutting and wrenching regime, and then were transplanted as bare-root plants.

All the plants were planted in pits of 30 cm depth in ripped lines with ripping at a depth of 30 cm. Each planting spot was further cultivated with a spade. Each randomised complete block was planted by only one person. All the plots were kept completely weed free using initially a mixture of Hexazinone and Turbuthylazine, and subsequently a mixture of Turbuthylazine, Clopyralid and Haloxyfop herbicides for 5 years following planting.

All 18 interior trees in each 40-tree plot in a 12 x 12 m zone (plus the 90 interior trees in the big clonal mixture plot) were measured leaving a single boundary row of trees to

exclude affects of inter-genotypic interactions. Height poles, and later Vertex hypsometers, and diameter tapes were used to measure tree heights and diameters at breast height over bark (DBH) with the precision of 10 cm and 0.1 cm respectively. Tree heights were recorded from establishment year 1993 to 2006. DBH (1.4 m) was recorded from 1997 to 2006 except years 2001 and 2002. Assessments were recorded every winter between second fortnight of August and the first week of September when tree stem growth more or less stops in Canterbury. Mortality, windthrow, stem damage, and any pathogen infections were noted every year at the time of making other assessments.

At age 5 years (1998), three trees each of four clones (clone 4, 6, 9 and 10) having different growth patterns were destructively sampled and foliage, branch, and stem oven-dry biomasses were recorded. At age 11 years (2004), 30 clonal trees (4 of clone 1, 5 of clone 2, 5 of clone 3, 6 of clone 6, 4 of clone 7, 5 of clone 8 and 1 of clone 10) of genetically identical clones were destructively sampled *in an adjoining experiment* established on the same date, but at stockings of 833 and 2500 stems/ha. The foliage, branch and stem oven-dry biomass were recorded. The specific leaf areas of new and old (>1 year age) needles of destructively sampled clones were also estimated at ages 5 and 11 years. Leaf area index (LAI) was measured at age 13 years (2006) for each plot using a plant canopy analyser (LAI-2000) instrument, as prescribed in its instruction manual (LICOR, 1991). Time-of-flights were recorded using the non-destructive acoustic wood quality measurement tool TREETAP version 4, developed at the University of Canterbury, Christchurch, New Zealand, over a 1.300-m path length, with start and stop probes placed at 0.3 and 1.6 m above the base of each tree. Eight repeated sonic measurements on each side (windward and leeward) of the standing trees were made through bark on each stem at age 13 years (2006). In total, 467 trees in monoclonal and 105 in clonal mixture plots were "tapped". Height of live crown was also measured at age 13 years (2006) using Vertex hypsometers. The measurements recorded every year on trees of clones in monoclonal and clonal mixture plots were used to compare productivity; growth; development of initial growth and survival, individual tree and stand level models; evaluation of morphological indicators of initial growth and survivals; evaluation of effectiveness of mensuration-based and process-based yield models, and evaluate influence of mode of deployment on stem wood stiffness and stem form.

CHAPTER 3

IMPACT OF PLANTING STOCK QUALITY ON INITIAL GROWTH AND SURVIVAL OF RADIATA PINE CLONES AND MODELLING INITIAL GROWTH AND SURVIVAL

3.1 Abstract

The effectiveness of several morphological characteristics of planting stock as indicators of field performance was assessed in an experiment established with ten radiata pine clones at Dalethorpe, Canterbury, New Zealand. Greater initial heights of three clones resulted in transplant stress. Sturdiness was the best predictor of survival in a plot level analysis and initial heights were the best predictors of survival during the first year after planting in an individual tree level analysis. Morphological differences between clones resulted in differences in survival up to age 4 years. Overall variability in height and diameter at breast height over bark at age 4 years was more in clonal mixture plots compared to monoclonal plots.

3.2 Introduction

Good quality of seedlings is a prerequisite for successful establishment (Ritchie, 1984; Bernier *et al*. 1995). The quality of planting stock is defined as "fitness for purpose", which for a seedling is its ability to survive and then grow rapidly when planted in the field (Duryea, 1984; Ritchie, 1984). The quality of planting stock is often assessed by morphological measurements such as shoot height, stem diameter (South *et al.* 2001), and shoot-root ratio or physiological characteristics such as root growth potential, root starch levels, root water potential, drought hardiness and frost hardiness. Sometimes

combinations of morphological and physiological measurements are used (Duryea, 1984; Menzies, 1988). Nursery growers usually use morphological characteristics to describe the quality of planting stock because of ease of measurement and influence of the morphological characteristics on the physiological states of planting stock (Thompson, 1985).

Genotype, transplant stress, and initial survival of planting stock jointly affect productivity, but these factors are rarely studied together in designed experiments. Initial survival and growth of planting stock depend upon quality of planting stock, care during plant transport between nursery and planting site, establishment practices, soil and climatic conditions, and their interactions. Young bare-root seedlings are prone to physical damage due to planting systems that comprise seedling lifting, packaging, transporting and placement (Mason and Trewin, 1987; Burdett, 1990). Physical damage of roots during lifting and moisture loss during transportation and storage sometimes lead to death of damaged roots and cause transplant stress. Moisture and nutrient status of a site at the time of planting also affect the growth and survival of seedlings (Burdett, 1990). So interactions between genotype, seedling state and site conditions might contribute to establishment success, and seedling state is often assessed using morphological measurements.

Several studies have addressed effects of morphological characteristics of seedlings on survival and growth. Anstey (1971) reported that radiata pine field growth and survival were greater with greater initial diameter. Pawsey (1972) reported that survival of *Pinus radiata* in the field was independent of seedling size whereas growth rate during the early years was found to be influenced by initial size of the seedlings. South *et al*. (1985) reported that survival of loblolly pine seedlings of root-collar diameter greater than 4.7 mm was significantly greater than seedlings of initial root-collar diameter of less than 1.6 mm and volume production at age 13 years was 17.5 percent greater than seedlings of initial root-collar diameter of 3.2-4.7 mm. Mason *et al*. (1996) reported that seedling ground-line diameter (GLD) was best correlated with tree performance of radiata pine seedlings at one site while GLD squared x height was most significant at another. Mason (2001) included GLD as a predictor of survival and growth of radiata pine in a juvenile growth model, and GLD was found to be most influential when environmental conditions were harsh.

Tuttle *et al.* (1987) reported that initial height of loblolly pine seedlings (1+0) was inversely related to total seedling height growth during the first two seasons, and a "Transplant Stress Index" (TSI) comprising the slope of the height growth versus initial height regression has been proposed as an indicator of moisture stress following planting (South and Zwolinski, 1997). The negative slope indicates the plants are experiencing planting check. For dry soil conditions a low shoot: root ratio (1.5 to 2.5) is viewed as desirable for bareroot stock (Thompson, 1985; Bernier *et al.* 1995) to promote survival.

Genotype may interact with initial management factors, and the study reported here set out to examine the effect of genotype and plant morphology on survival and growth of radiata pine after planting in an experiment designed to compare block plantings of clones with the same clones in mixture. The study had the following objectives:

- To compare morphologies of different micro-propagated radiata pine clones.
- To identify the best morphological predictors of initial growth and survival of the clones and compare these between genotypes.
- To develop initial height and ground-line basal area models for the clones.
- To compare stand structure of monoclonal and clonal mixture plots.

3.3 Materials and methods

3.3.1 Site

An experiment was established with radiata pine (*Pinus radiata* D. Don) clones on a site at Dalethorpe (latitude 42^{o}-45'S, longitude 171^{o}-55'E, elevation 520 m a. s. l.), 70 km west of Christchurch, Canterbury, New Zealand in September 1993. The soil at the site was well-developed silt-loam (NZ Soil Bureau, 1968). Mean annual precipitation was 1058 mm from 1993-2006 (NIWA, 2006). Precipitation was distributed fairly evenly throughout the year although a marked dry period can occur during February and March (McCracken, 1980).

3.3.2 Design of the experiment

The ten clones were deployed in two modes of deployment (monoclonal and clonal mixture) in a complete randomised block design with three replications. Each block thus comprised eleven treatments: Each monoclone and the clonal mix contained all ten clones randomised in equal proportions. All plots were of rectangular shape (16 x 20 m), and contained 40 trees (5 x 8) except for one clonal mixture plot (64 x 20 m) that was larger (5 x 32 trees). Trees were spaced at 2 m within rows, and rows were spaced at 4 m which produced a stocking of 1250 stems/ha. The total area of the experiment was 1.15 hectares, which comprised 9600 sq m of monoclonal plots and 1920 sq m of clonal mixture plots. The only silviculture applied to the trial was a pruning to 2.5 m at age 7 years. A common silivicultural regime in Canterbury is an initial stocking of 1250 stems per hectare thinned to 600 stems per hectare at ages 6-7 years (MAF, 2005; SPBL, 2006). Thinning was not carried out in this experiment and a stocking of 1250 stems/ha was maintained unless mortality reduced it.

3.3.3 Planting material

Clones were propagated by organogenesis from controlled pollinated mature seeds that were surface sterilised and germinated into sterile tissue cultures. After propagation they were hardened off in a nursery, conditioned with an undercutting and wrenching regime, and field-transplanted as bare-root plants. Ten clones (labelled 1 to 10) were planted in this experiment, derived from control-pollinated crosses. Clones 3, 7 and 10 were propagated from different seeds of same control-pollinated cross and were “full-sibs”. Clones 1 & 9 and clones 6 & 8 were propagated from different seeds of each of two crosses. Clones 2, 4 and 5 were from three additional crosses. Clones deployed in this experiment therefore represented six different families. The exact pedigrees of the clones were not revealed by the organization that provided the clones for this experiment, although they were said to have growth and form ratings between 25 and 30 (Sorensson, personal communication). Overall initial size of the plants varied from 11 to 49 cm in height and 4 to 13 mm in ground-line diameter (GLD).

3.3.4 Establishment practices

All the plants were planted in pits of 30 cm deep in ripped lines with ripping at a depth of 30 cm. Each planting spot was further cultivated with a spade. Each randomised complete block was planted by only one person. All the plots were kept completely weed free using initially a mixture of Hexazinone and Turbuthylazine, and subsequently a mixture of Turbuthylazine, Clopyralid and Haloxyfop herbicides for 5 years following planting.

3.3.5 Assessments

Leaving buffer lines between the plots, the height and ground-line diameter of 18 individual trees in each plot, and 90 trees in the one big clonal mixture plot were recorded from establishment in year 1993 to 1996, and height and diameter at breast height over bark (DBH) from 1997 to 2006. Ground-line basal areas per hectare were calculated for each plot from 1993 to 1996. Observations regarding insect-pest or disease attack if any were recorded.

Transplant stress indices (TSI) proposed by South and Zwolinski (1997), defined as the "slopes of the linear relationships between shoot height at the beginning of the growth period and height increment", were calculated for each clone at the end of the first year. Percent survivals and coefficients of variation in heights for ages 1 to 4 years were calculated for each clone from plot data.

At time of planting ten individuals of each clone were randomly selected for destructive sampling. Initial heights and initial diameters of these plants were recorded. Destructively sampled plants were separated into shoot, foliage and root components. These components were oven-dried and then weighed.

Root-fibrosity, which is the ratio of fine roots biomass to total root biomass, was calculated for each clone from the destructively sampled plants. To calculate individual tree shoot biomass, foliage biomass, root biomass and root-fibrosity of the other plants, nonlinear relationships between individual heights and shoot biomass, foliage biomass, root biomass and root-fibrosity were developed from destructively sampled plant data. Initial heights

and initial diameters were both tried as independent variables in these nonlinear relationships. Initial heights were chosen to develop the relationships because initial heights gave better fits than initial diameters. Values of the parameters of the relationships were used to estimate the individual tree foliage, shoot, root biomass and root-fibrosity of trees planted in the experiment and clonal values were calculated from plot data. The biomass relationships were of the form:

$$M = \alpha Y^{\beta} \quad (1)$$

Where M = mass of foliage or shoot or roots or root-fibrosity, Y = height from ground level and α & β were parameters of the relationships.

Shoot: root ratio, foliage: shoot ratio and sturdiness were calculated as outlined in the next section.

3.3.6 Variables estimated

Proportions of above ground parts, particularly foliage, and below ground roots are important from a water balance perspective. Shoot: root ratio is used as an indicator of drought avoidance potential of seedlings (Bernier *et al.* 1995) and sturdiness as a measure of resistance to out-planting shock (Menzies, 1988). Shoot: root ratios, foliage: shoot ratios and sturdiness were calculated for each plant as follows.

$$Sturdiness = \frac{Height\ after\ planting}{GLD\ after\ planting} \quad (2)$$

$$Shoot - Root\ Ratio = \frac{Shoot\ \ biomass}{Root\ \ biomass} \quad (3)$$

$$Foliage - Shoot\ Ratio = \frac{Foliage\ \ biomass}{Shoot\ \ biomass} \quad (4)$$

Values for each clone were calculated from plot data.

3.3.7 Data analysis

Procedure GLM (General linear models) of SAS (SAS Institute Inc. 2000) was used for analysis of variance to find out whether clones differed significantly in initial heights, ground-line diameters, diameters at breast height over bark (DBH) at age 4 years, survivals at ages 1 and 4 years, shoot: root ratios, foliage: shoot ratios, sturdiness and root-fibrosity at time of planting. The Student-Newman-Keuls (SNK) multiple range test was used at P=0.05 to distinguish differences between clones. The smallest critical range of SNK test was used as measure of statistical power for each variable. Initial heights and initial diameters were used as covariates in analysis of covariance to find out whether clones differed in sturdiness, shoot: root ratio, root fibrosity and survivals at age 4 years.

A further analysis of survival was conducted using a logistic regression procedure, testing various morphological measurements and combinations thereof as predictors of individual tree death during the first year following planting. Clone was tested as a class variable in this procedure once a model including morphological measurements had been constructed.

Linear contrasts were used during the analysis of variance to compare the overall heights, diameters and coefficients of variation in heights and diameters at the time of planting and at age 4 years in both monoclonal and clonal mixture plots.

Regressions were developed from individual tree data between height increments at age 1 year and initial heights after planting to estimate a transplant stress index (TSI) for each clone at the level of the entire experiment. There were too few plants in each plot for TSI to be calculated reliably within plots. South *et al.* (2003) noted that large numbers of seedlings in each experimental unit are required in order to reliably estimate TSI.

Procedure NLIN (nonlinear) of SAS was used to fit initial height and ground-line basal area yield models for each plot up to ages 4 and 3 respectively. Ground-line basal area was modelled than ground-line diameter, because ground-line basal area also takes into account the stand stocking. The mean height function (Mason and Whyte, 1997) used was as follows:

$$H_t = H_0 + \alpha T^{\beta} \qquad (5)$$

Where H_t = mean height at stand age T, H_0 = mean height after planting, T = stand age and α & β were estimated coefficients.

The equation fitted to mean ground-line basal area data was as follows:

$$G_t = G_0 + \alpha T^{\beta} \quad (6)$$

Where G_t = mean ground-line basal area at stand age T, G_0 = mean ground-line basal area after planting, T = stand age and α & β were estimated coefficients.

The Student-Newman-Keuls multiple range test was conducted to analyse the parameters of models fitted to individual plots.

For the survival model, initial heights and diameters, sturdiness, shoot: root ratios, foliage: shoot ratios and root fibrosity were tried as predictors of survival at age 4 years. Plot data were used for the survival model. A linear model gave a better fit to survival data than nonlinear models tried.

$$Y = \alpha + \beta_0 X_0 \quad (7)$$

Where Y = plot survival at age 4 years, and X_0 was predictor variable.

Residual analysis was also carried out to check goodness of fits of initial growth and survival models. Plots of observed values – predicted values (hereafter called "residuals") versus predicted values, and residuals versus independent variables were inspected for bias, and the SAS procedure UNIVARIATE was employed with "normal" option and the Shapiro-Wilkes test was used to test for normality of residuals. Correlations between various tree morphological variables were also examined to identify the best predictors of survival at age 4 years.

Discriminant analysis, which is used to separate two or more groups on the basis of analysing several variables simultaneously (Manly 1986) was carried out on parameters of

initial height and initial ground-line basal area models fitted to each plot. Lower values of canonical discriminant functions indicated poorer performance. Separation in growth behaviours was evaluated by plotting values of canonical discriminant functions 1 and 2 calculated for each plot.

Foliar nutrients (Phosphorus, Potassium, Calcium, Magnesium, Nitrogen, Mangnese and Potassium: Magnesium ratio) status at age 4 years were analysed to evaluate effects of nutrients status on initial productivity of clones.

3.4 Results

3.4.1 Initial morphology of planting stock

Clones differed significantly in initial heights (P=0.0567, according to the smallest critical range of the SNK test), ground-line diameter (P=0.0055), shoot: root ratio (P<0.0001), sturdiness (P=0.001) and root-fibrosity (P<0.0001) at time of planting (Tables 3.1 and 3.2). Clones did not differ in sturdiness when a separate analysis of covariance was performed using initial heights and initial diameters as covariates.

Table 3.1: Mean sizes of clones at age 1 and age 4 years. Values in each column followed by the same letter are not significantly different according to the SNK (Student-Newman-Keuls multiple range) test (P<0.05). In the table variables are mean heights after Planting (MH0), mean heights at age 4 years (MH4), mean ground-line diameters after planting (MD0), mean diameters at breast height over bark at age 4 years (MD4). In monoclonal plots 540 trees and in clonal mixtures 126 trees were measured.

Clone	MH0 (m)	MH4 (m)	MD0 (cm)	MD4 (cm)
1	0.25 c	2.71cde	0.62 b	4.29 bcde
2	0.28 abc	3.13 bc	0.77 ab	4.92 bcd
3	0.25 c	2.54 e	0.73 b	3.97 cde
4	0.25 c	3.38 b	0.69 b	5.35 b
5	0.26 bc	3.03 bcd	0.72 b	5.03 bc
6	0.27 bc	2.62 de	0.86 a	3.86 de
7	0.33 ab	2.87cde	0.66 b	4.77 bcde
8	0.28 abc	2.93 cde	0.68 b	4.33 bcde
9	0.28 abc	3.74 a	0.71 b	6.51 a
10	0.35 a	2.46 e	0.67 b	3.76 e
SNK Critical range	0.07-0.11	0.32-0.54	0.09-0.17	0.71-1.21

Table 3.2: Mean values of morphological indicators shoot-root ratios, sturdiness, root-fibrosity and foliage-shoot ratio for each clone. Values in each column followed by the same letter are not significantly different according to the SNK (Student-Newman-Keuls multiple range) test (P<0.05). In monoclonal plots 540 trees and in clonal mixtures 126 trees were measured.

Clone	Shoot : Root	Sturdiness	Root Fibrosity	Foliage : Shoot
1	5.60 c	42.17 bc	0.77bc	0.80 ab
2	4.41 e	37.45 c	0.74 cd	0.76 b
3	4.10 e	34.62 c	0.90 a	0.75 b
4	5.50 c	38.80 c	0.92 a	0.88 ab
5	4.84 d	36.71 c	0.90 a	0.81 ab
6	7.20 a	34.65 c	0.89 a	0.86 ab
7	5.28 c	52.40 ab	0.80 b	0.90 a
8	6.17 b	41.87 bc	0.91 a	0.82 ab
9	5.45 c	40.19 c	0.69 d	0.81 ab
10	4.12 e	54.80 a	0.73 cd	0.86 ab
SNK critical range	0.41-0.70	8.76-14.16	0.05-0.08	0.11-0.19

3.4.2 Transplant Stress

Negative values of TSI (Table 3.3) for clones 2, 7 and 10 suggested that these clones faced more severe transplanting stress during first year of their growth than the other clones did.

Table 3.3: Mean survival of clones at ages 1 and 4 years. Values in each column followed by the same letter are not significantly different according to the SNK (Student-Newman-Keuls multiple range) test (P<0.05). In the table TSI is transplant stress index and CVH0 & CVH1 are coefficient of variation for heights at the age 0 (just after planting) and 1 year respectively. In monoclonal plots 540 trees and in clonal mixtures 126 trees were measured.

Clone	Survival age 1	Survival age 4	TSI	CVH0	CVH1
1	100 a	100 a	0.18	19.43 a	24.63 a
2	98.15 a	96.30 a	-0.17	18.97 a	16.83 a
3	100 a	100 a	0.17	21.16 a	21.98 a
4	98.15 a	98.15 a	0.24	20.34 a	22.96 a
5	100 a	100 a	0.01	15.25 a	21.20 a
6	100 a	100 a	0.51	19.86 a	24.11 a
7	83.33 b	81.48 b	-0.28	15.35 a	23.06 a
8	100 a	100 a	0.33	18.89 a	22.76 a
9	100 a	100 a	0.46	22.67 a	23.62 a
10	96.3 a	90.74 ab	-0.12	21.10 a	23.25 a
SNK critical range	10.27-17.53	9.76-16.65	-	8.91-15.16	9.4-16.04

3.4.3 Initial height growth

Clone 9 grew more rapidly than other clones followed by clone 4 during the establishment period (Figures 3.1 and 3.2). Slight interchanges in ranks were found at age 3 years. Clones significantly differed in height (P<0.0001) at age 4 years. Clones 3 and 10 were the shortest clones at age 4 years. Clone 3 grew very slowly both in monoclonal and clonal mixture plots. Foliar nutrient analysis at age 4 years revealed that nutrients did not limit growth of clones except for clone 3 which exhibited Magnesium and Boron levels lower than critical levels (Appendix I) of these nutrients for radiata pine. Low levels of these nutrients might have affected growth of clone 3.

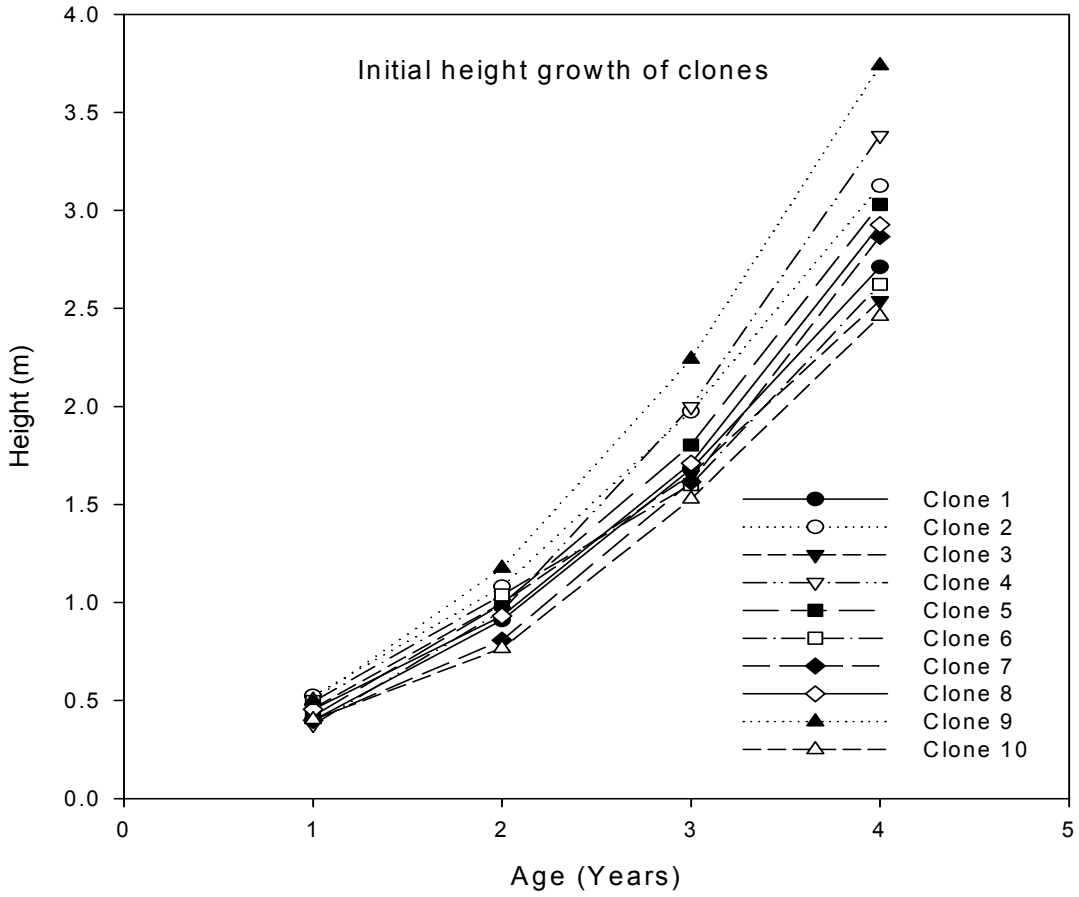


Figure 3.1 - Initial height growth of clones in monoclonal plots.

Figure 3.2 – Differences in height growth between clones were obvious, with clone 9 in the monoclonal plot on the right and clone 2 in the mononclonal plot on the left in this image at age 3 years (photo – E. Mason, University of Canterbury).

3.4.4 *Initial height growth model*

Table 3.4 shows the mean parameters of the height equation (5) fitted for each plot. The residuals were mostly within ± 0.06 m of the model, and all were within ± 0.09 m. The fitted parameters differed significantly (P<0.0001) between clones (Table 3.4).

Table 3.4: Height and ground-line basal area after planting and mean parameters of the models of initial height and ground-line basal area fitted for clones. Values in each column followed by same letter were not significantly at 5% level according to SNK (student-Newman-Keuls multiple range) test. In monoclonal plots 540 trees and in clonal mixtures 126 trees were measured.

Clone number	H_0 (m)	Parameter estimates of height models		G_0 (m^2/ha)	Parameter estimates of ground-line stand basal area models	
		α	β		α	β
1	0.25 c	0.171881 a	1.920191 cde	0.039977 b	0.153163 a	3.067787 ab
2	0.28 abc	0.233481a	1.812689 def	0.061602 b	0.137566 a	3.308896 ab
3	0.25 c	0.230678 a	1.659253 f	0.054764 b	0.19825 a	2.833023 ab
4	0.25 c	0.165854 a	2.123754 bc	0.050489 b	0.115815 a	3.242054 ab
5	0.26 bc	0.180577 a	1.969448 cde	0.0544 b	0.157501 a	3.215549 ab
6	0.27 bc	0.216568 a	1.716661 ef	0.076047 a	0.198465 a	2.688468 b
7	0.33 ab	0.091386 b	2.40457 a	0.046361 b	0.094572 b	3.234431 ab
8	0.28 abc	0.154111 a	2.047293 bcd	0.048125 b	0.126538 a	3.140132 ab
9	0.28 abc	0.232895 a	1.961397 cde	0.053018 b	0.114166 a	3.636866 a
10	0.35 a	0.097037 b	2.246841 ab	0.046943 b	0.080102 b	3.435849 ab
SNK critical range	0.07-0.11	0.04-0.08	0.18-0.31	0.013-0.023	0.07-0.12	0.51-0.88

3.4.5 Initial ground-line basal area growth

Clone 9 grew most rapidly in ground-line basal area followed by clones 5 and 2 (Figure 3.3). Clones significantly differed (P=0.0007) in stand ground-line basal area at age 3 years. Clones 7 and 10 had lowest ground-line basal area at age 3 years.

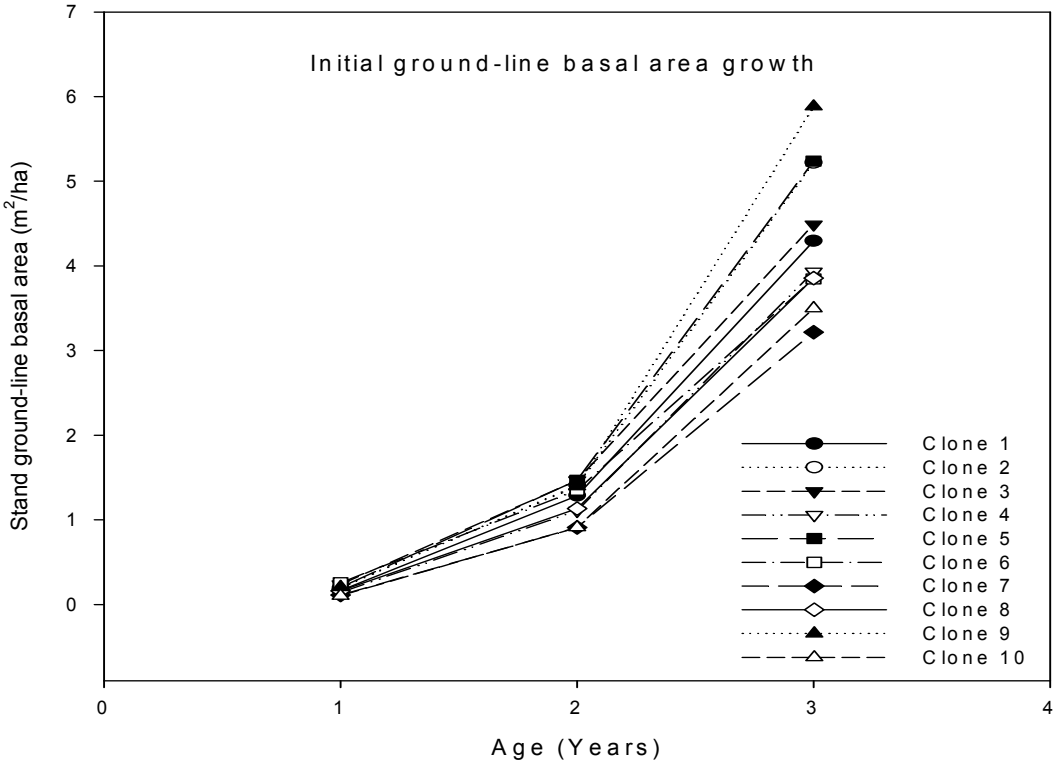


Figure 3.3 - Initial ground-line basal area growth of clones in monoclonal plots.

3.4.6 *Initial ground-line basal area model*

Table 3.4 shows the mean parameters of the ground-line basal area equation (6) fitted for each model. The residuals became smaller with age; at age 3 years they were within ± 0.1 m^2/ha of the predictions. The parameters α (P=0.027) and β (P=0.048) significantly differed among clones (Table 3.4).

Discriminant analyses of parameters of both fitted functions for each plot showed different groupings of clones (Figure 3.4). The first two canonical discriminant functions explained 67 and 27 percent of variation in data respectively. Greater positive values of canonical

function 1 indicated that clone 9 grew most rapidly, and greater negative values for clones 3 and 6 indicated that these clones grew slowly during the establishment period.

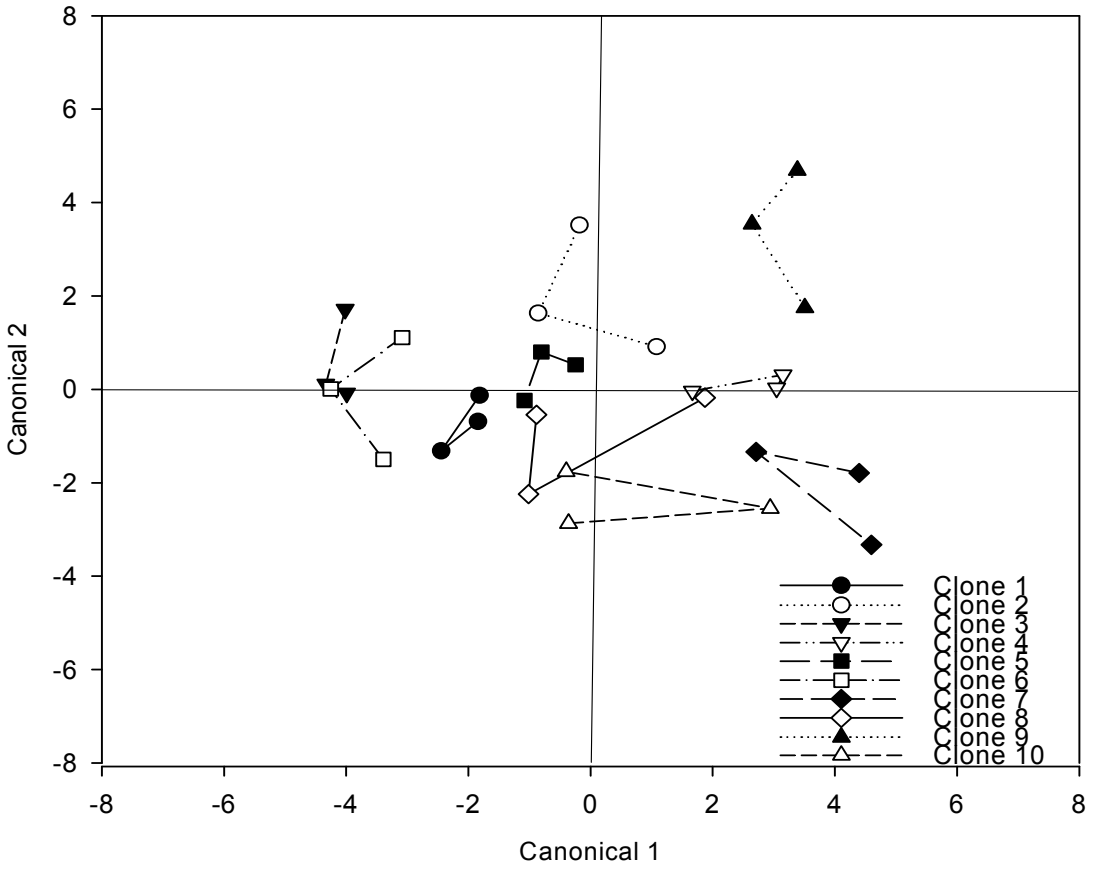


Figure 3.4 - Clonal groupings for initial growth based on canonical functions. Three points for each clone represent three different canonical values of canonical 1 and canonical 2 for three plots in different blocks.

3.4.7 Survival

Clones 2, 7 and 10 had lower survivals at age 1 compared to other clones and their survivals further decreased at age 4 years (Table 3.3). Clone 7 had the lowest survival of 81 percent at age 4 years (P=0.0122). These clones also tended to have more negative TSI values. Initial survival at age 1 and age 2 years was correlated with height growth rate at these ages with coefficient of correlation of 0.47 and 0.60 respectively (Table 3.5).

Table 3.5: Correlations between various variables studied. A higher value of sturdiness means less sturdy plants. In monoclonal plots 540 trees and in clonal mixtures 126 trees were measured. Plot values were used to develop these relationships.

Variables	Coefficient of correlation	Pr> IrI
Heights at planting and Survival at age 4 years	-0.577	0.0008
Heights at planting and Root fibrosity	-0.507	0.0042
Sturdiness at planting and Survival at age 4 years	-0.619	0.0003
Height growth rate at age 1 year and survival at age 1year	0.477	0.0076
Height growth rate at age 2 years and survival at age 2 years	0.609	0.0004

3.4.8 Survival model

Sturdiness and mean initial heights of planting stock as individual factors were weakly correlated to plot-level survival at age 4 years with r^2 values of 0.38 and 0.33 respectively (Table 3.6, Figure 3.5). Clone was not significant when added as an independent variable in the survival model (8) once morphology was represented in the model. Residual analysis was conducted to examine the goodness of fits (Figures 3.6 and 3.7).

$$Y = \alpha + \beta_0 x_0 + \beta_1 x_1 \quad (8)$$

Where Y = plot survival at age 4 years, and x_0 and x_1 were sturdiness or initial heights and clone as independent variables.

Table 3.6: Effectiveness of various predictors of survival in survival model. In monoclonal plots 540 trees and in clonal mixtures 126 trees were measured. Plot values were used in this analysis.

Predictor variable	r^2	Intercept	Pr> ItI	Predictor	Pr> ItI
Initial Heights	0.33	123.06	<0.0001	-94.38	0.0008
Initial Diameters	0.02	87.26	<0.0001	13.22	0.4532
Sturdiness	0.38	121.18	<0.0001	-0.59	0.0003
Shoot: root ratio	0.06	85.66	<0.0001	2.08	0.1585
Root fibrosity	0.05	80.21	<0.0001	19.95	0.2166
Foliage: shoot ratio	0.03	112.08	<0.0001	-18.69	0.3483

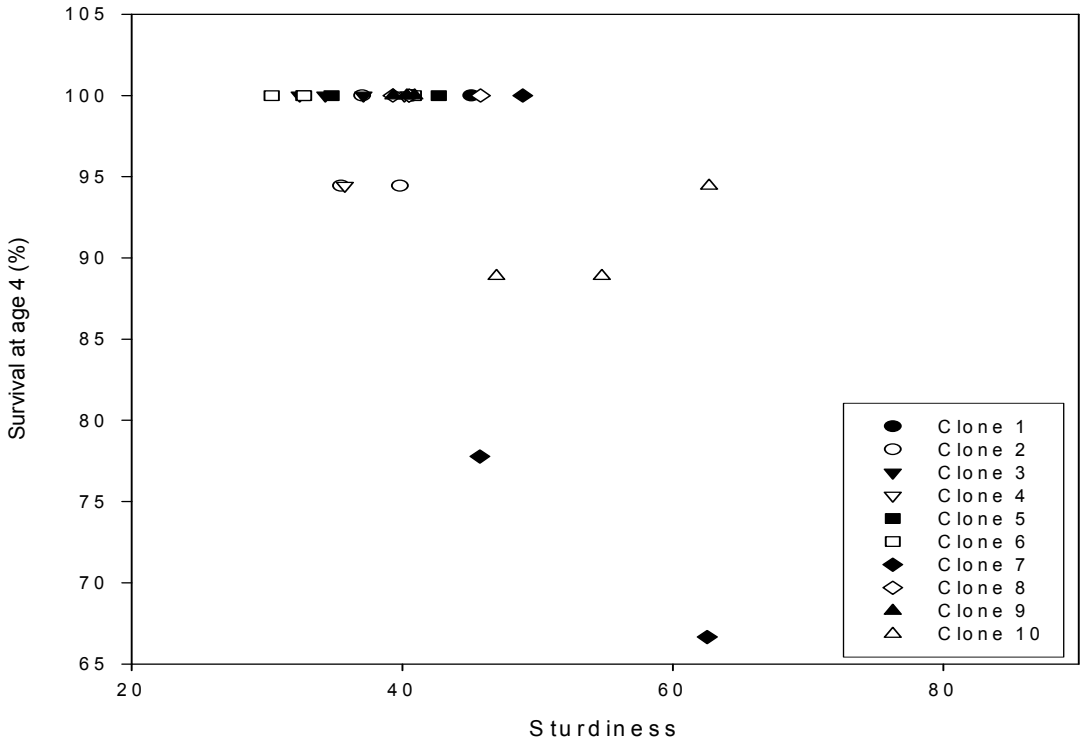


Figure 3.5 - Sturdiness at planting versus survival of radiata pine plants at age 4 years calculated from plot data. Three points for each clone represent three different values for three plots in different blocks.

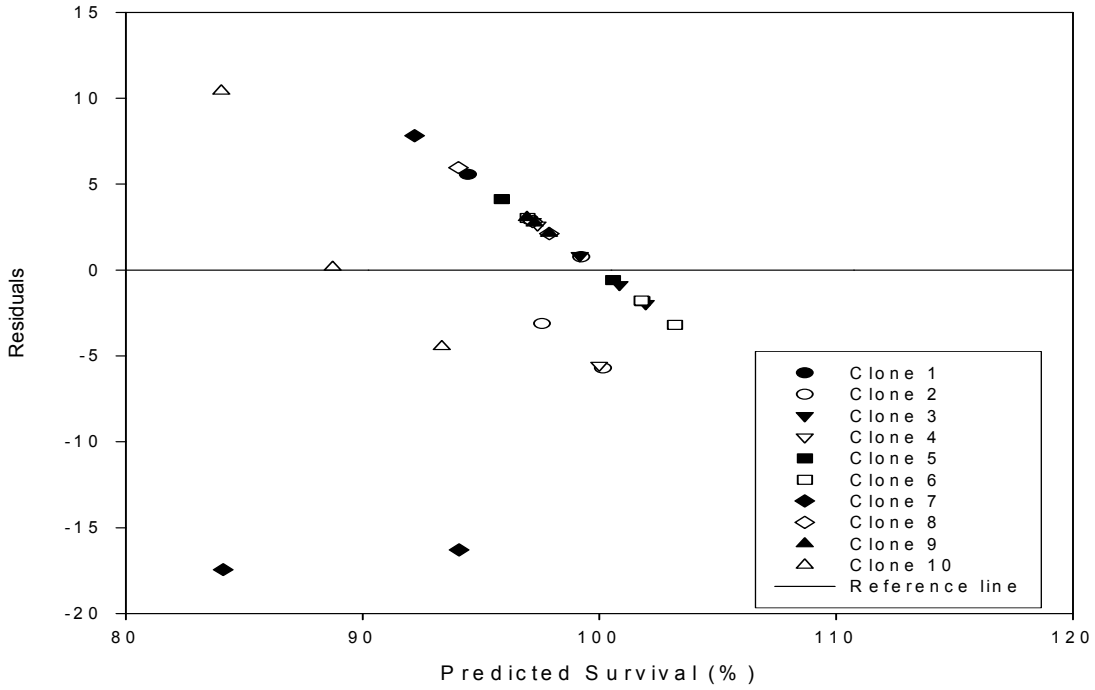


Figure 3.6 - Plot of residuals versus predicted survival of radiata pine plants at age 4 years. Three points for each clone represent three different values for three plots in different blocks.

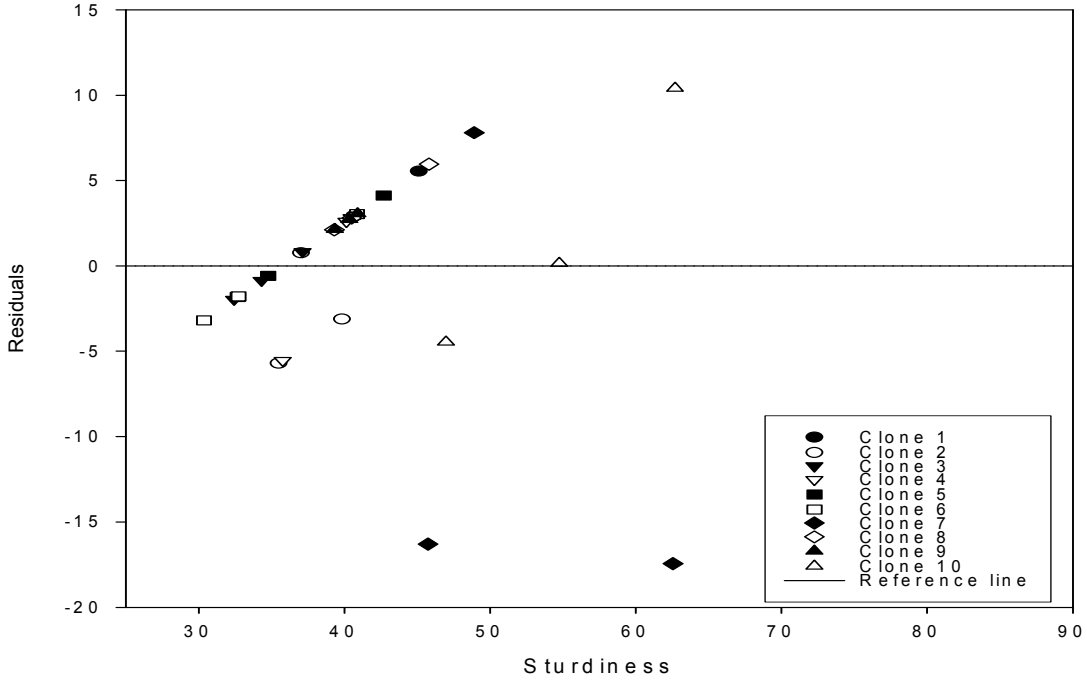


Figure 3.7 - Plot of residuals versus sturdiness of radiata pine plants at the time of planting. Three points for each clone represent three different values for three plots in different blocks

The logistic procedure revealed that height at time of planting was the best predictor of individual tree death, with taller trees at time of planting being more prone to mortality ($P<0.0001$). The concordance of this model was 76% and the discordance was 20%. Neither other morphological measurements nor clone were significant as additional terms in the model.

3.4.9 Clones in monoclonal versus clonal mixture plots

There were no significant differences in overall initial heights ($P=0.27$), diameters ($P=0.27$), and variations in heights ($P=0.13$) and diameters ($P=0.32$) at the time of planting between monoclonal and clonal mixture plots. At age 4 years mode of deployment did not affect sizes, but significantly more variations in overall height ($P=0.004$) and diameter ($P=0.001$) were found in clonal mixtures compared to monoclonal plots (Table 3.7).

The analysis revealed that greater initial genotypic variability within a plot led to significantly greater later variability (measured as coefficient of variation (CV)) in heights ($P=0.0041$) and diameters ($P=0.0012$) at age 4 years in the clonal mixture plot compared to monoclonal plots (Table 3.7).Values followed by different letters under columns CV Height and CV Diameter at age 4 years in table 3.7 represent significant differences between monoclonal and clonal mixture plots. Variability in tree sizes within clones didn't differ with mode of deployment at age 4 years (Table 3.8) indicating that between tree competition wasn't evident by age 4 years.

Table 3.7: Comparison of overall sizes and coefficient of variation (CV) of heights and diameters of monoclonal versus Clonal mixture plots at time of planting (Age 0) and at age 4 years. Values in each column followed by same letter were not significantly at 5% level according to minimum critical value of SNK test. In monoclonal plots 540 trees and in clonal mixtures 126 trees were measured.

Clone or Plot	Mean Height		Mean Diameter		CV Height		CV Diameter	
	Age 0	Age 4	Age 0	Age 4	Age 0	Age 4	Age 0	Age 4
1	0.25 c	2.71 cde	0.62 b	4.29 bcde	19.43 a	13.50 b	22.63 a	25.90 abc
2	0.28 abc	3.13 bc	0.77 ab	4.91 bcd	18.97 a	11.20 b	20.89 a	18.46 c
3	0.25 c	2.54 e	0.73 b	3.97 cde	21.16 a	10.16 b	23.20 a	22.52 bc
4	0.25 c	3.38 b	0.69 b	5.35 b	20.34 a	13.99 b	27.67 a	19.73 bc
5	0.26 bc	3.03 bcd	0.72 b	5.03 bc	15.25 a	11.73 b	23.06 a	21.62 bc
6	0.27 bc	2.62 ed	0.86 a	3.86 de	19.86 a	16.91 ab	23.35 a	35.55 a
7	0.33 ab	2.87 cde	0.66 b	4.74 bcde	15.35 a	16.89 ab	28.61 a	25.91 abc
8	0.28 abc	2.93 cde	0.68 b	4.33 bcde	18.89 a	18.04 ab	23.84 a	32.41 ab
9	0.28 abc	3.74 a	0.71 b	6.51 a	22.67 a	11.55 b	26.94 a	21.46 bc
10	0.35 a	2.46 e	0.67 b	3.76 e	21.10 a	16.86 ab	25.96 a	25.56 abc
Clonal Mixture	0.25 c	2.83 cde	0.67 b	4.39 bcde	24.64 a	21.96 a	21.91 a	35.58 a
SNK critical range	0.07-0.11	0.31-0.53	0.1-0.16	0.7-1.2	9.65-16.66	6.88-11.87	7.5-12.9	8.01-13.82

NOTE: Values of clonal mixture in the table represent the overall values of mixture plots of ten clones.

Table 3.8: Comparison of coefficient of variation (CV) of heights and diameters of monoclonal versus Clonal mixture plots at time of planting (Age 0) and at age 4 years. Values in each column followed by same letter were not significantly at 5% level according to minimum critical value of SNK test. In monoclonal plots 540 trees and in clonal mixtures 126 trees were measured.

Clone or Plot	CV Height (Age 0)		CV Height (Age 4)		CV Diameter (Age 0)		CV Diameter (Age 4)	
	Monoclone	Clonal mix	Monoclone	Clonal mix	Monoclone	Clonal mix	Monoclone	Clonal mix
1	19.43 a	20.70 a	13.50 b	14.63 a	22.63 a	21.88 a	25.90 abc	27.67abc
2	18.97 a	20.31 a	11.20 b	14.88 a	20.89 a	21.92 a	18.46 c	21.64 c
3	21.16 a	22.31 a	10.16 b	10.88 a	23.20 a	22.42 a	22.52 bc	23.34 bc
4	20.34 a	21.64 a	13.99 b	14.98 a	27.67 a	26.78 a	19.73 bc	21.69 c
5	15.25 a	18.05 a	11.73 b	12.80 a	23.06 a	22.91 a	21.62 bc	22.97 bc
6	19.86 a	22.29 a	16.91 ab	16.74 a	23.35 a	24.39 a	35.55 a	35.84 a
7	15.35 a	22.31 a	16.89 ab	17.17 a	28.61 a	27.56 a	25.91 abc	28.44 abc
8	18.89 a	21.67 a	18.04 ab	19.52 a	23.84 a	23.89 a	32.41 ab	33.04 ab
9	22.67 a	23.31 a	11.55 b	13.93 a	26.94 a	26.08 a	21.46 bc	23.26 bc
10	21.10 a	20.55 a	16.86 ab	17.92 a	25.96 a	24.31 a	25.56 abc	27.41 abc
Average	19.30	21.31	14.08	15.35	24.62	24.21	24.91	26.53
SNK critical range	9.65-16.66	8.14-13.90	6.88-11.87	8.07-13.78	7.5-12.9	6.71-11.46	8.01-13.82	10.09-17.22

3.4.10 Risks of clonal plantings

During the second year after planting, clone 3 was severely attacked by pine woolly aphid (*Pinus laevis* (Maskell). Every plant of clone 3, whether in clonal mixture or in monoclonal plots, was fully covered with aphids so that the bark appeared white (Figure 3.8). No other clones were affected during that year. The infection declined markedly in year three, appearing in trace amounts on only a few trees of a variety of clones.

Figure 3.8 – Clone 3 was covered in pine woolly aphid only in year 2 after planting, and no other clones were affected including its full-sib relatives 7 and 10 (photo – E. Mason, University of Canterbury).

3.5 Discussion

3.5.1 Initial morphology, growth and survival

Genotype, morphological and physiological state of planting stock, site conditions (site preparation, soil fertility, soil moisture, altitude, temperature, and rain fall), initial management practices and their interactions contribute to initial establishment success. Rapid initial growth and high survival after transplanting require an appropriate balance between water and food requirements and supply. When plants are transplanted the roots

need to establish contact with water and nutrient supplies in a new environment (Menzies, 1988) by initiating and elongating new roots so that foliage can maintain photosynthetic activity (Burdett, 1990). Initial height, shoot: root ratio and proportion of biomass in foliage and fine roots are indicators of plant water balance because greater height, greater foliage or shoot biomass could result in more transpiration and lower proportions of fine roots can result in lower uptakes of water and nutrients. In this study clones differed with respect to initial heights, foliage: shoot ratio, shoot: root ratio, initial diameters, sturdiness and root-fibrosity. Clones that faced transplant stress had greater initial heights, shoot: root ratio, lower sturdiness and lower root-fibrosity compared to other clones. O'Reilly *et al.* (2002) suggested that shoot-root ratio should not exceed 3:1 for most of species. Thompson (1985) and Bernier *et al*. (1995) emphasised that a quality bare-root seedling should have low shoot: root ratio (1.5 to 2.5) under dry soil conditions to ensure the best survival. All clones in this study had greater shoot: root ratios (Table 3.2), and so water supply may have been more critical as a consequence.

Sturdiness indicates the balance between height and diameter. Due to positive correlations of height and foliage biomass, and of diameter and root biomass, sturdiness indicates the likely water relations experienced by seedlings following planting. A sturdiness value of 50 or less is considered a good indicator of initial survival for most species (Trewin, 2000). For radiata pine seedlings a sturdiness value between 40 and 60 is considered ideal depending upon site conditions (Menzies, 1988). Clones 7 and 10 had sturdiness values of 52 and 55 respectively which were inadequate for dry conditions. This suggests that these clones did not have a good balance between height and diameter which likely led to an imbalance between transpiration and water uptake, contributing to transplant stress and lower survival of these clones. Sturdiness which takes into account both initial height and diameter was found to be the best predictor of plot mean survival, while height at time of planting was slightly better in the logistic model.

Clone 9 had rapid initial growth. This clone had comparatively lower initial height, lower shoot: root ratio, greater sturdiness but lower root-fibrosity than clones 7 and 10 that experienced transplant stress. Clones 7 and 10 had greater root-fibrosities and low shoot: root ratios compared to other clones. But greater initial heights and low sturdiness of these clones resulted in transplant stress and lower survival. The significant differences in initial

morphology of clones and initial growth behaviours suggested that combinations of various morphological indicators should be used as criteria to determine the quality of planting stock for particular sites. The results of this study support the use of sturdiness (the balance between height and diameter) as a predictor of establishment success of planting stock, but more research is required because correlations between morphology and survival rates were relatively low. Including physiological indicators might help to determine the quality of planting stock. RGP is one of the physiological indicators that has been widely used as indicator of quality of planting stock, although researchers differ about the effectiveness of this indicator (Simpson and Ritchie, 1997; Davis *et al.* 2005). In this study RGP was not measured, but testing effectiveness of this indicator in future studies might help to determine effectiveness of this physiological indicator of quality of planting stock of radiata pine.

Differences in initial morphology of clones apparently contributed to differences in initial growth and survivals of clones, as shown by the fact that once the survival model included morphological factors, clone was not significant. Therefore, it is important to tailor nursery practices such as under-cutting, wrenching and top pruning to each clone in order to produce plant morphologies that will enhance the likelihood of survival after transplanting.

Standards for radiata pine seedlings and cuttings have been developed for some morphological indicators, but as clonal forestry with micro-propagated planting stock has become feasible there is need to develop standards for micro-propagated planting stock quality for different site conditions. This experiment was established in Sept. 1993 and climatic data (Appendix II) revealed that the total rainfall at the site during Oct. 1993 was only 39.2 mm which might have also contributed to transplant stress and lower survival of some clones.

Burdett (1990) emphasised that root system quality (root distribution, root length, root surface area, root permeability and root viability) influences establishment success. The roots of bare-root seedlings are subject to damage or death during lifting, storage, transport, and planting due to various mechanical and physiological stresses (Mason and Trewin, 1987; Burdett, 1990). This may restrict the ability of seedling to establish contact with soil moisture and nutrient reserves at planting site. Container grown seedlings rarely

suffer root damage during extraction and may, therefore, have a greater proportion of fine roots than bare-root seedlings which may promote early and quick seedling growth and survival (Nelson, 2003; Burdett, 1990). Therefore deployment of container-grown planting stock at dry sites may improve initial growth and survival.

The parameters of initial growth models in this study showed that genotypes with differing initial sizes had different growth patterns. The discriminant analysis of parameters indicated that by analysing the parameters of the initial growth models clones of similar or different initial growth patterns can be identified.

3.5.2 Clonal deployment

Greater variability in initial heights between clones deployed in clonal mixture plots and during the establishment period might have resulted in greater variability in mixture plots than monoclonal plots. Uniformity in raw material for greater product recovery is a trait desired by the forest industry, which suggests that using uniform planting stock and monoclonal deployment may enhance uniformity of raw material.

Greater susceptibility to insect-pest attack exhibited by one clone suggests that the deployment of such susceptible clones monoclonally over large regions may involve greater risks of damage from insect-pest and diseases. Lindgren (1993) emphasised that a single event of insect-pest and disease infestation might wipe out whole plantation if one clone is deployed over a large area. Deployment of such clones in mixtures of number of clones would minimise the losses because in mixture they would form a small proportion of total area planted. The opinion of researchers differs with respect to risks to monoclonal and clonal mixture mode of deployment. The argument in favour of monoclonal deployment is that the salvage in monoclonal stand is easy and the infested clones can be replaced by other clones (Libby, 1987b and Zobel 1993) Libby (1987a; 1987b) suggested two modes of clonal deployment “widespread intimately mixed plantations” and “mosaics of monoclonal plots”. The benefits of greater uniformity and minimum risk might be achieved by deploying small blocks of number of clones in “mosaics of monoclonal plots” mode of deployment rather than deploying single productive clone over large estate. The majority of researchers believe that deployment of 15-30 unrelated clones in a region

would minimise the risk of insect-pest and disease infestation to clonal plantations (Libby, 1987b; Robert and Bishir, 1997; Zobel, 1993; Park, 2002). Therefore, when the risk of insect-pest and disease is a concern, then clonal mixtures or mosaics of monoclonal blocks of 15-30 clones may be preferable modes of deployment.

3.6 Conclusions

Clones differed significantly in initial heights, initial ground-line diameters, shoot: root ratios, root-fibrosity and sturdiness; factors that were correlated with survival at age 4 years. Height at time of planting was the best predictor of survival of clones at age 1 year, and initial height was also the best predictor of transplant stress index, however correlations between initial height and survival were relatively low. Clones that exhibited poor survival had more negative TSIs and lower sturdiness than those that had 100% survival.

During the first year after planting clone survival ranged from 100% for six clones to as low as 83% for the clone most prone to mortality. Differences in mortality between clones were correlated with plant morphology, and so after initial height had been added to a logistic model of mortality, clone was insignificant as a class variable. Sturdiness was slightly superior to initial height in a plot-level analysis. Root–fibrosity was not a good predictor of survival.

Nonlinear functions fitted well to initial height and ground-line basal area yield data up to ages 4 and 3 years respectively. Analyses of parameters of models of initial height and basal area showed that clones differed markedly in initial growth.

Plots of mixed clones were significantly more variable in size than monoclonal plantings at age 4 years.

CHAPTER 4

PRODUCTIVITY OF RADIATA PINE (*Pinus radiata* D. DON) CLONES IN MONOCLONAL AND CLONAL MIXTURE PLOTS AT AGE 12 YEARS

4.1 Abstract

Productivities of monoclonal plots and clonal mixtures of ten radiata pine (*Pinus radiata* D. Don.) clones were compared in a trial established in 1993 at Dalethorpe, Canterbury, New Zealand. Ten monoclonal and one mixture of the ten clones were planted in a complete randomised block design with three replications using 40-tree plots (un-thinned, pruned to 2.5 m, stocking of 1250 stems per hectare). The study was conducted to determine if mode of deployment (monoclonal versus clonal mixture) affected overall productivity and how or if each clone was affected by mode of deployment.

The main conclusion was that mode of deployment did not significantly change overall stem volume productivity at age 12 years. All clones contributed similarly to overall stem volume productivity in monoclonal plots, whereas in clonal mixture plots 50 % of the volume was contributed by four dominant clones. Coefficient of variation (CV) within clones was greater in clonal mixtures compared to monoclonal plots by 3.2% in height and 4.7% in diameter at breast height over bark (DBH). Mean DBH was 13 % more uniform (12.6 versus 14.2 % CV), mean height was 12 % more uniform (7.8 versus 8.7 %) in monoclonal plots compared to clonal mixture plots. Overall survival was 90% and was not affected by mode of deployment. Clones exhibited more frequent and greater interchanges of ranks in monoclonal plots. One third of the ten clones were over-productive or under-productive in clonal mixture plots relative to their productivities in monoclonal plots. The results of this study suggest that plantation growers should select their preferred mode of

clonal deployment based on considerations other than productivity, such as crop uniformity, risks management, and operational efficiencies in tending, harvest, log segregation and subsequent processing and marketing.

4.2 Introduction

Radiata pine (*Pinus radiata* D. Don.) has adapted well to New Zealand conditions. Clonal forestry, the planting of forests with selected tested clones (Zhou *et al*., 1998; Sorensson and Shelbourne, 2005, Kube and Carson, 2004) is being considered by many plantation growers. There are some issues that need to be resolved in order to enhance benefits of clonal forestry. A key issue is mode of deployment (Tuskan, 1998; Ritchie, 1996; El-Kassaby and Moss, 2004), which is of great interest to foresters, conservationists and processors.

There have been two main approaches to clonal deployment in forestry: monoclonal and clonal mixture deployment. The advantages and disadvantages of these modes of deployment have been outlined by several researchers (Libby, 1987b; Lindgren, 1993; Zsuffa *et al.* 1993; Debell and Harrington, 1993). The issue of mode of deployment revolves around mainly productivity, crop or product uniformity, and associated biotic and abiotic risks. Greater uniformity in stem size, stem form and internal wood properties might help processors to reduce the cost of segregation and allocation of logs for different end product uses. A monoclonal stand is genetically invariable and is likely to be more uniform from tree-to-tree than other crop types (Sorensson and Shelbourne, 2005).

Risk is also an important factor particularly in long rotation plantations. Presently in New Zealand some major crops are dominated by few clones: e.g. 70% of the apple estate is in two clones, and 90% and 95% respectively of the kiwifruit and avocado estates are in one clone (Sorensson and Shelbourne, 2005). The opinions of researchers still differ with respect to the issue of mode of clonal deployment due to a paucity of research on this topic. Some researchers have compared productivity of monocultures with that of mixtures of different species mainly in hardwoods, but the impacts of mode of deployment on productivity of clonal plantations have been rarely studied, particularly in conifers.

Studies conducted to compare productivity of clones of short rotation *Populus* and *Salix* in monoclonal and clonal mixtures have reported mixed results. Markovic and Herpka (1986) reported 4th year results of productivity of five *Populus* clones which were each planted in monoclonal plots and also in clonal mixture plots. They reported slightly higher volume, mean height and mean diameter growth in clonal mixtures compared to monoclonal plots. Dawson and McCracken (1995) reported increased biomass yields of *Salix* clones at age 3 years in clonal mixture plots when compared to either the mean yield of component clones or the individual yields of any of the components grown in monoclonal plots. Debell and Harrington (1997); Benbrahim *et al.* (2000) compared the yield of *Populus* clones at age 3 and 8 years respectively in monoclonal and clonal mixture plots. They found that mode of deployment did not affect productivity although there were clonal differences in yield. Foster *et al.* (1998) reported a tendency of binary mixtures of Eastern cottonwood (*Populus deltoides*) clones at age 4 years to under-yield (productivity of mixtures was less than the proportionate combined yield of monoclonal plots) at one site and over-yield (productivity of mixtures was greater than the proportionate combined yield of monoclonal plots) at another.

Studies conducted in short rotation *Populus* do not clearly indicate that a clonal mixture mode of deployment is more productive than a monoclonal deployment for long rotation crops. One study in long duration species relevant to radiata pine has been reported by Zhou *et al.* (1998). They compared performances of two clones of Chinese fir (*Cunninghamia lanceolata* (Lamb) Hook.) in monoclonal blocks and row plots at age 9 years. They reported 27-30 % greater volume per hectare of monoclonal blocks of clones compared to single row plots over seedling check plots. To resolve the issue of mode of deployment particularly for medium to long rotation timber species, there is need to compare various modes of deployment for productivity, uniformity and risks.

The study described here was carried out with following objectives.

- To compare the productivity of monoclonal and clonal mixture plots.
- To compare relative growth patterns, within clone size variations, clonal rankings and mortality between two modes of deployment.

4.3 Materials and Methods

4.3.1 Site

An experiment was established with radiata pine on a site at Dalethorpe (latitude 42°-45'S, longitude 171°-55'E, elevation 520 m above sea level.), 70 km west of Christchurch, Canterbury, New Zealand in September 1993. The soil at the site was a well-developed silt-loam (NZ Soil Bureau, 1968). Mean annual precipitation was 1058 mm from 1993-2006 (NIWA, 2006). Precipitation was distributed fairly evenly throughout the year although a marked dry period can occur during February and March (McCracken, 1980).

4.3.2 Design of the experiment

Ten clones were deployed in two modes of deployment (monoclonal and clonal mixture) in a randomized complete block design with three blocks. Each block thus comprised eleven treatments: Each monoclone and the clonal mix contained all ten clones randomized in equal proportions. All plots were of rectangular shape (16 x 20 m), and contained 40 trees (5 x 8) except for one clonal mixture plot (64 x 20 m) that was larger (5 x 32 trees). Trees were spaced at 2 m within rows, and rows were spaced at 4 m producing an initial stocking of 1250 stems/ha. The total area of the experiment was 1.15 hectares, which comprised 9600 sq m of monoclonal plots and 1920 sq m of clonal mixture plots. The only silviculture applied to the trial was a lift-pruning to 2.5 m at age 7 years. A common silivicultural regime in Canterbury is an initial stocking of 1250 stems per hectare thinned to 600 stems per hectare at ages 6-7 years (MAF, 2005; SPBL, 2006). Thinning was not carried out in this experiment and a stocking of 1250 stems/ha was maintained unless mortality reduced it.

4.3.3 Planting material

Clones were propagated by organogenesis from controlled pollinated mature seeds that were surface sterilised and germinated into sterile tissue cultures. After propagation they were hardened off in a nursery in the North Island (Fletcher Challenge Forests Ltd. Biotechnology Centre, TeTeko) with an undercutting and wrenching regime, and then were

transplanted as bare-root plants. Ten clones (numbered 1 to 10) were planted in this experiment, derived from control-pollinated crosses. Clones 3, 7 and 10 were propagated from different seeds of same control-pollinated cross and are "full-sibs". Clones 1 & 9 and clones 6 & 8 were also propagated from different seeds of each of two crosses. Clones 2, 4 and 5 were from three additional crosses. Clones deployed in this experiment therefore represented six different families. The exact pedigrees of the clones were not revealed by the organization that provided the clones for this experiment, although they were said to have growth and form ratings (Sorensson, personal communication) between 25 and 30.

4.3.4 Establishment practices

All the plants were planted in 30 cm deep pits in ripped lines with ripping at a depth of 30 cm. Each planting spot was further cultivated with a spade. Each randomised complete block was planted by only one person. All the plots were kept completely weed free using initially a mixture of Hexazinone and Turbuthylazine, and subsequently a mixture of Turbuthylazine, Clopyralid and Haloxyfop herbicides for 5 years following planting.

4.3.5 Assessments

All 18 interior trees in each 40-tree plot in a 12 x 12 m zone (plus the 90 interior trees in the big clonal mixture plot) were measured leaving a single boundary row of trees to exclude affects of inter-genotypic interactions. Height poles, and later Vertex hypsometers, and diameter tapes were used to measure tree heights and diameters at breast height over bark (DBH) with the precision of 10 cm and 0.1 cm respectively. Tree heights were recorded from establishment year 1993 to 2005. DBH (1.4 m) was recorded from 1997 to 2005 except years 2001 and 2002. Assessments were recorded every winter between second fortnight of August and the first week of September when tree stem growth more or less stops in Canterbury. Mortality, windthrow, stem damage, and any pathogen infections were noted every year at the time of making other assessments.

4.3.6 Variables calculated

Mean heights and mean DBH were calculated for every plot (monoclonal or clonal mixture), and overall means for each clone. To compare the development of clones, relative yield indices (RYI) for heights (ages 1-12 years) and stand basal area (ages 4-12 years) of clones were calculated both in monoclonal and clonal mixture modes of deployment using equation (1). RYI values thus hover near 1 (100%).

$$Relative\ Yield\ Index = \frac{Individual\quad clone\quad mean}{Overall\ mean\ of\ mode\ of\ deployment} \tag{1}$$

Mean top height (MTH) which is defined as the height predicted by the Petterson height/dbh curve for a DBH corresponding to the quadratic mean DBH of the 100 largest trees per hectare (Goulding, 2005) was calculated for each clone. Quadratic mean DBH of the two largest trees in each plot were used in a Petterson function (2) to calculate MTH for each plot or clone. MTH indicates potential height productivity of species at a particular site. In New Zealand, the Petterson function is used to estimate mean top height is not measured but instead is estimated using the Petterson function (2).

$$MTH = 1.4 + \left[b + \left(\frac{a}{DBH} \right)^{-2.5} \right] \tag{2}$$

Where MTH is mean top height in meters, DBH was diameter at breast height in cm, constant 1.4 was breast height in meters and a and b were coefficients.

The coefficients a and b were calculated for each plot from linear regressions (3) developed between observed individual tree heights and diameters (DBH).

$$Y = a + b * DBH \tag{3}$$

Where $Y = \dfrac{DBH}{(H - 1.4)^{0.4}}$

H = Total height in meters, DBH = Diameter at breast height over bark in cm, 1.4 was breast height in meters and a, b were coefficients.

Stand basal area per hectare for each plot was calculated at age 12 years from plot basal areas in monoclonal plots and from mean clonal basal area in clonal mixture plots. Zhao's (1999) volume equation (4) was used to calculate average volume of each monoclonal and clonal mixture plots. Zhao's volume equation was used in this study because this equation has yielded greater accuracy in stand volume prediction of radiata pine stands in Canterbury than has been demonstrated for other candidate equations.

$$V = \alpha\, G^{\beta} MTH^{\gamma} \qquad (4)$$

Where $\alpha = 0.6225102886$, $\beta = 0.9670398052$ & $\gamma = 0.8466802294$

V was stand volume (m^3/ha), G was stand basal area (m^2/ha) and MTH was mean top height in meters.

Size variability within clone was calculated as coefficient of variation (%).

4.3.7 Data analysis

Procedure GLM (General linear models) of SAS (SAS Institute Inc. 2000) was used to compare the productivity of clones in both modes of deployment, and interactions of clones and mode of deployment at age 12 years for height, DBH, height CV, DBH CV, MTH, stand basal area and stand volume. The following model was used for analysis of variance:

$$Y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\gamma)_{ik} + e_{ijk} \qquad (5)$$

Where Y_{ijk} is mean height or DBH or height CV or DBH CV, MTH or stand basal area or stand volume of i^{th} clone, j^{th} block and k^{th} mode of deployment, μ is overall mean, α_i is i^{th} clone, β is j^{th} block, γ is k^{th} mode of deployment, $(\alpha\gamma)_{ik}$ is the interaction of i^{th} clone and k^{th} mode of deployment and e_{ijk} is error.

The Student-Newman-Keuls (SNK) multiple range test was used at P=0.05 to distinguish differences in mean heights, mean DBH, mean top heights, stand basal areas and stand volumes of clones at age 12 years. The smallest critical range of the SNK test was used as measure of statistical power for each variable. Linear contrasts were used during the analysis of variance to compare the overall productivity between the two modes of deployment.

Stand volume was chosen to compare productivity of clones and overall productivity of modes of deployment, because it involves height, DBH and stocking per hectare.

To evaluate individual clone performance in both modes of deployment two different analyses were adopted:

- The deviations of individual plot stand volume of each clone from mean stand volume of mode of deployment were calculated for both modes of deployment. The performance of each clone was evaluated by plotting the deviations of monoclonal and clonal mixture plots.

- Discriminant analysis, which is used to separate two or more groups on the basis of analyzing several variables simultaneously (Manly, 1986) was carried out on relative yield indices calculated for mean clone heights and stand basal areas. Separate discriminant analyses in SAS (SAS-Institute, 2000) were carried out for monoclonal and clonal mixture plots to determine whether or not clones differed in yield between modes of deployment. Indices calculated for ages 10-12 years were used because competition becomes intense after canopy closure, so evaluation of clones based on near mid-rotation performance would be more reliable. The performance of clones by mode of deployment was evaluated based on values of canonical function 1, which explained the greatest variability in data (84% in monoclonal and 86 % in clonal mixture plots). Lower values of canonical discriminant function 1 indicated poorer performance.

4.3.8 Limitations of the study

The experiment was limited for the following reasons:

- The experiment was not replicated over a variety of sites.
- A greater stocking (1250 stems/ha) was retained at age 12 years than in a commonly used stocking regime of 600 stems/ ha at this age in order to accentuate the impacts of between clone competition and also to ensure that the development of the experiment was not compromised by slight differences in thinning treatments between clones.
- There were a limited number of onsite replications.
- The experiment comprised only 10 clones.

4.4 Results

4.4.1 Overall productivity

Overall survivals of clones in monoclonal and clonal mixture plots were similar (Table 4.1). Mortality, although low overall, increased with age**.** At age four, mortality was 3.3 % both in monoclonal and clonal mixture plots. Afterwards, mortality began to increase in both modes of deployment due to increased competition among trees and windthrow damage among fast growing clones (Figure 4.1), but statistically there were no differences in mortality between the two modes of deployment up to age 12 years. Clones 1, 3 and 6 had 100 percent survival in monoclonal plots and clone 5 in clonal mixture plots at age 12 years (Table 4.1). Fast growing clones 4 and 9 had greater windthrow mortality both in monoclonal and clonal mixture plots.

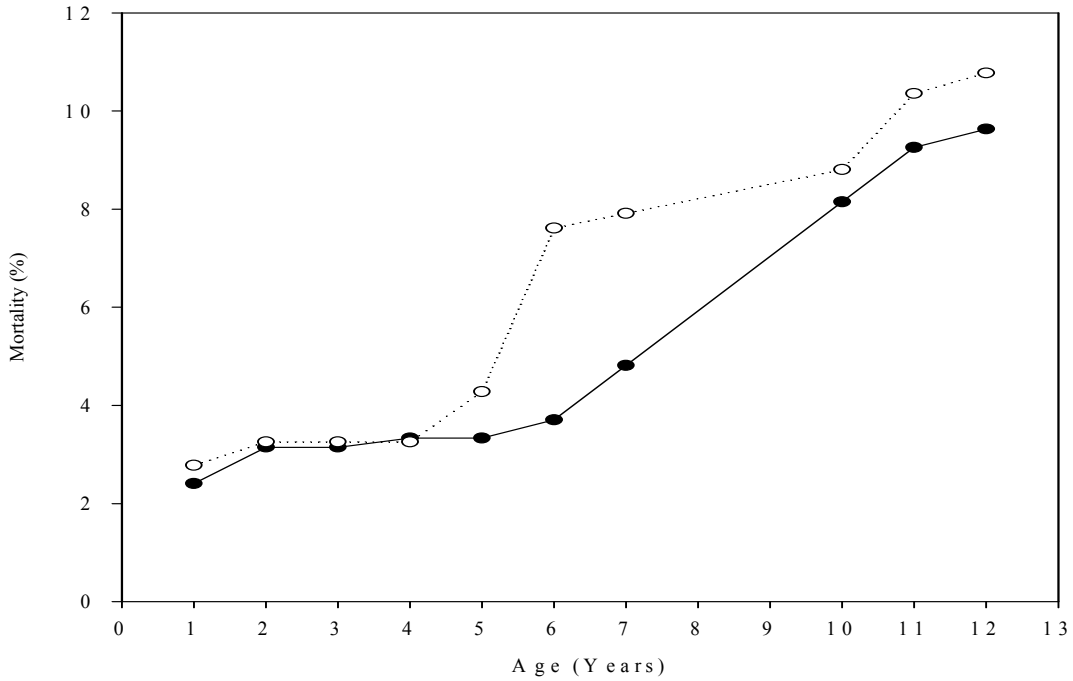


Figure 4.1: Trend of mortality in monoclonal and clonal mixture plots. Mortality did not differ between modes of deployment. Filled circles represent mortality in monoclonal plots and open circles in clonal mixture plots.

During the second year after planting, clone 3 was severely attacked by pine woolly aphid (*Pinus laevis* (Maskell)). Every plant of clone 3, whether in clonal mixture or in monoclonal plots, was fully covered with aphids, whereas no other clones, including clones 7 and 10 which were members of the same family, were affected during that year. The infection declined markedly in year three, appearing in trace amounts on only a few trees of a variety of clones. Clones differed significantly in their individual stem productivity when deployed monoclonally. Mean heights (P<0.0001) mean DBH (P<0.0001) and mean top heights (P=0.0017) of clones significantly differed in monoclonal plots (Table 4.1 and 4.2). Mean top heights of clones also significantly differed in clonal mixture plots (P=0.002), and overall between modes of deployment (P=0.003). Clones differed in stand basal area in monoclonal plots, but did not in clonal mixture plots. Stand volume differed neither in monoclonal nor in clonal mixture plots. DBH of clones significantly differed (P=0.019) between modes of deployment, although overall DBH values between modes of deployment were similar at age 12 years (Table 4.1 and 4.3). Clone 7 exhibited significantly greater DBH in monoclonal plots compared to clonal mixture plots.

Table 4.1: Mean height, mean DBH, coefficient of variation (CV) of mean height and DBH, and survivals in monoclonal and clonal mixture plots at age 12 years. Values in each column followed by the same letter were not significantly different according to student-Newman-Keuls multiple range (P<0.05) test. 540 trees in monoclonal plots and 126 trees in clonal mixture plots were measured.

Clone	HEIGHT					DBH					SURVIVAL	
	MONO-CLONAL		CLONAL MIXTURE		CV Difference (%)	MONO-CLONAL		CLONAL MIXTURE		CV Difference (%)	MONO-CLONAL	CLONAL MIXTURE
	Height (m)	CV (%)	Height (m)	CV (%)		DBH (cm)	CV (%)	DBH (cm)	CV (%)		(%)	(%)
1	13.6 cd	5.9 b	13.9 abc	6.2 a	0.3	26.0 cd	11.6 ab	29.1 abc	7.3 cd	-4.3	100 a	93 a
2	13.8 bcd	7.9 b	13.5 abc	11.8 a	3.9	25.2 d	15.7 a	25.1 cde	20.2 ab	4.5	89 ab	97 a
3	13.3 d	5.1 b	13.7 abc	8.5 a	3.4	24.7 d	8.2 b	25.6 bcde	12.7 bcd	4.5	100 a	96 a
4	14.9 a	6.0 b	14.4 ab	6.5 a	0.5	25.6 cd	9.7 ab	28.3 abcd	12.3 bcd	2.6	87 ab	67 a
5	14.2 abc	10.1 ab	14.1 abc	7.1 a	-3	27.4 bc	14.4 ab	30.1 ab	19.1 abc	4.7	94 a	100 a
6	13.6 cd	7.1 b	13.5 abc	6.8 a	-0.3	25.5 d	14.0 ab	24.8 cde	7.9 cd	-6.1	100 a	83 a
7	13.2 d	7.2 b	12.8 c	10.9 a	3.7	28.9 ab	13.2 ab	23.5 e	25.5 a	12.3	82 ab	97 a
8	14.2 abc	7.5 b	13.4 bc	10.6 a	3.1	26.0 cd	11.7 ab	26.4 bcde	11.9 bcd	0.2	98 a	92 a
9	14.6 ab	14.3 a	15.0 a	3.8 a	-10.5	29.4 a	12.5 ab	31.5 a	6.5 d	-6	65 b	75 a
10	13.9 bcd	7.1 b	13.3 bc	14.7 a	7.6	26.3 cd	14.5 ab	24.1 de	18.6 abc	4.1	89 ab	94 a
Overall	13.9	7.8	13.7	8.7	0.9	26.5	12.6	26.8	14.2	1.7	90	89
SNK critical range	0.8-1.4	6-10.3	1.5-2.6	12.9-22.9		1.6-2.7	6.3-10.8	4.8-8.1	11.9-21.2		25-43	40-68

Table 4.2: Stand basal area, mean top height and stand volume of clones in monoclonal and clonal mixture plots at age 12 years. Values in each column followed by the same letter were not significantly different according to student-Newman-Keuls multiple range ($P<0.05$) test. Deviations in the table were differences between overall mean and individual clone mean. 540 trees in monoclonal plots and 126 trees in clonal mixture plots were measured.

Family	Clone	Stand Basal Area (m^2/ha)		Mean Top Height (m)		Stand volume (m^3/ha)			
		Monoclonal	Mixture	Monoclonal	Mixture	Monoclonal	Deviation	Mixture	Deviation
B	1	67.0 ab	76.8 a	14.0 de	14.1 ab	340.0 a	6.4	389.6 a	67.1
D	2	56.8 ab	61.4 a	14.9 bcd	13.0 cd	306.2 a	-27.4	295.2 a	-27.3
A	3	60.3 ab	63.0 a	13.7 e	14.1 ab	301.5 a	-32.1	323.9 a	1.4
E	4	56.6 ab	53.1 a	15.4 abc	14.6 a	314.7 a	-18.9	277.1 a	-45.4
F	5	70.7 a	90.7 a	15.4 abc	14.0 abc	387.9 a	54.3	456.6 a	134.1
C	6	65.0 ab	51.4 a	14.6 bcde	13.6 bcd	342.2 a	8.6	260.0 a	-62.5
A	7	67.3 ab	54.7a	13.9 de	12.9 d	339.1 a	5.5	262.1 a	-60.4
C	8	66.3 ab	63.5 a	15.5 ab	13.1 bcd	368.3 a	34.7	306.1 a	-16.4
B	9	54.3 b	74.4 a	16.1 a	14.8 a	316.1 a	-17.5	395.8 a	73.3
A	10	61.3 ab	54.9 a	14.4 cde	12.7 d	319.9 a	-13.7	258.4 a	-64.1
Overall		62.6	64.4	14.8	13.7	333.6	0	322.5	0
SNK critical range		15.8-26.9	39.8-67.9	1.1-1.8	0.9-1.6	96.5-164.6		209.2-357	

Table 4.3: Analysis of variance: for heights, DBH, heights CV, DBH CV, mean top heights, stand basal area and stand volume at age 12 years. 540 trees in monoclonal plots and 126 trees in clonal mixture plots were measured.

Sources of variation	Degree of freedom	Sizes		Coefficient of Variation		Productivity			Survival
		Height (Pr>F)	Diameter (Pr>F)	Height (Pr>F)	Diameter (Pr>F)	Mean top heights Pr>F)	Stand basal area (Pr>F)	Stand volume (Pr>F)	(Pr>F)
Block	2	0.026	0.332	0.005	0.142	0.341	0.994	0.974	0.462
Clone	9	0.003	0.0002	0.757	0.001	0.515	0.336	0.294	0.212
Mode of deployment	1	0.429	0.498	0.938	0.318	0.003	0.685	0.644	0.817
Clone*Mode of deployment	9	0.864	0.019	0.276	0.028	0.396	0.681	0.726	0.813
Error	38								

Volume productivity of clones deployed monoclonally was statistically similar to that of clones deployed as 10-clone mixtures (Table 4.2). Fast growing clone 5 produced 16.3 % more volume at age 12 years over the average of all ten clones grown in monoclonal plots or 20.3 % more volume of all ten clones grown in clonal mixtures plots. In clonal mixture plots, clone 5 contributed disproportionately more volume than did other clones, with its volume gain doubling to 41.6 %.

Clones contributed almost equally to overall volume productivity in the monoclonal mode of deployment, whereas in clonal mixture plots their contribution was disproportionate. About 50% of volume was contributed by four clones in clonal mixture plots. This indicated that some clones were more productive in clonal mixture plots.

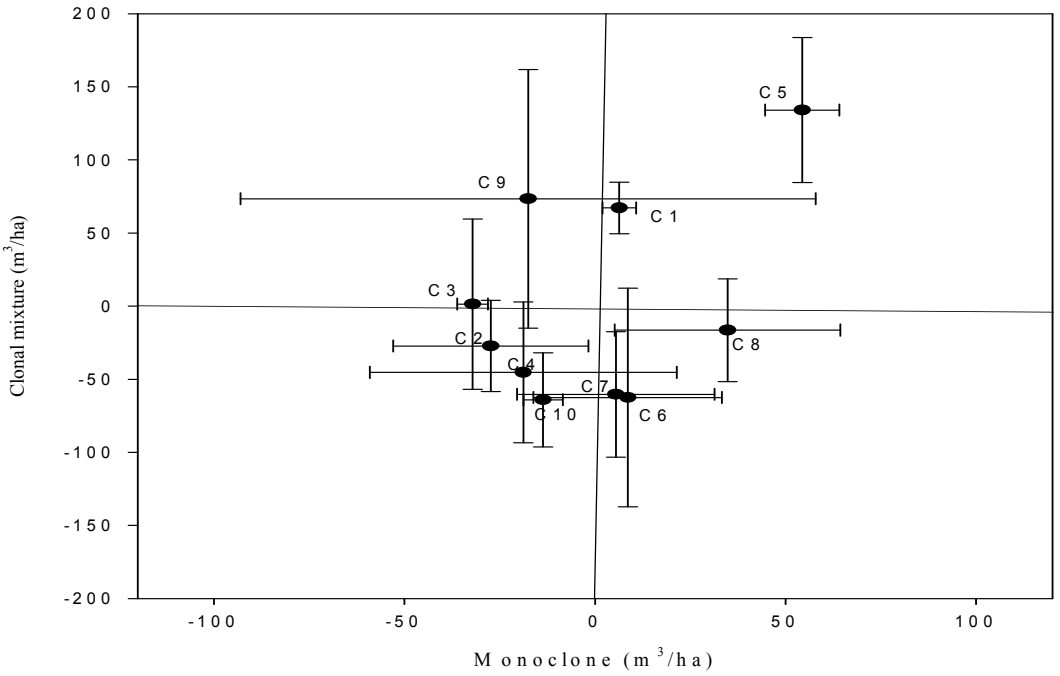


Figure 4.2: Deviations of stand volume productivities of clones in monoclonal versus clonal mixture plots with bars indicating raw standard errors.

Although, there were quite distinct differences in volume productivity of clones in clonal mixture plots, but they were statistically non-significant. These non-significant differences between clones might have resulted in type-II error due to lower power of the analysis in clonal mixture plots. Stand volume productivity of clones varied within modes of deployment. Productivities of clones within modes of deployment varied due in part to variable mortality (e.g. clones 4 and 9) in different plots. The productivities of clones in

clonal mixture were determined by calculating deviations of volume productivities of clones from average productivity of clonal mixture plots because deviations from one index value provided a better comparison than comparing the stand volume productivity of each clone with nine values for the rest of the clones. On average roughly 30 % of clones were more productive, and 30% were under-productive in clonal mixture plots compared to their growth in monoclonal plots (Figure 4.2). Clone 9 was more productive in clonal mixture plots, whereas clones 6, 7 and 8 were more productive in monoclonal plots (Table 4.2, Figure 4.2). Clones 1 and 5 were productive in both modes of deployment. Values of canonical function 1, which explained 84% and 86% variation in monoclonal and clonal mixture plots also corroborated these results (Table 4.4). Relative stand basal area yield and relative height yield indices contributed 76 % and 24 % respectively to canonical function 1 in monoclonal plots and 80 % and 20 % respectively to canonical function 1 in clonal mixture plots. Greater positive values of canonical function 1 of clones 1 and 5 in both modes of deployment revealed that these clones performed equally well in both modes of deployment (Table 4.4).

Table 4.4: Values of canonical function 1 of relative height yield and relative stand basal area yield. Values in each column followed by the same letter were not significantly different according to the Student-Newman-Keuls multiple range (P<0.05) test. 30 plot values calculated for each variable were used for this analysis.

Clone	Canonical 1	
	Monoclonal	Clonal Mixture
1	3.7 bc	6.7 b
2	-4.1 g	-1.7 cd
3	0.3 e	-1.0 c
4	-5.4 gh	-3.0 d
5	5.7 a	10.8 a
6	1.0 de	-6.5 ef
7	4.6 ab	-7.0 f
8	2.4 cd	-1.0 c
9	-6.7 h	7.7 b
10	-1.8 f	-4.9 e
SNK Critical range	1.70 – 2.89	1.70 – 2.89
Percent Variability explained	84	86

4.4.2 Variability

Although overall variation in DBH did not differ significantly between modes of deployment (P=0.318), variation within clones significantly differed (P=0.028) with mode of deployment (Table 4.1 and 4.3). In monoclonal plots, within-clone DBH was 13 % more uniform (12.6 versus 14.2 % CV), mean height was 12 % more uniform (7.8 versus 8.7 %) than equivalent within-clone values in clonal mixture plots. Clone 3 was the most uniform clone with a coefficient of variation of 5.1 % in height and 8.2 % in DBH when grown monoclonally.

Overall monoclonal plots had coefficients of variation of 7.8 % in height and 8.2 % in DBH. The overall coefficients of variation in clonal mixture plots were 13.9 % in height and 17.2 % in DBH.

Variability among trees of the three dominant clones (1, 5 and 9) in clonal mixtures was compared with variation between trees of all ten clones in clonal mixture plots at age 12 years. The purpose of this comparison was to find out whether a mixture of clones having similar growth pattern produce more uniform stand compared to a mixture of clones of different growth patterns. If a mix of clones having similar growth patterns enhances size uniformity and productivity then deployment of such clones might be better option to mange risks and produce uniform raw material. The result showed that variability within ten clones was 52 % more (13.9 % versus 9.1 % CV) than within trees of the three dominant clones in height and 25 % more in DBH (17.2 % versus 13.7 %).

4.4.3 Clonal rankings

Clones exhibited more frequent and greater interchanges of ranks in monoclonal plots (Figures 4.3-4.6) than in clonal mixture plots. Clones 1, 6 and 8 had relatively lower stand basal area at age 4 years, but they started growing rapidly and surpassed some clones that were growing rapidly during the establishment period (Figure 4.4). Clone 9 exhibited a steady decline in ranking due to greater mortality mainly because of windthrow (Figure 4.4). In clonal mixture plots clones exhibited few interchanges of ranks except for clone 4 which exhibited a sudden drop in rank due to windthrow damage (Figure 4.6).

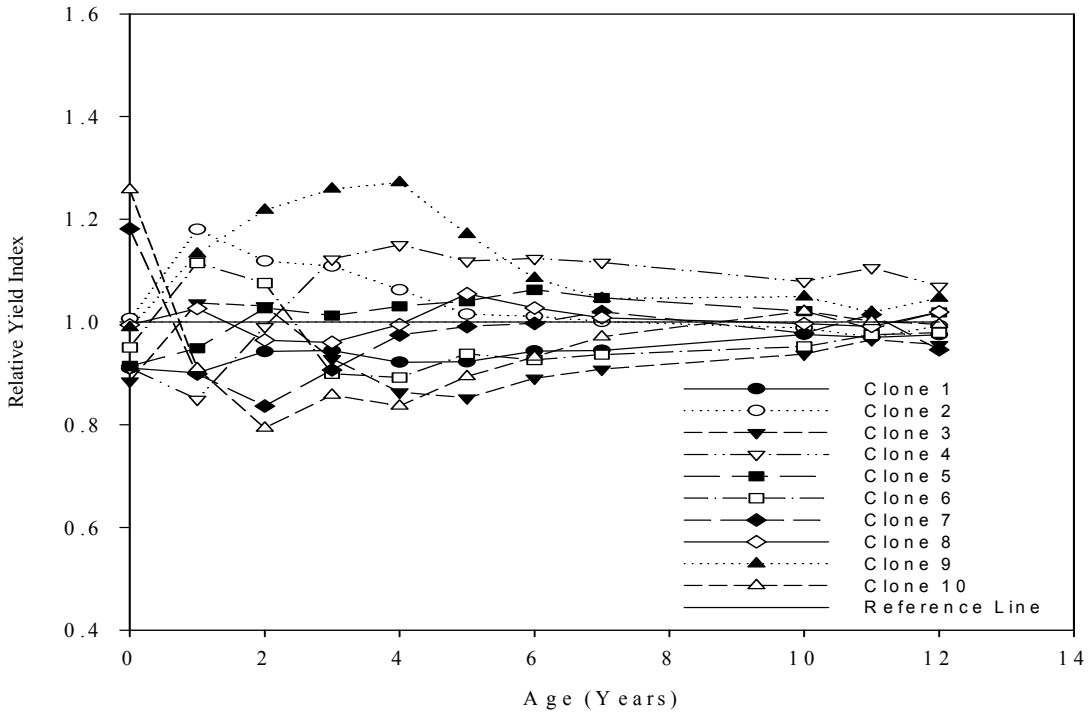


Figure 4.3: Relative yield indices of height in monoclonal plots over time.

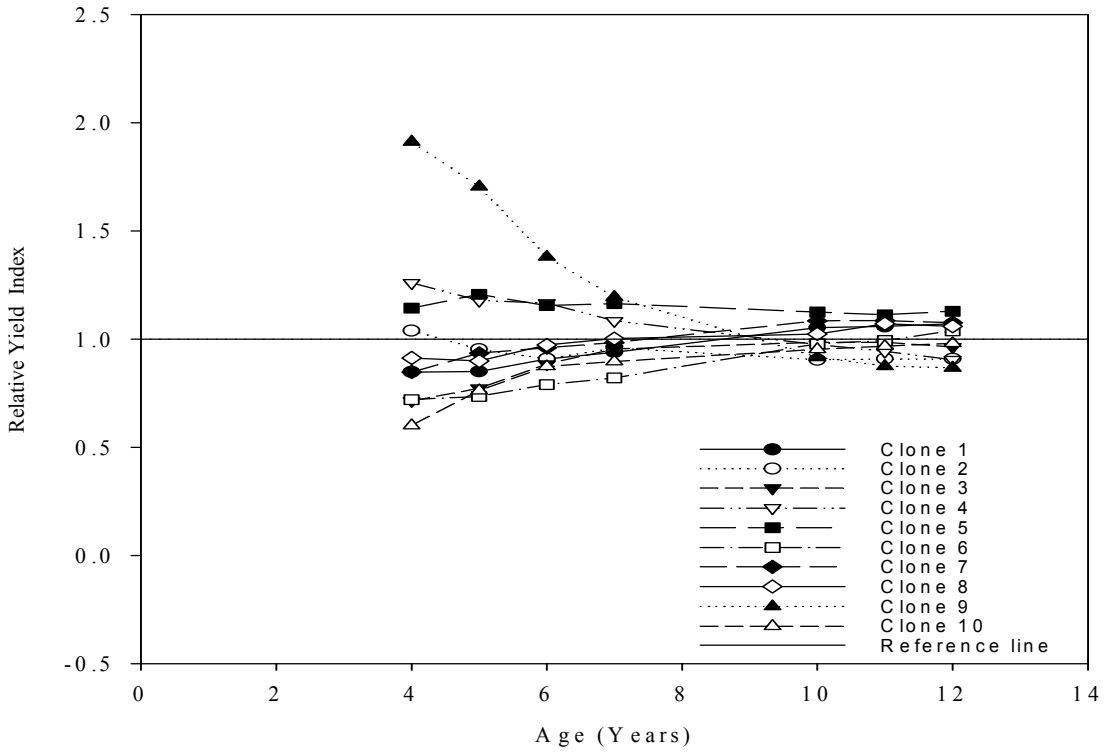


Figure.4.4: Relative yield indices of stand basal area in monoclonal plots over time.

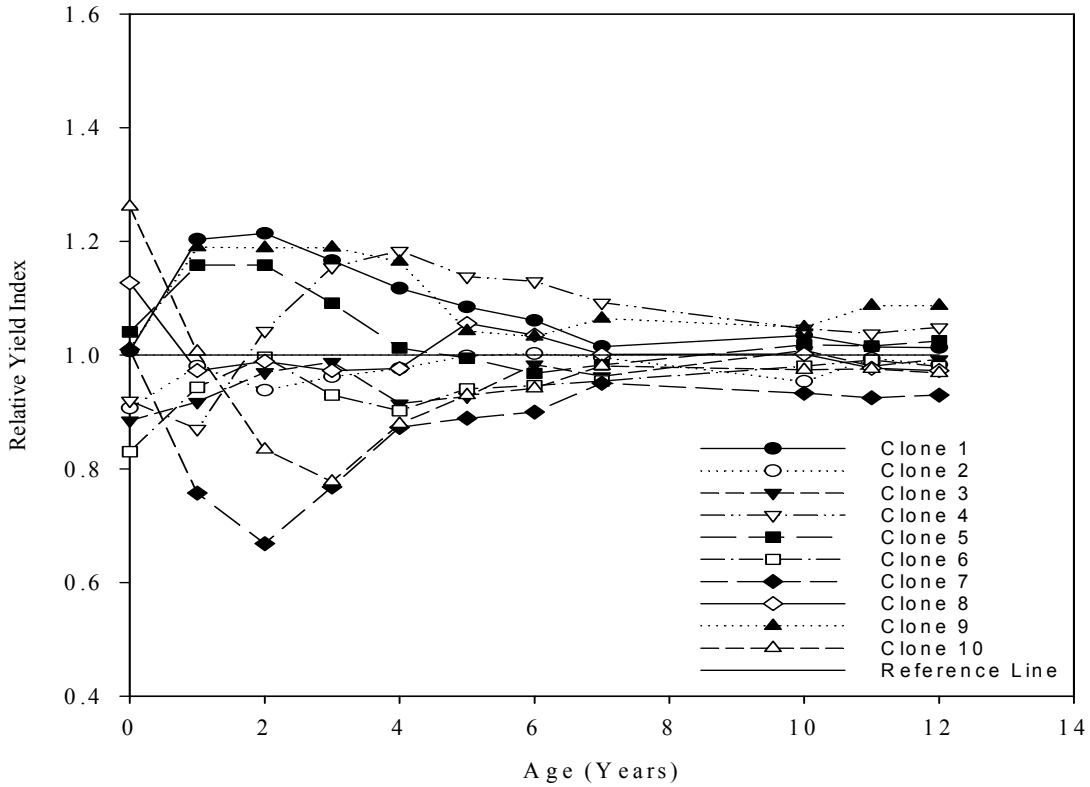


Figure 4.5: Relative yield indices of height in clonal mixture plots over time.

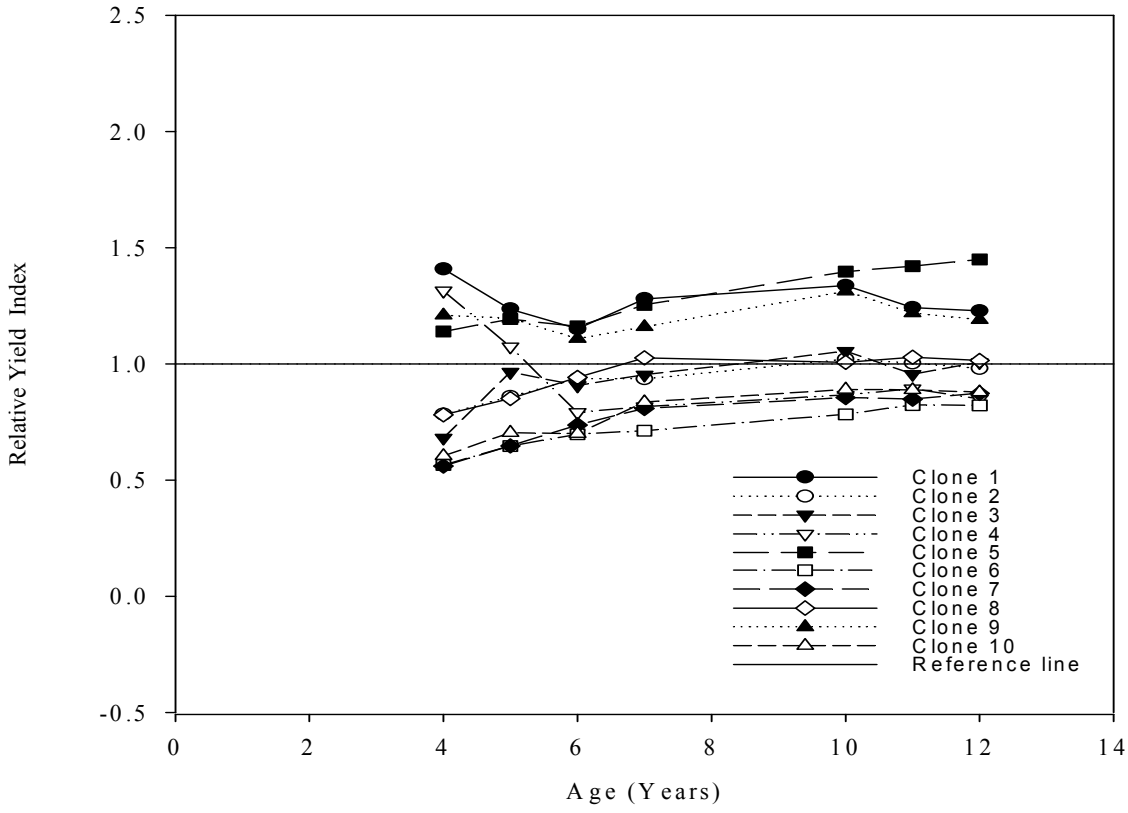


Figure 4.6: Relative yield indices of stand basal area in clonal mixture plots over time.

4.5 Discussion

This study compared the productivity of clones between two modes of deployment at one site. The main limitations of this study were limited numbers of onsite replications, higher stocking than usual for radiata pine plantations in New Zealand, few clones, a site that did not represent sites where many New Zealand plantations grow, and absence of replications of the experiment at different sites. This latter limitation was important because clone x site interactions might affect productivities of clones. CellFor Corp. has over 90 clonal field testing trails in loblolly pine (*Pinus taeda*), slash pine (*Pinus elliottii*) and radiata pine (*Pinus radiata*), and the results in loblolly pine up to age 4 years indicated stable site performance with minimal genotype x environment interactions (Pait, 2004). Although normal final crop stocking at age 12 years is 600 stems per hectare at the site of the experiment, comparisons of productivity of modes of deployment may well be typical of radiata pine at different stockings and sites. Overall survival was 90%, mean DBH was 26.8 cm and mean height was 13.9 m. Initial management practices, competition and windthrow contributed to overall mortality and also influenced stand dynamics. Survival did not differ with mode of deployment which is in agreement with results reported by Benbrahim *et al.* (2000) and also by Debell and Harrington (1997). In this study windthrow resulted in greater mortality of fast growing clones 4 and 9 in both modes of deployment. Deployment of wind tolerant clones or deploying clones of similar growth rate in clonal mixtures might reduce windthrow mortality.

A conclusion of interest to commercial foresters is that overall productivity did not differ statistically (P=0.644) with mode of clonal deployment, a conclusion also found in similar designs involving older poplar clones (Benbrahim *et al.* 2000). Clones contributed disproportionately to overall productivity due to dominance and suppression in clonal mixture plots. Due to greater acquisition of resources by dominant trees, they grew vigorously and contributed more to overall productivity. McCracken and Dawson (1996) also reported significantly greater proportions of the yield contributed by dominant large stools of *Salix* spp. in clonal mixture plots.

Crop uniformity is important for ease of management, operational efficiency and maintaining the consistency in end product quality. Sutton (1981) commented on crop uniformity during a discussion at a symposium:

"*The more uniform the crop, and the more uniformly large the crop, the better***"**

The obvious disadvantage of deploying clones in mixtures is greatly reduced stand uniformity in traits like tree size, log quality and especially heritable traits like wood quality. As expected, stem size within clones was more variable in clonal-mixture plots (CV DBH 14.2 %, height 8.7 %) than in monoclonal plots on average (DBH 12.6%, height 7.8 %). Interestingly, competition among clones in clonal mixtures also tended to inflate within-clonal size variation in seven out of ten clones by an average of 3.2% for Height CV, and by 4.7% for DBH (calculated from Table 4.1).

This study indicated that foresters can grow more uniform stands by deploying clones monoclonally (e.g. clone 3 exhibited least coefficient of variation of 5.1 % in height and 8.2 % in DBH in monoclonal plots compared to overall coefficient of variation of 13.9 % in height and 17.2 % in DBH in clonal mixture plots). This suggests that clonal forestry can offer much more uniform stands compared to family forestry which is one of the important advantage of clonal forestry (Carson and Burdon, 1989; Carson, 1986; Libby and Rauter, 1984; Sorensson and Shelbourne, 2005).

The lower variability of clonal mixtures of the three dominant clones compared to mixture of ten clones also suggests that deploying clones of similar growth patterns and competitiveness might enhance uniformity in clonal mixtures, but this hypothesis needs to be tested through further experiments and with a larger number of clones.

This study showed that performance of some clones differed between deployment mode in all traits measured (mean height, mean top height, diameter, basal area and growth patterns). Debell and Harrington (1997) also reported that performance of *Populus* clones differed between monoclonal and clonal mixtures. This might be because in monoclonal plots all trees were of equal competitiveness and therefore utilized resources similarly, and in clonal mixtures interactions of genotypes of varied competitiveness resulted in

suppression of some clones, which led to differences in performance between modes of deployment.

The clones did not exhibit significant differences in productivity in clonal mixture plots which might be because of lower power of the analysis due to fewer trees per plot compared to monoclonal plots.

Analysis also revealed that within family performance of clones also differed. Clone 1 had greater survival compared to clone 9 of the same family in both modes of deployment (Table 4.1). Stand volume productivity of clone 1 was above average in both modes of deployment but, clone 9 performed poorly in monoclonal plots (Tables 4.1, 4.2 and Figure 4.1). Clone 3 differed in survival and stand volume productivity from clones 7 and 10 of the same family (Tables 4.1, 4.2 and 4.4). Canonical function 1 analysis of relative height and relative stand basal area yield also revealed within family differences in performance (Table 4.4). These within family performance differences indicate the possibility of genetic recombination within families.

McCracken and Dawson (1996) reported greater infestation of rust disease (*Melampsora epitea* variety epitea) on one clone of willow grown in monoclonal plots, and so the aphid infestation reported here has a precedent. When the same willow clone was grown in clonal mixture, disease onset was delayed and slowed build up of disease resulted in lower disease levels in clonal mixture stands (McCracken and Dawson, 1997), but we found no similar reduction in aphid infestation in mixtures in our study.

What made this study particularly interesting were strong indications that some clones were more able to grow well when subject to competition than others and they demonstrated this trait at early ages 7 or 8 years onwards. Panetsos (1980) evaluated the influence of inter-genotypic competition under various spacings and showed that inter-genotypic competition masked the expression of certain clones and concluded that competitive ability should be under genetic control. So selection of competition-resistant clones might enhance stand productivity.

Inter-changes in ranks over time have been reported in clonal mixtures (Zsuffa, 1975; Ares 2002) and between spacings in monoclonal plots (Debell and Harrington 1997) of *Populus*. This study revealed greater interchanges of ranks in monoclonal plots than in clonal mixture plots (Figures 4.3-4.6). The growth rates of clones relative to one another changed with age. Some clones grew rapidly during the first few years. Others grew more moderately at the beginning, but sometimes they outperformed the early fast-growers. Clones 1, 6, and 8 showed similar growth patterns in monoclonal plots (Figure 4.3). Many factors such as genotype, initial management practices, environment and genotype x environment interactions and competition affect growth rates of clones, which might cause interchanges of ranks. These factors might mask the longer term performances of clones, if evaluations are done too early.

This study suggests that the choice of mode of clonal deployment needs to be made for reasons other than productivity, such as crop uniformity, risk management, and operational efficiencies in tending, harvest, log segregation and subsequent processing and marketing. In general, operational efficiency and risks of insect pest and disease infestation are the major factors that would affect the choice of mode of deployment.

One important implication of this study for clonal screening studies is that individual tree plots might result in good selection for deployment in clonal mixtures, but may fail to detect clones that start slowly but which might ultimately be effective performers in monoclonal deployments. Single tree plot field test designs might also over-estimate gains for some genotypes. Stagner *et al.* (2007) compared the predicted gains (%) in volume relative to the trial mean using single tree plot (STP) and block plots in a Eucalypus hybrid clonal trial, and reported that one clone had a predicted growth gain of 74 % over the trial mean in single tree plots, but in block plots yielded only 7 % more growth. Therefore, selection of clones might be useful in block plots for deployment in monoclonal mode of deployment. Libby (1987a) recommended four levels of testing for screening genotypes:

Level I: *Initial screening*. Screening of large number of genotypes in single tree plots.

Level II: *Candidacy testing.* Use of 2-6 ramets of each genotype to identify genotype x environment interactions and selecting better clones for further testing or deployment in plantations as clonal mixtures.

Level III. *Clonal performance testing*. This step involves testing stability over contrasting sites using 2-6 ramets of each clone at different sites to evaluate each clone's appropriate range of sites for deployment (Level IIIa), and to evaluate per unit area productivity of clones using large contiguous plots of each clone (Level IIIb). The number of clones tested in this level will moderately be small (< 200).

Level IV. *Compatibility testing*. Clones selected at level III can then be tested in sequenced mixtures to identify compatible sets of clones that would make complementary demands on their environments at same time and would enhance overall per unit area productivity. This level of testing is recommended at advanced stage of selection programs when number of clones to be tested will be small (20-50).

This study falls under level IIIb of Libby's testing scheme and also suggests that to deploy clones in commercial monoclonal block plantations, selections carried out in block plot test designs at higher levels of selection programs, when fewer genotypes are compared, might be more effective than using single tree plots. To deploy clones in clonal mixtures, level IV testing can be used to select compatible clones.

4.6 Conclusions

Mode of clonal deployment did not significantly change overall productivity, as measured in stand volume (m^3/ha) or other growth variables (height, DBH, basal area) except MTH at age 12 years in un-thinned plots. Survival also did not interact with mode of deployment.

At least one third of the ten clones were relatively over-productive or under-productive in clonal mixture plots compared to their productivities in monoclonal plots. All clones contributed equally to overall volume production in monoclonal plots, whereas in clonal

mixtures 50% of the volume was contributed by four clones. One clone disproportionately contributed more volume to overall productivity in clonal mixture plots.

As expected, deploying clones in a mixture substantially increased stem size variability compared to that within monoclonal plots. In monoclonal plots, within clone mean DBH was 13 % more uniform (12.6 vs. 14.2 % CV), mean height was 12 % more uniform (7.8 vs. 8.7 %). A mixture of three dominant clones was 52 % more uniform in height (13.9 % versus 9.1 % CV) and 25 % in DBH (CV of 17.2 % versus 13. 7 %) compared to a mixture of ten clones. Clone 3 was most uniform when deployed monoclonally (a CV of 5.1 % in height and 8.2 % in DBH). Mode of deployment significantly altered DBH of one clone.

Overall monoclonal plots had coefficients of variation of 7.8 % in height and 8.2 % in DBH, while the overall coefficients of variation in clonal mixture plots were 13.9 % in height and 17.2 % in DBH.

CHAPTER 5

INFLUENCE OF INTRA- AND INTER-GENOTYPIC COMPETITION ON GROWTH AND PRODUCTIVITY OF RADIATA PINE CLONES

5.1 Abstract

Influence of intra- and inter-genotypic competition on productivity of radiata pine clones was examined to age 12 years in a trial established in 1993 at Dalethorpe, Canterbury, New Zealand. Ten clones were planted in a randomised complete block design in three replications in monoclonal and clonal mixture plots at initial stocking of 1250 trees per hectare. The study compared competition in monoclonal and clonal mixtures, *i.e* how clones performed in two different competitive environments.

Tree diameter and competition index exerted a significant influence on diameter increment in a distance-dependent diameter-increment model. At age 12 years overall competition did not differ with mode of deployment, but individual clones experienced significantly (P<0.0001) different levels of competition in monoclonal and clonal mixture plots. Competition remained uniform over time in monoclonal plots, whereas in clonal mixture plots trees of some clones experienced greater competition from neighbouring trees of different genotypes and were suppressed. Two of the ten clones suffered from significantly (P<0.0001) more competition at age 12 years in clonal mixture plots than in monoclonal plots. Significantly different competitive environments for trees of the same clone in both modes of deployment significantly affected diameter of clones (P=0.019) at age 12 years. Overall coefficient of variation (CV) of competition experienced by trees doubled in clonal

mixtures compared to monoclonal plots (30% versus 15%). Clones exhibited inter-changes of ranks in monoclonal plots. Trees of two suppressed clones, 6 and 8, exerted significantly more competition on neighbouring trees compared to other clones. The study indicated that inter-genotypic competition might exclude some better clones in single tree screening trials that could perform well if deployed monoclonally.

5.2 Introduction

Various studies and reviews have compared the productivities of monoculture and polyculture of species of different genera (Bristow *et al.* 2006; Forrester *et al*. 2004; 2006, Debell *et al.* 1997a; Parotta, 1999; Piotto *et al.* 2004; and Petit *et al.* 2006) and reported intermediate to greater productivity of mixtures than monocultures of species. Increasing reliance on plantations for quality timber, uniform raw material for industry, and rapid development of clonal forestry has limited tree use in plantations to a few species from even fewer genera. This has further enhanced the intensity of monocultures. Clonal forestry, which emphasises the use of highly productive clones for enhancing productivity of plantations, requires a choice of mode of clonal deployment. A few studies have compared the productivities of short rotation hardwood species in monoclonal and polyclonal plots and reported results ranging from no differences in overall productivity (Debell and Harrington (1997); and Benbrahim *et al.* 2000) to greater productivity of clonal mixtures (Markovic and Herpka 1986; Dawson and McCracken 1995).

Productivity of clonal plantations depends upon genotype, site conditions, environment, management practices, competition, and genotype x environment interactions. Influence of competition on growth of trees, productivity of plantations and size inequality depends upon genetic differences, available resources and stand density (Pretzsch, 2003; Park *et al.* 2003). Interactions between trees of the same species have been labelled “intra-specific competition” and between trees of different species is called “inter-specific competition” (Shainsky *et al*. 1992; Liu and Burkhart 1994; Park *et al*. 2003; Bristow *et al*. 2006). Effects of intra-specific and inter-specific competition have been reported in few studies that compared the productivity of monoculture and polyculture of different species, mainly of hardwoods. There is a paucity of studies comparing productivity and competitive interactions in monoclonal and clonal mixture plots in conifers.

Various competition indices have been developed to quantify competition between same-aged trees. These indices were categorised as distance-dependent and distance-independent competition indices (Munro, 1974). Distance-independent competition indices do not require spatial data whereas the distance-dependent indices do require spatial data to simulate diameter growth of individual trees. Single-tree spatial models use information about the distances to, and sizes of, neighbouring trees. Distance-dependent competition indices can be categorised in three groups:

- *Area overlap indices:* The first distance-dependent indices developed were based on measures of area overlap of influence zones between subject trees and competitors. The influence-zone of a tree is defined as an area over which the tree obtains or competes for site factors (Opie, 1968). Stabler (1951) first defined this concept and used the sum of linear overlaps within competition circles of subject trees and of competitors as a competition index. Various modifications of this concept has been done, *e.g.* Bella (1971); Daniels *et al*. (1986); Tome and Burkhert, (1989). A limitation of these indices is that size differentiation between a subject tree and its competitors was assumed to have no effect on competitive interactions.

- *Distance-weighted size ratio indices:* Size ratio indices calculate sums of ratios of subject tree dimensions to competitor tree dimensions. These ratios are often weighted by distances of the subject tree to its competitors. Hegyi's (1974) competition index, which is the sum of ratios of diameters at breast height weighted by distances between competitor and subject trees, is the most widely used size-ratio index. Various modifications of this model have been used *e.g.* without distance (Brodie and Debell, 2004); distance + 1 (Biging and Dobbertin, 1992); use of distance squared (Weiner, 1984). The size-ratio indices are useful for situations where there is uncertainty about the radius of the influence zone.

- *Area potentially available indices:* Brown (1965) first introduced area potentially available indices as measures of point density. The area potentially available is calculated by bisecting inter-tree distances to construct polygons of available area for

each tree, often using a weight according to tree size. Moore *et al.* (1973) used tree basal areas to determine the location of the perpendicular bisectors.

To develop models for plantations to simulate their growth and productivity, there is a need to develop effective competition indices to include the effects of competition. In New Zealand, Tennent (1975) used a 'competition quotient' based on area overlap indices, and reported that the competition quotient was useful for analysis of competition among individual trees. Tennent, (1982) developed a distance-dependent individual tree growth model for *Pinus radiata* and evaluated the effectiveness of several competition indices and reported that Gerrard's (1969) and Hegyi's, (1974) competition indices performed equally well in diameter, basal area and height increment models. Richardson *et al.* (1999) evaluated various competition indices of interspecific plant competition between *Pinus radiata* and Buddleia (*Buddleija davidii* Francher) or Broom (*Cytisus scoparius* L.), two important forest weeds in New Zealand. The best competition index combined measures of weed height relative to tree height, proximity of the weed to the tree, and weed abundance, and was negatively correlated with an index of light availability. Size-ratio competition indices might be more useful to quantify competition for forest plantations because of ease of data capture of common variables such as DBH or basal area, height and distances between trees.

Clones of the same species might differ in growth patterns and competitiveness. There is a need to develop competition indices that can also evaluate the effects of genotypes of neighbours on subject trees. This approach might be useful to identify the strongly competiting genotypes and might be useful to inform selections in single tree plots in progeny tests.

This study described had the following objectives:

- To evaluate effectiveness of a competition index that includes genotypes of neighbouring plants as a predictor in an individual tree diameter increment model.
- To compare competition within monoclonal with that inside clonal mixture plots.
- To analyse the influence of competition on tree and stand mortality, uniformity and productivity.

5.3 Materials and Methods

5.3.1 Site

An experiment was established with radiata pine (*Pinus radiata* D. Don) on a site at Dalethorpe (latitude 42°-45'S, longitude 171°-55'E, elevation 520 m above sea level), 70 km west of Christchurch, Canterbury, New Zealand in September 1993. The soil at the site was well-developed silt-loam (NZ Soil Bureau, 1968). Mean annual precipitation was 1058 mm from 1993-2006 (NIWA, 2006). Precipitation was distributed fairly evenly although site is prone to marked dry period during February and March (McCracken 1980).

5.3.2 Design of the experiment

Ten clones were deployed in monoclonal and clonal mixture plots in a complete randomised block design with three replications. Each block consisted of eleven treatments. Ten treatments were different clones tested monoclonally. The eleventh treatment involved all ten clones randomised in equal numbers inside each clonal-mixture plot. All plots were of rectangular shape (16 x 20 m) as in Figure 5.1, and contained 40 trees (5 x 8), except for one clonal mixture plot (64 x 20 m) that was larger (5 x 32 trees). Trees were spaced at 2 m within rows and 4 m between (1250 stems/ha). Total size of the experiment was 1.15 hectares, with 9600 sq m (83 %) of monoclonal and 1920 sq m of clonal mixture plots. No pruning treatments were applied to the experiment from 0-6 years. At age 7 years all trees were pruned to a height of 2.5 m. The trial was not thinned at any stage, although the normal silivicultural regime in Canterbury is an initial stocking of 1250 stems per hectare thinned to 600 stems per hectare at ages 6-7 years (MAF, 2005; SPBL, 2006).

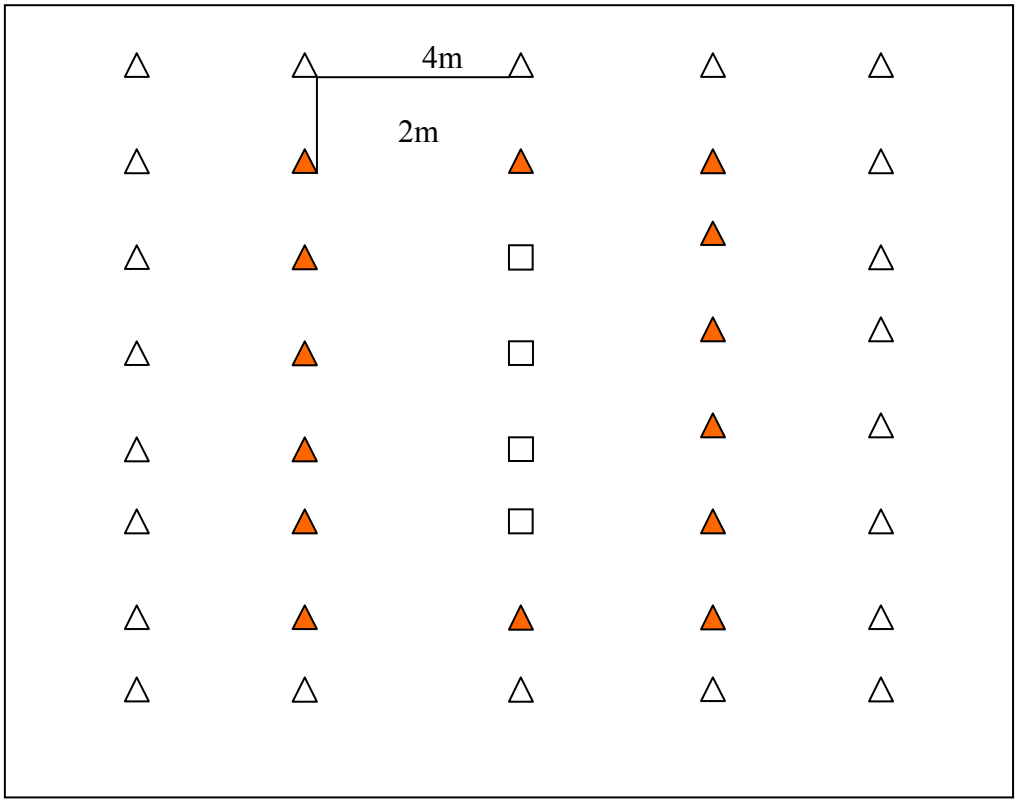


Figure 5.1: Layout of the experimental plot of 40 trees (16 x 20 m). In figure empty triangles represents buffer trees, dark triangles and squares represent trees measured, and squares only represent trees for which competition from eight surrounding trees were calculated.

5.3.3 Planting material

The ten clones (1-10) planted in this experiment were propagated by organogenesis from controlled pollinated mature seeds that were surface sterilised and germinated into sterile tissue cultures. After propagation they were hardened off in a nursery, conditioned with an undercutting and wrenching regime, and transplanted as bare-root plants. Clones 3, 7 and 10 were propagated from different seeds of same cross. Clones 1 & 9 and clones 6 & 8 were also propagated from different seeds of each of two crosses. Clones 2, 4 and 5 were from three different crosses. Clones deployed in this experiment therefore represented six different families. The exact pedigrees of the clones were not revealed by the organization that provided the clones for this experiment, although they were said to have growth and form ratings between 25 and 30 (Sorensson, personal communication).

5.3.4 Establishment practices

All the plants were planted in pits of 30 cm depth in ripped lines with ripping at a depth of 30 cm. Each planting spot was further cultivated with a spade. Each randomised complete block was planted by only one person. All the plots were kept completely weed free using initially a mixture of Hexazinone and Turbuthylazine, and subsequently a mixture of Turbuthylazine, Clopyralid and Haloxyfop herbicides for 5 years following planting.

5.3.5 Assessments

18 interior trees in each 40 tree plot (or 90 trees in one big clonal mixture plot) were assessed, avoiding boundary trees to exclude affects of inter-genotypic interactions. Height poles, Vertex hypsometers and diameter tapes were used to record tree heights and diameter at breast height over bark (DBH) to a precision of 10 cm and 0.1 cm respectively. Tree heights were recorded annually from establishment year 1993 to 2005. DBH (1.4 m) were recorded from 1997 to 2005 except years 2001 and 2002. Assessments were recorded every winter between the second fortnight of the month August and the first week of September when tree stem growth typically stops in Canterbury. Mortality, windthrow, stem damage, and any pathogen infections were noted yearly.

5.3.6 Variables calculated

Hegyi's competition index (equation 1) was selected to evaluate intra and inter-genotypic competition because it takes into account the influences of stem sizes, number of competitors and distances between competitors on growth of subject trees. This index is also useful in situations where there is uncertainty about the radius of influence zones of trees (Gadow and Hui, 1999).

$$CI = \Sigma\left(\frac{DBH_j}{DBH_i} * \frac{1}{d}\right) \qquad (1)$$

Where CI is overall competition index of i^{th} subject tree, DBH_j is diameter at breast height of j^{th} competitor, DBH_i is diameter at breast height of subject tree and d is distance between j^{th} competitor and i^{th} subject tree.

For the present study equation (1) was also modified by substituting distance squared for distance (equation 2), because simple physical models suggest that the influence of one object on another decreases with the inverse of distance squared (Weiner, 1982; 1984). Competition indices were calculated for each interior four trees (Figure 5.1) in all plots and 28 trees in the one big clonal mixture plot from ages 4 to 12 years except for ages 8 and 9 years. Results from the two indices were then compared. Equations (1) and (2) were used to calculate competition indices.

$$CI = \Sigma\left(\frac{DBH\,j}{DBH_i} * \frac{1}{d^2}\right) \qquad (2)$$

Mean heights, DBH, mortality of each clone in both modes of deployment were calculated from ages 4 to 12 years. Annual diameter increments were calculated to use in the distance-dependent diameter increment model to identify clones exerting greater competition on trees of other clones. Indices of competition exerted by individual clones on subject trees were calculated using equations (1) and (2) from ages 4 to 12 years. Stand basal areas were calculated from plot basal area for monoclonal plots and from clone basal area in clonal mixture plots.

5.3.7 Distance-dependent diameter increment model

A diameter increment model (3) was developed to evaluate the effectiveness of competition indices as an independent variable in distance-dependent models.

$$DI = \alpha + \beta\, D + \beta_1\, C \qquad (3)$$

Where α, β, β_1 were parameters, C was competition Index (overall competition experienced by subject tree from eight neighbouring trees), DI = annual diameter increment, and D = initial diameter.

Indices calculated using equations (1) and (2) were used to compare the effectiveness of distance and distance squared in distance-dependent model (3). The influence of neighbouring clones on growth of each other in clonal mixture plots was analysed by applying a distance-dependent diameter increment model (4) developed to assess the competition exerted by neighbouring trees when genotypes of the neighbouring trees were known.

$$DI = \alpha + \beta D + \beta_1 C_1 + \beta_2 C_2 + \beta_3 C_3 + \ldots\ldots\ldots\ldots\ldots + \beta_{10} C_{10} \quad (4)$$

Where α, β, β_1 to β_{10} were parameters, C_1 to C_{10} were indices of competition exerted by respective neighbouring clones on growth of subject tree, DI = annual diameter increment, and D = diameter at the beginning of a growth period. Growth periods were set as one year.

A nonlinear exponential model (5) was also tried with the linear term in equation (4) as a power term in equation 5:

$$DI = exp\left(\alpha + C^{\beta}\right) \quad (5)$$

Where $\alpha=\alpha_1 C_1 + \alpha_2 C_2 + \alpha_3 C_3 + \alpha_4 C_4 + \alpha_5 C_5 + \alpha_6 C_6 + \alpha_7 C_7 + \alpha_8 C_8 + \alpha_9 C_9 + \alpha_{10} C_{10}$

$\beta= \beta_1 C_1 + \beta_2 C_2 + \beta_3 C_3 + \beta_4 C_4 + \beta_5 C_5 + \beta_6 C_6 + \beta_7 C_7 + \beta_8 C_8 + \beta_9 C_9 + \beta_{10} C_{10}$

C = competition Index, C_1 to C_{10} were indices of competition exerted by respective neighbouring clones on growth of subject tree.

The models were tested for bias, homogeneity and normality of residuals (Observed value – predicted value). A log transformation of the dependent variable was applied wherever necessary to ensure normality of residuals.

5.3.8 Data Analysis

Procedures GLM (General linear models) and NLIN (Non-linear models) of SAS (SAS Institute Inc. 2000) were used to compare the productivity of clones across modes of deployment.

The following statistical model was used for analysis of variance:

$$Y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\gamma)_{ik} + e_{ijk} \quad (6)$$

Where Y_{ijk} is mean DBH or competition index of i^{th} clone, j^{th} block and k^{th} mode of deployment, μ is overall mean, α_i is i^{th} clone, β is j^{th} block, γ is k^{th} mode of deployment, $(\alpha\gamma)_{ik}$ is interaction of i^{th} clone and k^{th} mode of deployment and e_{ijk} is error. A Student-Newman-Keuls (SNK) multiple range test was used at P=0.05 to distinguish differences in mean DBH or competition indices of clones at age 12 years. Smallest Critical range of SNK test was used as measure of statistical power for each variable.

5.4 Results

5.4.1 Diameter increment models

Effectiveness of competition indices in growth models

The diameter increment model exhibited a significant (P<0.0001) inverse relationship with diameter (r^2=0.43). Inclusion of competition as an independent variable in the model along with diameter was significant, which also slightly improved the fit (r^2=0.46). Residual analysis (Figure 5.2 and 5.3) was carried out to test the goodness of fit.

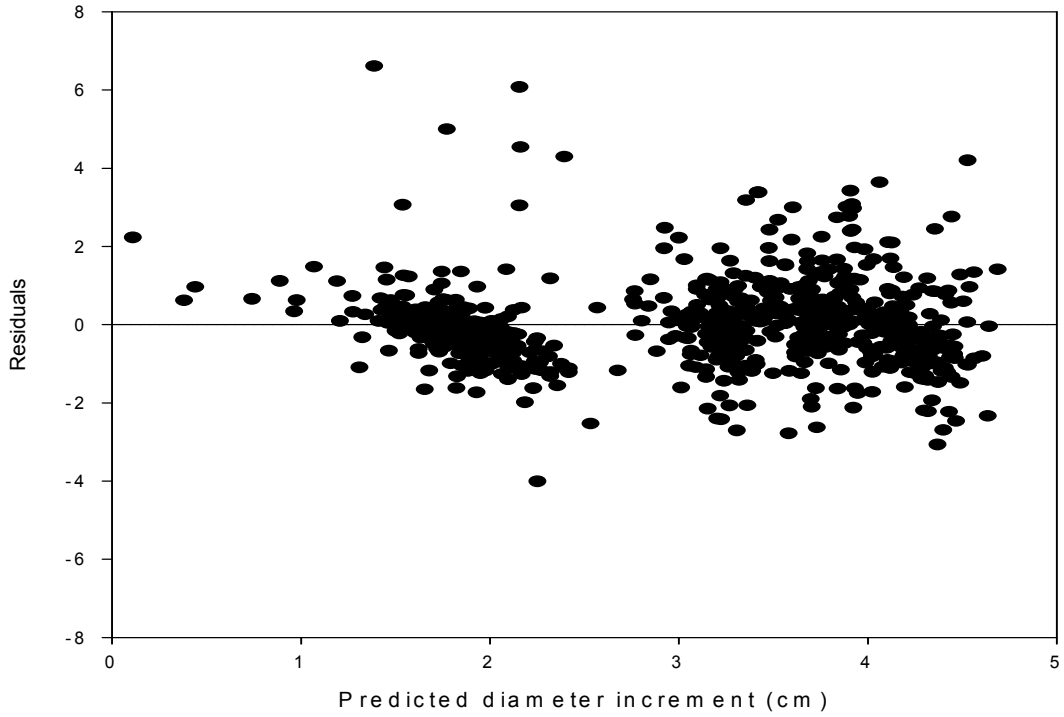


Figure 5.2: Plot of residuals (observed diameter increments-predicted diameter increments) versus predicted diameter increments of model (3).

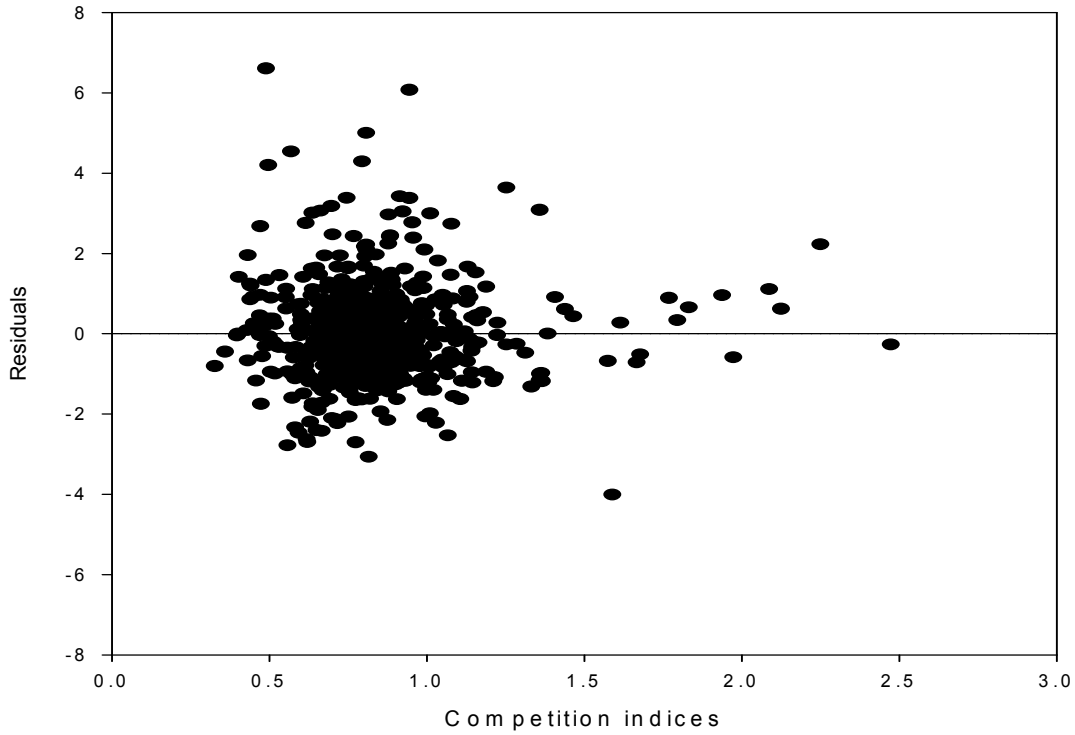


Figure 5.3: Plot of residuals (observed diameter increments-predicted diameter increments) versus competition indices of model (3).

Effectiveness of distance versus distance square in distance-dependent models

The inverse squared competition index (equation 2) provided a slightly superior fit to the data when compared with the simple index (equation 1) (Table 5.1).

Table 5.1: Comparison of statistics of two diameter increment models tested using competition indices calculated from equations (1) and (2).

Equation	r^2	Mean square error	Parameters		
			Intercept	initial diameter	Competition index
1	0.45	1.09	5.46	-0.125	-0.27
2	0.46	1.09	5.79	-0.129	-1.143

Effectiveness of competition indices of genotype in distance-dependent models

Inclusion of clonal competition indices in the distance-dependent diameter increment model (4) improved the fit of model (r^2=0.50) compared to a model lacking information of genotype (r^2=0.46). The linear model gave a better fit than the nonlinear model and was more effective at identifying genotypes exerting more influence on subject trees. Residual analysis (Figures 5.4 and 5.5) was carried out to test the goodness of fit.

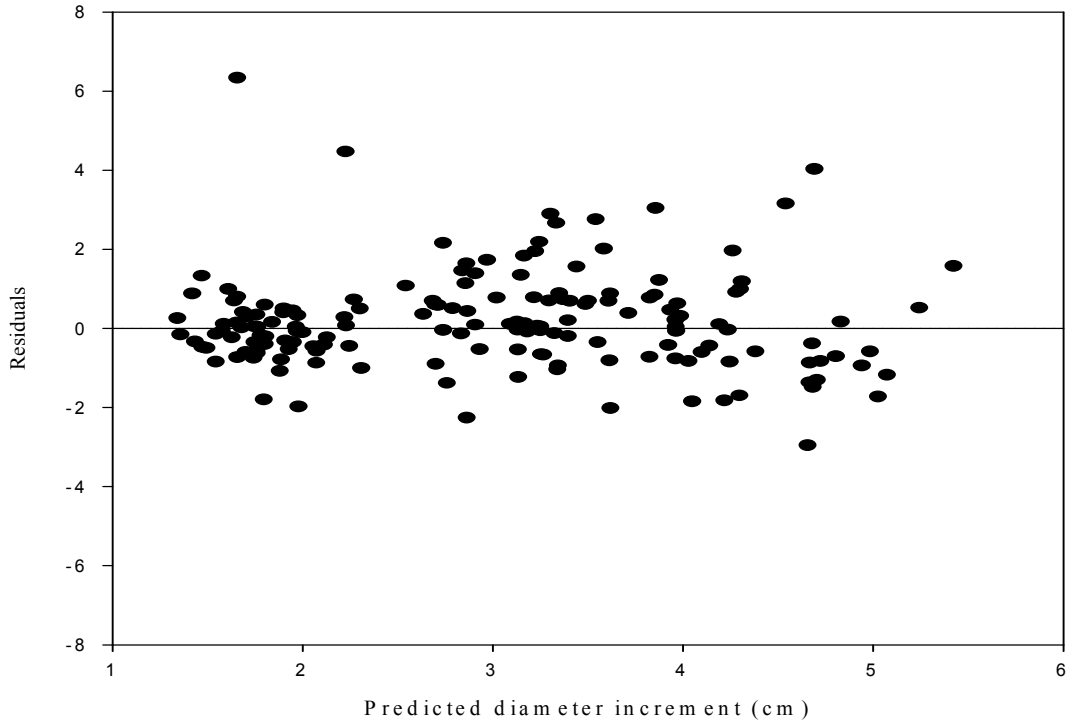


Figure 5.4: Plot of residuals versus predicted diameter increments for model (4).

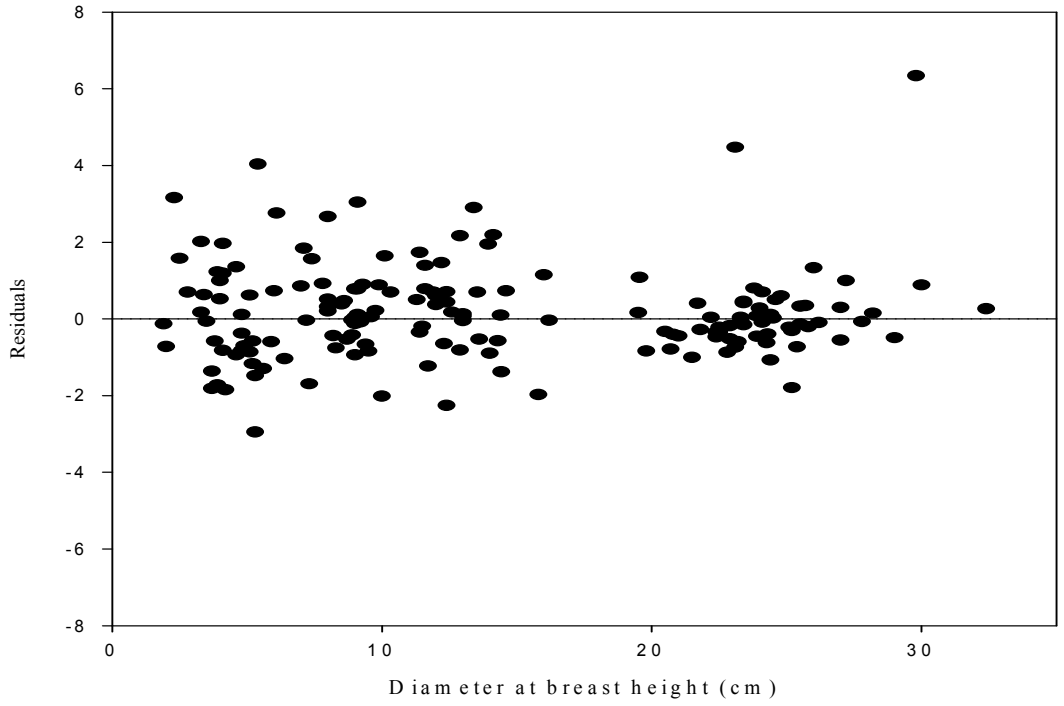


Figure 5.5: Plot of residuals versus diameter at breast height for model (4).

A linear model with competition indices of individual neighbouring genotypes (representing the competition posed by different genotypes) identified two clones, 6 and 8, with significantly negative estimates of competition indices (Table 5.2).

Table 5.2: Parameters of annual diameter increment model. C1 to C10 were the parameters of competition posed by clones 1 to 10 on diameter increment of subject tree in clonal mixture plots. Competition posed by eight neighbouring trees on each subject tree (36 trees) was calculated using equation (2).

Parameters	One year diameter increment model (1/distance squared)	
	Estimate	Pr > |t|
C1	-1.214	0.1806
C2	-0.536	0.1891
C3	0.767	0.7508
C4	0.050	0.9739
C5	-1.957	0.1356
C6	-2.974	**0.0068**
C7	-0.388	0.5838
C8	-2.709	**0.0170**
C9	-1.101	0.1169
C10	-0.627	0.7121
Intercept	5.807	**<.0001**
Diameter	-0.130	**<.0001**

5.4.2 Competition

Analysis of variance conducted on competition indices calculated for each clone using equation (2) in monoclonal and clonal mixture plots, to compare competition between monoclonal and clonal mixture plots, showed that overall competition at age 12 years did not differ between modes of deployment, although individual clones experienced different levels of competition in monoclonal and clonal mixture plots (Table 5.3). Analysis of variance revealed that trees of clones 7 and 10 experienced significantly (P<0.0001) greater competition in clonal mixture plots (Table 5.4) than in monoclonal plots (Figures 5.6 and 5.7).

Table 5.3: Analysis of variance: for DBH, stand basal area, competition index, and coefficient of variation of DBH and competition at age 12 years.

Source of variation	Diameter (Pr>F)	Stand Basal Area (Pr>F)	Competition Index (Pr>F)	Coefficient of Variation	
				Diameter (Pr>F)	Competition Index (Pr>F)
Blocks	0.332	0.994	0.226	0.142	0.699
Clones	0.0002	0.336	0.007	0.001	0.0006
Deployment	0.498	0.685	0.995	0.318	0.003
Clone x Deployment	0.019	0.681	<0.0001	0.028	0.0002

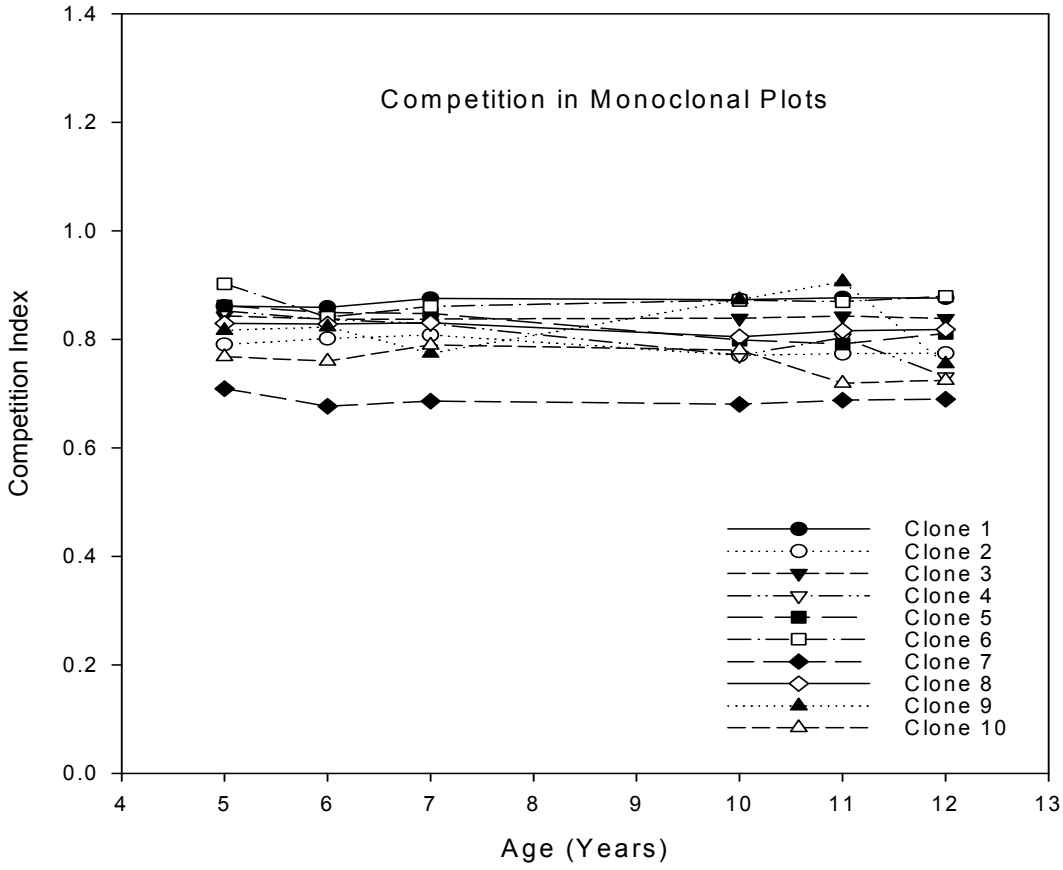


Figure 5.6: Intra-genotypic competition in monoclonal plots over time. Clones with greater values of competition index suffered from greater competition.

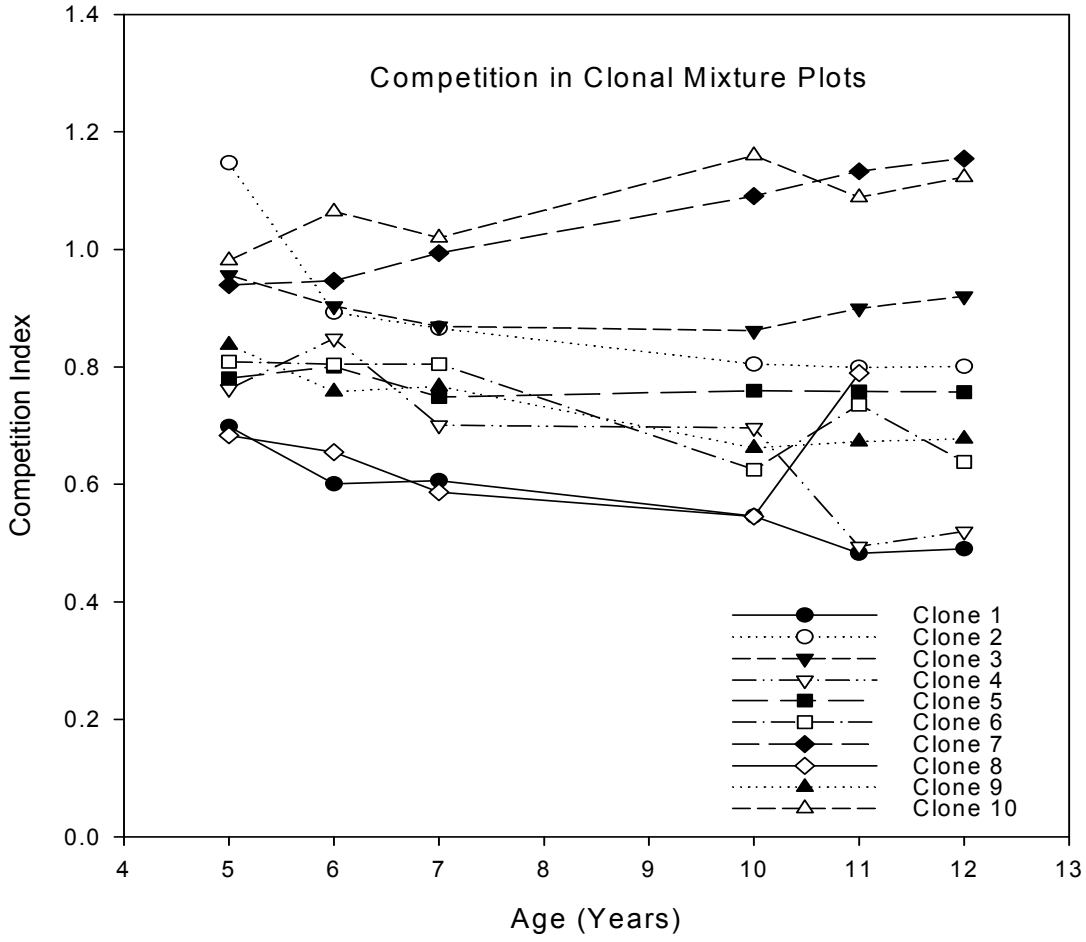


Figure 5.7: Inter-genotypic competition in clonal mixture plots over time. Clones with greater values of competition index suffered from greater competition and were less competitive.

5.4.3 Survival

Overall survival was similar in both modes of deployment at age 12 years. Survival was 1% greater in monoclonal plots after canopy closure compared to clonal mixture plots (Table 5.4). Trees of clone 9 suffered from windthrow damage both in monoclonal and clonal mixture plots.

Table 5.4: Survival (%), stand basal area (m^2/ha) and competition indices of clones in monoclonal and clonal mixture plots at age 12 years. Estimate of competition index for clone 8 couldn't be determined due to mortality of trees of this clone in clonal mixture plots. Values in each column followed by the same letter were not significantly different according to student-Newman-Keuls multiple range (P<0.05) test. 540 trees in monoclonal plots and 126 in clonal mixture plots were measured for calculating survivals and stand basal area. Competition indices for 120 and 36 trees were calculated in monoclonal and clonal mixture plots.

Clone	Survival (%)		Stand Basal Area (m^2/ha)		Competition Index	
	Monoclone	Clonal Mixture	Monoclone	Clonal Mixture	Monoclone	Clonal Mixture
1	100 a	93 a	67.0 ab	76.8 a	0.87 a	0.50 d
2	89 ab	97 a	56.8 ab	61.4 a	0.77 ab	0.81 bcd
3	100 a	96 a	60.3 ab	63.0 a	0.83 ab	0.90 abc
4	87 ab	67 a	56.6 ab	53.1 a	0.73 ab	0.49 d
5	94 a	100 a	70.7 a	90.7 a	0.81 ab	0.73 cd
6	100 a	83 a	65.0 ab	51.4 a	0.87 a	0.61 cd
7	82 ab	97 a	67.3 ab	54.7a	0.68 b	1.16 a
8	98 a	92 a	66.3 ab	63.5 a	0.81 ab	-
9	65 b	75 a	54.3 b	74.4 a	0.73 ab	0.66 cd
10	89 ab	94 a	61.3 ab	54.9 a	0.72 ab	1.10 ab
Overall	90	89	62.6	64.4	0.79	0.80
SNK critical range	25-43	40-68	15.8-26.9	39.8-67.9	0.18-0.30	0.35-0.68

5.4.4 Influence of competition on productivity of clones

DBH of certain clones significantly changed (P=0.019) with mode of deployment, although overall DBH values were similar. DBH of clone 7 was greater than many other clones in monoclonal plots (Figure 5.8), whereas it had the smallest clonal DBH in clonal mixtures (Figure 5.9). Although, there were quite distinct differences in stand basal area productivity of clones in clonal mixture plots, but they were statistically non-significant. These non-significant differences between clones might have resulted in type-II error due to lower power of the analysis in clonal mixture plots. Overall stand basal area did not differ with mode of deployment (P=0.685), and clone x mode of deployment interaction for stand basal area was also non-significant (P=0.681). Clone 9 exhibited greater average DBH in monoclonal plots (Figure 5.8), but lowest stand basal area (Figure 5.10) at age 12 years due to greater mortality of this clone. Clones 1, 5 and 9 dominated in tree basal area productivity (Table 5.4) in clonal mixture plots (Figure 5.11). Clone 9 performed poorly in stand basal area productivity in monoclonal plots due to its greater mortality. Clone 5 was highly productive in both modes of deployment.

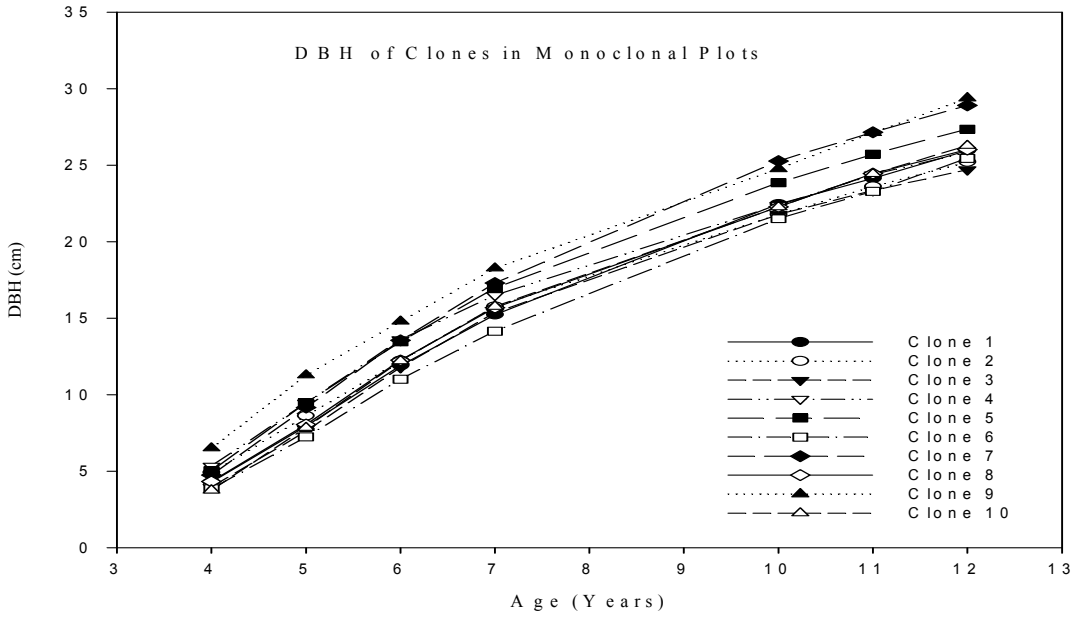


Figure 5.8: Trend of DBH productivity of clones in monoclonal plots from age 4 to 12 years.

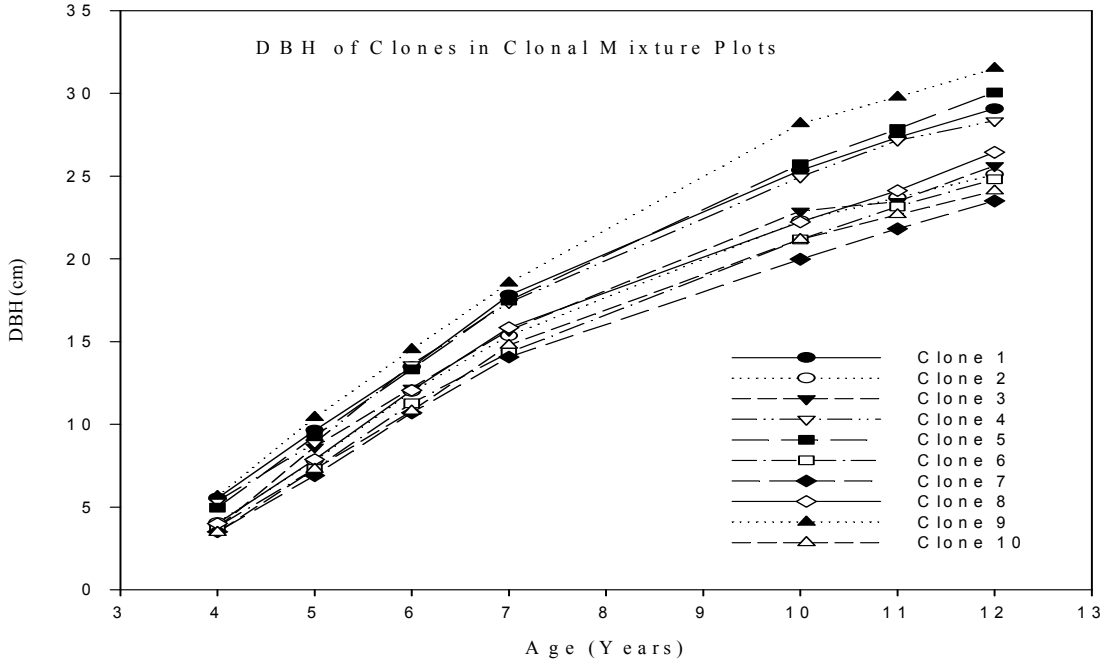


Figure 5.9: Trend of DBH productivity of clones in clonal mixture plots from age 4 to 12 years.

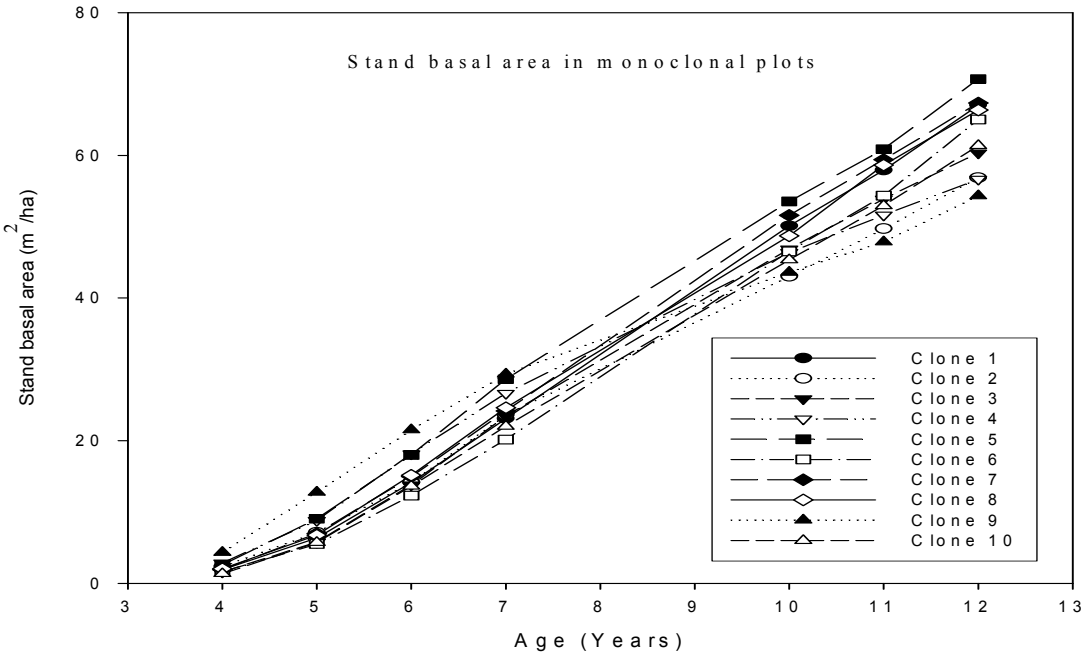


Figure 5.10: Trend of stand basal area productivity of clones in monoclonal plots from age 4 to 12 years.

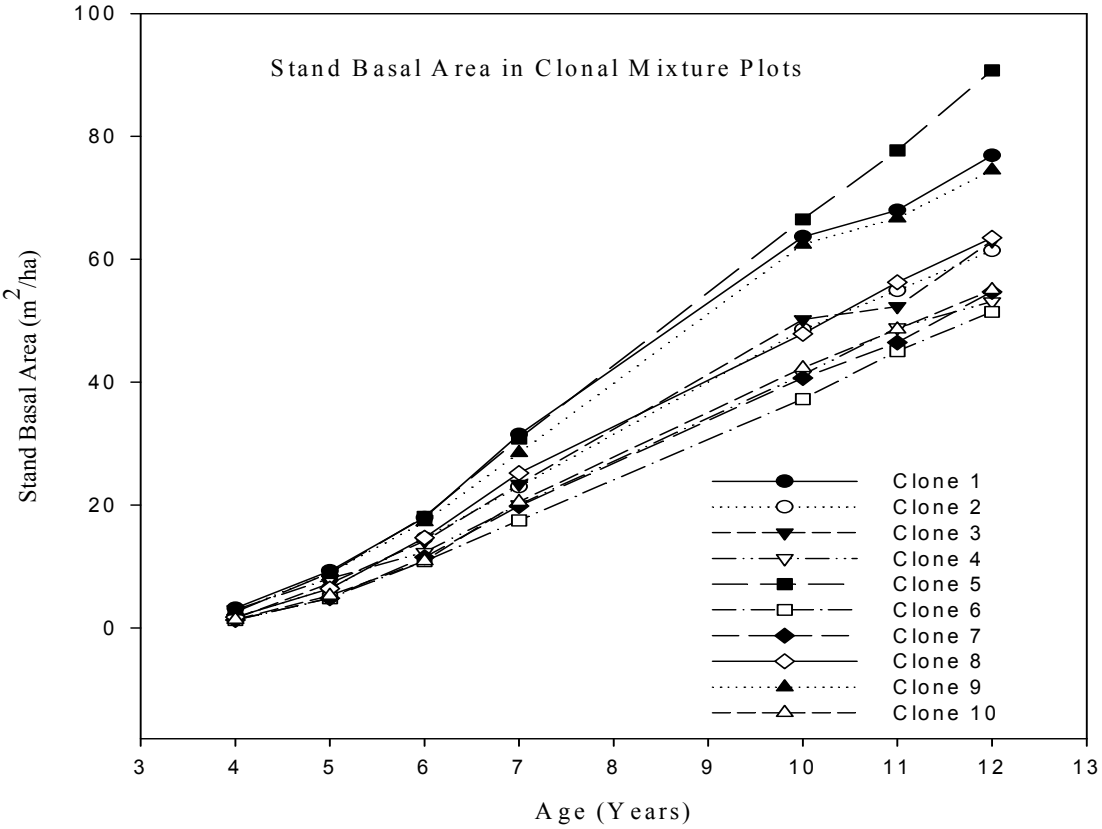


Figure 5.11: Trend of stand basal area productivity of clones in clonal mixture plots from age 4 to 12 years.

5.4.5 Variability

Coefficient of variation of competition in clonal mixture plots was significantly greater (P=0.003) compared to monoclonal plots (Table 5.3). Competition remained uniform in monoclonal plots over time, whereas in clonal mixtures dominant clones experienced less competition and suppressed clones experienced greater competition (Figure 5.6 and 5.7). This led to significantly greater variability (P=0.0002) in competition experienced by trees of the same genotype in clonal mixture plots compared to monoclonal plots. Variability in competition in clonal mixtures was twice that of monoclonal plots (30% versus 15%) and that significantly increased between clone variability in DBH (Figures 5.8 and 5.9) and stand basal area (Figures 5.10 and 5.11).

5.4.6. Changes in ranks

Interchanges of clonal ranks were more prominent in monoclonal plots (Figures 5.8 and 5.10). Clone 6, 7, 8 and 10 grew slowly during the establishment period. Slow growth of clones 7 and 10 was probably due to transplant stress, but over time they recovered and started growing rapidly and surpassed some clones (Chapter 3 and 4). Clone 7 at age 12 years dominated in monoclonal plots in DBH and stand basal area, whereas the same clone exhibited the lowest DBH and stand basal area in clonal mixture plots. Clonal rankings almost stabilised around age 7 years in clonal mixture plots, after which only slight interchanges of ranks occurred just among suppressed clones.

5.5 Discussion

Distance-dependent individual tree models generally take into account the sizes of nearby competing plants, as well as the distances to them (Munro, 1974; Garcia, 1988). This study demonstrated that including an inverse squared distance, and estimating coefficients for the genotypes of neighbouring clonal trees, both improved the fit of a distance-dependent model of diameter increment.

This kind of representation may provide improved models for managers of clonal mixtures. Clone 6 was, for example more competitive, for a given equivalent DBH, than other clones. Xu (2000) found that this clone allocated more photosynthate than normal to its foliage biomass. This greater allocation to foliage may explain its enhanced competitiveness. These findings highlight how distance-dependent modelling can be used to screen out overly competitive clones that might be undesirable in mixed clone deployment. In addition, studies of allocation and allometry may have the potential to improve clonal screening when compared to trials that simply examine stem measurements.

Trees compete for nutrients, moisture and light. Initially they compete primarily for nutrients and moisture, but after canopy closure, the competition for light increases (Weiner and Thomas, 1986). The ramets of a clone may compete more severely for available resources in monoclonal stands because of similar demands on available

resources (Libby and Cockerham, 1980). But, the results of this study didn't confirm this hypothesis, because in monoclonal stands greater genetic and size uniformity might have resulted in competition for water and nutrients only, and in clonal mixtures the clones might have competed for light to a greater extent also. Sakai *et al*. (1968) compared intra-clonal and inter-genotypic competition in *Cryptomeria japonica* D. Don forests and reported lower intra-clonal competition compared to inter-genotypic competition. Usually, the competition after canopy closure is primarily due to competition for light (Weiner and Thomas, 1986). In this study trees that grew rapidly during the establishment period had the advantage of capturing more light after canopy closure in clonal mixtures, and tended to dominate the stand, whereas slow beginners became suppressed by initially dominant clones.

Dominance and suppression in clonal mixtures led to greater within-clone and within-plot variation in DBH. The trees interacting with each other in monoclonal plots were of similar morphologies, growth pattern and competitiveness, and grew similarly in size which resulted in greater uniformity in size and competition experienced over time. In clonal mixtures clones had different morphologies, growth patterns and competitiveness. Clones 6 and 8 were slow beginners, and clones 7 and 10 experienced transplant stress due to greater initial heights of planting stock which led to their slow growth during establishment period (Chapter 3). The plants of these clones eventually grew rapidly in monoclonal plots, whereas they were suppressed by dominant clones in clonal mixture plots. Increased variation in stem sizes over time also enhanced within-clone and within-plot variation in competition experienced by trees in clonal mixture plots.

The use of uniformly high quality planting stock, proper initial management and deployment of clones of similar growth patterns might enhance productivity of clonal mixture plantations. Differences in initial quality of planting stock and initial growth patterns resulted in asymmetric competition in clonal mixture plots and the clones that grew fast in the beginning utilized a disproportionately large share of available resources to the detriment of the growth of smaller neighbours and influenced the productivity of clones.

Competition resulted in stratification of the stand canopy in clonal mixture plots after canopy closure. This enhanced mortality of the suppressed shorter trees. Trees of dominant clone 9 suffered windthrow damage, both in monoclonal and clonal mixture plots. So dominance and suppression of trees may have led to overall slight increases in mortality in clonal mixture plots, and the design of the experiment may not have been powerful enough to show that the observed difference was statistically significant.

Changes in ranks have been reported both in monoclonal (Debell and Harrington 1997) and clonal mixtures over time (Zsuffa 1975; Ares 2002). Clones also exhibited changes in ranks in this study from age 4 to age 12 years, mainly in monoclonal plots. Clones 6, and 8 were slow beginners, but they then began growing rapidly and improved their ranks in monoclonal plots. In clonal mixture plots slight inter-changes of rank were exhibited by suppressed clones.

Results of this study suggest that inter-genotypic competition in clonal mixture screening trials (single tree plots) might cause researchers to miss some clones that could perform well if deployed monoclonally. In many breeding programs selections are made in single tree plots (White, 2001) that represent a clonal mixture mode of deployment. This study showed that inter-genotypic competition influenced performances of individual trees or genotypes. Liu and Burkhart (1994) also reported that inter-genotypic competition from hardwood species exerted more influence in reducing the basal area growth of loblolly pine trees under higher levels of competition in mixtures. Panetsos (1980) found that competition masked the expression of actual potentials of clones under greater competitive environments. This study found that in clonal mixtures, clones 6, 7, and 8 failed to express their potential and were suppressed in mixture, whereas the same clones performed above average in monoclonal plots. A number of studies that compared the effectiveness of block plot, single tree plot or row plot progeny test designs have concluded that screening in single tree plots or row plots would be impractical due to inter-genotypic competition effects if the selected genotypes would be deployed in pure blocks in operational plantations (Franklin, 1989; Foster 1989; Foster *et al*. 1998; Stagner *et al*. 2007). They recommended that selections should be done in block plot progeny test if they are to be deployed in pure plantations or in single tree plots if they are to be deployed in mixtures. In a recent study Stanger *et al.* (2007) compared the effectiveness of single tree plot and block

plot field designs in a Eucalyptus hybrid clonal experiment in Zululand and reported that gains predicted using single tree plot data were gross overestimates compared to the realized gains measured on the block plots. One clone had a predicted gain of 74 % in single tree plots, but in reality only yielded 7 % more in block plots. The results of this trial demonstrated that single tree plot field design might lead to over or under estimation of yield due to inter-genotypic interactions. Therefore, testing of small number of selected clones in block plots at higher level of selection programs might give better estimates of realistic gains from particular clones to be deployed in monoclonal mode of deployment. Libby (1987a) had also recommended testing in block plot test design to evaluate clones for per unit area productivity at higher levels of selection programs.

Productive versus competitive clones

Clones 1, 5 and 9 dominated in clonal mixture plots and were more productive in stand basal area (Table 5.4) and stand volume (Chapter 4, table 4.2) compared to other clones. Greater initial growth of trees of these clones meant that they exerted a large influence on growth of initially slower growing clones. These clones had greater average heights and DBH at age 12 years in clonal mixture plots (Chapter 4, table 4.1) Clones 6 and 8 grew slowly but exerted greater influence on growth of trees of other clones (posed greater competition to other clones) in clonal mixture plots (Table 5.2), therefore, were more competitive. These clones were productive in monoclonal plots, but under-productive in clonal mixtures. Clone 1 possessed higher position in the canopy in clonal mixtures, therefore, might have captured more light compared to suppressed clones that resulted in greater productivity of this clone in clonal mixture plots.

Kelty (2006) and Forester *et al*. (2006) reviewed several studies that compared the productivity of monoculture and mixed plantations of timber species and nitrogen fixing species and reported that higher stand-level productivity in mixed plantations was the result of two kinds of species interactions: complimentary resource use between species due to stratification of canopy, and improved nutrients availability by nitrogen fixing species for timber species. These principles may hold good for some clonal mixtures of different species, but we did not find them in the study reported here. Deploying light demanding and shade tolerant clones in mixtures might enhance productivity. Use of

unproductive but very competitive clones (such as clones 6 and 8) that cause reductions in growth of neighbours should be avoided in clonal mixtures. Libby (1987a) has also recommended testing of sets of small number of selected clones in clonal mixtures at different site conditions to select compatible clones to enhance the productivity of clonal mixture stands.

5.6 Conclusions

A distance dependent model that incorporated an inverse-squared distance to neighbouring plants in the competition index provided a slightly superior fit to the data compared to one that employed a simple inverse of distance.

Inclusion of clonal competition indices in the distance-dependent individual tree growth model improved the fit of the model compared to a model that lacking information about genotype. In particular two of the ten genotypes studied competed more vigorously for resources relative to their stem dimensions than did other clones. This study also demonstrated the effectiveness of a distance-dependent individual-tree-level model in identifying strong competitors that could check the growth of other clones in clonal mixtures.

Clones experienced different levels of competition in monoclonal and clonal mixture plots, and this resulted in differences in growth and productivity of some clones. Inter-genotypic competition enhanced both within- and between-clone variability in tree size.

CHAPTER 6

MODELLING STAND YIELD OF CLONES IN MONOCLONAL STANDS USING STAND-LEVEL MENSURATIONAL APPROACHES

6.1 Abstract

Effectivenesses of fitted stand yield models of mean top heights and stand basal areas at ages 7, 10 and 12 years were evaluated for prediction of age 13 years productivity of monoclonal stands in a clonal experiment established in 1993 with ten radiata pine clones at Dalethorpe, Canterbury, New Zealand. Ten clones were planted in a randomised complete block design in three replications in monoclonal plots at an initial stocking of 1250 stems per hectare. Five yield equations were used to fit the mean top height and stand basal area data. A Gompertz yield function and a Schumacher yield function fitted well to mean top height and stand basal area data respectively.

Analyses of the parameters of the individual plot mean top heights and stand basal area models indicated that models of clones differed due to differences in both yield pattern and asymptotic parameters. Parameters of fitted models depicted that clones may be significantly different in stand basal area yield, although analysis of stand basal area data failed to exhibit these differences from age 10 years onwards except at age 12 years. Two distinct groups of clones were identified using principal component analysis and nonlinear modelling. The parameters of models fitted to mean top heights and stand basal area data up to age 12 years gave closer predictions to observed values at age 13 years than parameters of models fitted to data up to ages 7 and 10 years.

The effectiveness of existing yield models of stand basal area and mean top height were evaluated to predict the yield of clones at age 13 years from initial age 6 years. Both models under predicted the stand basal area and mean top height for the majority of clones.

6.2 Introduction

Forest managers use growth and yield models to project future states of their forests for management and production planning purposes (Garcia, 1988), and increasingly for analysing growth responses to silvicultural operations and environmental factors. Bossel (1991) categorised growth models as descriptive (mensuration-based models), and explanatory (process-based models).

Three categories of forest simulation modelling have been proposed: mensuration-based growth and yield models, process-based (physiological) models, and hybrid models (Kimmins *et al*., 1990; Landsberg, 2003). Models can be classified as stand level and individual tree level in accordance with their levels of resolution (Burkhart and Tennent, 1977). Stand level models typically use stand values (mean top height, stand basal area, stocking, and volume per unit area) as the basic modelling units.

Models currently used in New Zealand are mostly stand level models created using a state-space system (Garcia, 1988; 1994). Mensuration-based growth and yield models are the simplest methods for predicting short-term future forest growth and productivity over which future growing conditions are not expected to change significantly (Kimmins *et al.,* 1990; Korzukhin *et al.* 1996) and can be tested rigorously through statistical analysis (Mohren and Burkhart, 1994; Korzukhin *et al.* 1996). The effectiveness of models depends upon their accuracy in prediction of long term or rotation-age productivity.

It is widely acknowledged that extrapolating mensuration-based models may lead to biased predictions. Genotype or species, silvicultural practices, competition, site conditions and their interactions determine the productivity at particular sites, and mensuration-based models usually fail to take these factors into account explicitly. Instead the models rely on knowledge of yield at a particular age as a surrogate for these factors that actually influence growth, with the expectation that growth patterns in the future will be consistent

with those observed in permanent sample plots generally. It is therefore relevant to ask whether such models might be used to project the future yields of clones when only initial yields are known.

Clonal forestry has become practically feasible in New Zealand with the development of new techniques of propagation, maintenance of juvenility, and cryo-perservation (Aimers-Halliday *et al.* 2003; Carson *et al*., 2004). Clonal forestry emphasises the use of best clones with respect to growth and form, wood qualities, resistance to insect-pest and diseases infestation, and desirable combinations of improvements in these traits.

Genotypes may grow differently under similar site conditions and similar silvicultural regimes. Growth and yield functions might be fitted to clonal stands' mensurational data to analyse their growth and productivities. Whyte and Woollens (1990) used modelling and discriminant analyses to analyse yield in stand basal area and mean top heights of radiata pine thinned to 200 stems/ha, 300 stems/ha, 400 stems/ha, 500 stems/ha, 600 stems/ha and 700 stems/ha densities and found that efficient stand basal area productivity was attained at a stocking of 300 stems/ha. Therefore modelling and multivariate analysis might be used in a similar way to analyse the growth and yield pattern of clones. If clones deployed at one site differ in their growth or yield pattern then fitting one growth or yield function to all clones might not give accurate predictions of future states of stands of different clones growing under similar conditions.

There is need to develop or select growth and yield functions that can represent reasonably well the changes in growth patterns of stands with minimum bias. Carson *et al.* (1999a) used genetic gain multipliers (relative growth of the improved seedlot compared to the unimproved seedlot) to predict the yield and genetic gains of improved seedlots over unimproved seedlot. Use of genetic gain multipliers to predict the productivities of monoclonal stands might not be useful because genetic gain multipliers have been developed using stands of improved and unimproved seedlots, so are more applicable to family forestry. They also assume that genetic gain does not vary with age, an assumption that would need to be verified before multipliers could be applied to models of clonal stands. The stands of different seedlots also represent clonal mixture stands, and growth of genotypes in monoclonal stands might differ from clonal mixture stands. Therefore, careful

analysis of age-age correlations by using traditional yield modelling to extrapolate clonal growth rates might be more useful. This study was planned with following objectives:

- To analyse and compare stand growth and yield of clones.
- To evaluate the effectiveness of some mensurational stand yield functions for predictions of future states of clonal stands growing under similar site conditions.
- To evaluate the effectiveness of existing yield models developed for Canterbury region for projecting yield of clones.

6.3 Materials and Methods

6.3.1 Site

An experiment was established with radiata pine (*Pinus radiata* D. Don) on a site at Dalethorpe (latitude 42°-45'S, longitude 171°-55'E, elevation 520 m above sea level), 70 km west of Christchurch, Canterbury, New Zealand in September 1993. The soil at the site was well-developed silt-loam (NZ Soil Bureau, 1968). Mean annual precipitation was 1058 mm from 1993-2006 (NIWA, 2006). Precipitation is distributed fairly evenly throughout the year although a marked dry period can occur during February and March (McCracken 1980).

6.3.2 Design of the experiment

Ten clones were deployed in two modes of deployment (monoclonal and clonal mixture) in a randomized complete block design with three blocks. Each block thus comprised eleven treatments: Each monoclone and the clonal mix contained all ten clones randomized in equal proportions. All plots were of rectangular shape (16 x 20 m), and contained 40 trees (5 x 8). Trees were spaced at 2 m within rows, and rows spaced at 4 m. No pruning treatments were applied to the experiment from 0-6 years, and at age 7 years all trees were pruned to a height of 2.5 m. Experiment was not thinned at any stage, although the normal silivicultural regime in Canterbury is an initial stocking of 1250 stems per hectare thinned to 600 stems per hectare at ages 6-7 years (MAF, 2005; SPBL, 2006).

6.3.3 Planting material

Clones were propagated by organogenesis from controlled pollinated mature seeds that were surface sterilised and germinated into sterile tissue cultures. After propagation they were hardened off in a nursery in the North Island (Fletcher Challenge Forests Ltd. Biotechnology Centre, TeTeko) with an undercutting and wrenching regime, and then were transplanted as bare-root plants. Ten clones (numbered 1 to 10) were planted in this experiment, derived from control-pollinated crosses. Clones 3, 7 and 10 were propagated from different seeds of same control-pollinated cross and are "full-sibs". Clones 1 & 9 and clones 6 & 8 were also propagated from different seeds of each of two crosses. Clones 2, 4 and 5 were from three additional crosses. Clones deployed in this experiment therefore represented six different families. The exact pedigrees of the clones were not revealed by the organization that provided the clones for this experiment, although they were said to have growth and form ratings (Sorensson, personal communication) between 25 and 30.

6.3.4 Establishment practices

All the plants were planted in pits of 30 cm depth in ripped lines with ripping at a depth of 30 cm. Each planting spot was further cultivated with a spade. Each randomised complete block was planted by only one person. All the plots were kept completely weed free using initially a mixture of Hexazinone and Turbuthylazine, and subsequently a mixture of Turbuthylazine, Clopyralid and Haloxyfop herbicides for 5 years following planting.

6.3.5 Assessments

Leaving one buffer row around each plot, the total tree heights and ground-line diameters (GLD) of 18 interior trees in each treatment were recorded from establishment year 1993 to 1996 using Vertex hypsometer and diameter tapes respectively. From 1997 to 2005 tree heights and diameters at breast height over bark (DBH) were recorded on interior plot trees, except during 2001 and 2002.

6.3.6 Variables calculated

Mean top heights (MTH) were calculated for each monoclonal plot from 1994 to 2005 except year 2001 and 2002. Coefficients of the Petterson equation (Goulding, 2005) were calculated for each plot from year 1994 to 2005. For years 1994 to 1996 the following linear form of the Petterson equation (1) was used.

$$Y = a + b * DBH \tag{1}$$

Where $Y = \frac{DBH}{(H - 1.4)^{0.4}}$ (2)

H was height of trees (m), DBH was diameter at breast height over bark (cm) and 1.4 was breast height (m).

When heights of the trees were less than 1.4 m, equation (2) was modified as follows:

$$Y = \frac{GLD}{H^{0.4}} \tag{3}$$

GLD was ground-line diameter of trees.

For year 1997 to 2005 nonlinear form of Petterson equation (4) was used to calculate the coefficients of the equation.

$$MTH = 1.4 + \left[b + \left(\frac{a}{DBH} \right)^{-2.5} \right] \tag{4}$$

Where MTH was mean top height in meters, DBH was diameter at breast height in cm, 1.4 was breast height in meters, and a and b were coefficients.

Mean top heights were estimated from fitted Petterson equations by estimating mean top diameter (mean diameter of the 100 largest stems/ha), and then using the equations to estimate the height corresponding to this mean top diameter. Stand basal areas per hectare for each plot were calculated from years 1997 to 2005 from plot basal areas.

6.3.7 Modelling equations

Yield equations used were listed in Table 6.1 (source: Whyte and Woollons, 1990; Woollons *et al.* 1990, 1992).

Table 6.1: Yield equations fitted to mean top height and stand basal area estimates.

Model	Equation	
Schumacher yield 1	$y = e^{\left(\alpha - \frac{\beta}{T}\right)}$	(5)
Schumacher yield 2	$y = e^{\left(\alpha - \frac{\beta}{T^{\gamma}}\right)}$	(6)
Gompertz yield	$y = e^{\left(\alpha - \beta\gamma^{T}\right)}$	(7)
Hossfeld yield	$y = \frac{\alpha T^{\gamma}}{\alpha\beta + T^{\gamma}}$	(8)
Von-Bertalanffy-Richards yield	$y = \alpha\left(1 - e^{(-\beta T)}\right)^{\theta}$	(9)

Fits were compared to select the best model. The minimum Mean Square Error (Appendix III and IV) for individual models, residual analyses of individual models for each equation, residual analyses of overall fit (to all plots taken together as one plot) and normality of residuals of models fitted to each clone were used as criteria for selecting the equations for mean top heights and stand basal areas. Plots of residuals versus predicted values and versus independent variables were examined to detect the bias. The best model was defined as the one that minimised the mean square error (MSE) while retaining a normal frequency distribution of residuals and exhibiting minimal bias.

6.3.8 Data analysis

The generalised linear model procedure of SAS (SAS institute Inc. 2000) was used to detect statistically significant differences between the parameters of the individual models fitted to mean top heights and stand basal areas of clones.

Principal component analysis as outlined by Manly (1986) was performed on parameters of stand basal areas and mean top height models separately, and collectively, to find out whether yield models of clones differed, and to identify the parameters that were responsible for differences between models. All the variables used in principal component analysis were standardised to avoid the influence of greater variance of one variable on principal components. The parameters of stand basal area models that represent their asymptotes and yield patterns were used to group the clones. Analysis of variance was carried out on values of principal component 1, and SNK (Student-Newman-Keuls) multiple range test (P<0.05) was carried out to allocate the clones to groups of similar clones. The smallest critical range of SNK test was used as measure of statistical power for each variable.

Nonlinear model (5) was also used to evaluate the differences in yield of clones and identify different groups of clones having similar asymptotes and yield patterns using stand basal areas data.

$$Y = e^{\left(\alpha - \frac{\beta}{T}\right)}$$

Where $\alpha = \alpha_0 + \alpha_1 C_4 + \alpha_2 C_9$ and $\beta = \beta_0 + \beta_1 C_4 + \beta_2 C_9$

Y = stand basal area (m^2/ha), T = age (Years), α, α_0, α_1, α_2, β, β_0, β_1 and β_2 were parameters of the model representing different yield patterns and asymptotes of three distinct groups exhibited by principal component analysis, C4 and C9 were dummy variables.

Stand basal area increments for age intervals 4-5, 5-7, 7-10 and 10-12 years were calculated to compare the growth rates of clones

To evaluate the effectiveness of the fitted individual plot models for prediction of future productivity of plots, the Gompertz and Schumacher yield functions were fitted to mean top height and stand basal area data respectively up to ages 7, 10 and 12 years. Parameters of the fitted models were used to simulate mean top heights and stand basal areas at age 13 years. The predicted mean top heights and stand basal areas of individual plots at age 13 years were compared with observed values. Residual (observed value – predicted value)

analyses were carried out for mean top height and stand basal area models fitted and existing models to detect bias in predictions.

6.3.9. Evaluation of existing yield models

Stand basal area model (10) and mean top height yield model (11) developed by Coulmann (2007) for Canterbury hills were evaluated for predicting the stand basal area and mean top height of clones at age 13 years from initial observed stand basal area and mean top height at age 6 years. Residual analysis was carried out to evaluate the effectiveness of models.

$$G_2 = G_1^{\left(\frac{T_1}{T_2}\right)} .e^{\left(\frac{\left(alt^{\lambda}-1\right)}{\lambda}+\alpha\right).\left(1-\frac{T_1}{T_2}\right)^{\beta}} \quad (10)$$

Where G_2 is the predicted stand basal area based on initial stand basal area (G_1), initial age (T_1), final age (T_2) and altitude (alt). λ = -0.159724, β = 0.989757 and α = 1.35388 are parameter values.

$$MTH_2 = e^{ln(MTH_1)\left(\frac{T_1+\gamma}{T_2+\gamma}\right)^{\beta}+\frac{\left(\alpha_0+\alpha_1.alt^2+\alpha_2.(alt-450).X\right)}{10000}.\left(1-\left(\frac{T_1+\gamma}{T_2+\gamma}\right)^{\beta}\right)} \quad (11)$$

Where MTH_2 is the predicted mean top height based on initial mean top height (MTH_1), initial age (T_1), final age (T_2) and altitude (alt). X is dummy variable which is equal to 0 where altitude < 450 m and equal to 1 where altitude ≥ 450 m. γ = 18.299, β = 1.65054, α_0=40696.9, α_1 = 0.0195852 and α_2= -33.1349 are parameter values.

6.4 Results

6.4.1 Mean top heights

At age 12 years, clones differed significantly (*P*=0.0017) in mean top heights (Table 6.2). The differentiation between clones started at age 3 years (Figure 6.1). The trajectories of mean top heights in Figure 6.1 clearly indicate that these differences reflect differences in

yield patterns among clones. The largest difference of mean top height at age 13 years was between clones 7 and 9, a difference of more than 2 metres (Figure 6.1, Table 6.2).

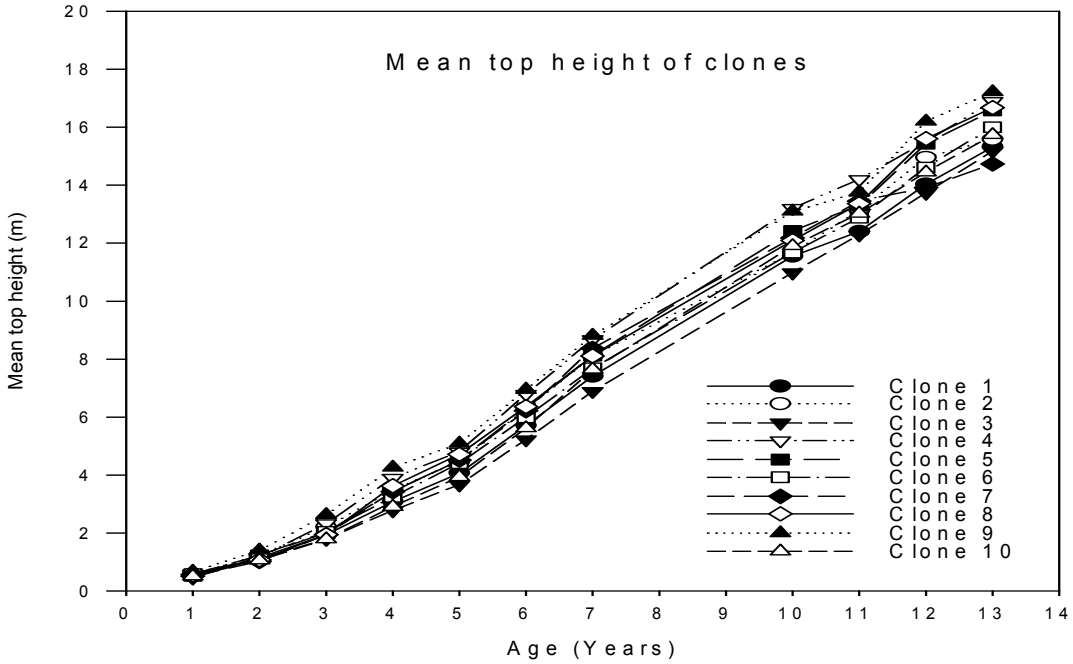


Figure 6.1: Calculated mean top heights of clones from age 1 to 13 years.

The best fitting equation to the mean top heights was the Gompertz nonlinear yield equation (7).

Individual analyses of the parameters of mean top heights models indicated that there were differences in the yield models of clones, showing distinct groupings for mean top heights parameters (Table 6.3). Principal component analyses of parameters taken together showed that principal components 1 and 2 explained 80 and 16 percent of variations respectively between the parameters of mean top heights models (Table 6.4). Eigen-vectors of principal components 1 and 2 indicated that differences between yield models were both due to differences between parameters representing yield patterns and asymptotes of models. All the parameters contributed almost equally to principal component one (Table 6.4). The most significant difference among mean top height yield models was between clones 7 and 9 (Figure 6.2) that confirmed the significant differences in mean top heights of these clones at ages 12 and 13 years (Table 6.2).

Table 6.2: Mean top heights of clones at age 1 to age 13 years. Values followed by the same letter are not significantly different according to smallest critical value of the SNK (Student-Newman-Keuls) multiple range test ($P<0.05$). 18 trees per plot were measured to calculate mean top height for each plot. Mean top heights for each clone were calculated from plot values.

Mean Top Heights (m)											
	Age (Years)										
Clone	1	2	3	4	5	6	7	10	11	12	13
1	0.52 bc	1.15 bc	1.95 cd	3.08 def	4.07 cd	5.71c	7.41de	11.55 bc	12.40 c	14.03 de	15.32 de
2	0.59 ab	1.23 ab	2.21 bc	3.49 c	4.46 bc	6.30 b	8.10 bc	11.68 bc	13.13 abc	14.95 bcd	15.58 cde
3	0.6 ab	1.13 bc	1.79 d	2.78 f	3.67 d	5.23 d	6.89 e	10.98 c	12.29 c	13.73 e	15.17 de
4	0.46 c	1.16 bc	2.33 b	3.90 ab	4.81 ab	6.79 a	8.68 ab	13.21 a	14.20 a	15.50 abc	16.89 ab
5	0.52 bc	1.23 ab	2.01 cd	3.43 cd	4.51 b	6.30 b	8.12 bc	12.42 ab	13.30 abc	15.43 abc	16.57abc
6	0.58 ab	1.23 ab	2.04 cd	3.25 cde	4.41 bc	5.99 bc	7.68 cd	11.68 bc	12.88 bc	14.61 bcde	16.00 bcd
7	0.51 bc	1.02 c	1.95 cd	3.43 cd	4.52 b	6.22 b	8.37 ab	12.18 ab	13.45 abc	13.91 de	14.73 e
8	0.56 bc	1.08 bc	1.95 cd	3.63 bc	4.72 ab	6.36 b	8.11 bc	12.09 abc	13.36 abc	15.60 ab	16.67 abc
9	0.67 a	1.4 a	2.63 a	4.26 a	5.09 a	6.95 a	8.81 a	13.09 a	13.75 ab	16.19 a	17.21 a
10	0.51 bc	1.06 bc	1.79 d	2.91 ef	3.94 d	5.62 cd	7.64 cd	11.90 bc	13.02 abc	14.44 de	15.73 bcde
SNK critical range	0.10-0.18	0.17-0.30	0.26-0.45	0.40-0.68	0.41-0.70	0.43-0.73	0.58-0.98	1.17-2.01	1.25-2.13	1.09-1.86	1.18-2.02

Table 6.3: Parameters of models fitted to mean top heights of clones. Values in each column followed by the same letter are not significantly different according to smallest critical value of the SNK (Student-Newman-Keuls) multiple range test (P<0.05).

Individual plot Parameters					Mean values of Parameters			
Block	Clone	α	β	γ	Clone	α	β	γ
1	1	3.035	4.208	0.828				
2	1	2.963	4.506	0.805	1	2.983 ab	4.363 b	0.811 ab
3	1	2.950	4.373	0.799				
1	2	3.111	3.958	0.836				
2	2	2.992	4.231	0.807	2	3.044 ab	4.124 bc	0.817 ab
3	2	3.028	4.183	0.807				
1	3	3.108	4.300	0.838				
2	3	3.066	4.436	0.823	3	3.080 a	4.364 b	0.830 a
3	3	3.064	4.355	0.828				
1	4	2.997	4.404	0.797				
2	4	3.035	4.536	0.786	4	2.991 ab	4.454 b	0.788 b
3	4	2.940	4.423	0.782				
1	5	3.103	4.363	0.816				
2	5	3.103	4.368	0.814	5	3.053 ab	4.335 b	0.810 ab
3	5	2.954	4.272	0.799				
1	6	2.975	4.329	0.813				
2	6	3.132	4.167	0.821	6	3.033 ab	4.203 bc	0.817 ab
3	6	2.991	4.113	0.818				
1	7	2.919	4.574	0.786				
2	7	2.825	4.915	0.759	7	2.847 b	4.843 a	0.767 c
3	7	2.797	5.040	0.756				
1	8	3.289	4.136	0.842				
2	8	3.050	4.466	0.815	8	3.095 a	4.262 b	0.816 ab
3	8	2.946	4.184	0.791				
1	9	3.170	3.863	0.828				
2	9	2.709	4.213	0.749	9	3.081 a	3.943 c	0.814 ab
3	9	3.128	4.142	0.811				
1	10	3.004	4.616	0.806				
2	10	3.128	4.608	0.827	10	3.018 ab	4.696 a	0.804 ab
3	10	2.922	4.866	0.780				
SNK critical range						0.032-0.052	0.053-0.086	0.006-0.007

Table 6.4: Eigen-values and Eigen-vectors of principal component analyses of mean top height models parameters. Principal components 1, 2 and 3 abbreviated as PC1, PC2 and PC3. Values in parenthesis are % contribution of parameters in respective principle components.

Mean Top Height

Parameter	Eigen-vectors PC1	Eigen-vectors PC2	Eigen-vectors of PC3
α	0.589 (34)	0.488 (31)	-6.43 (42)
β	-0.525 (30)	0.836 (54)	0.153 (10)
γ	0.612 (36)	0.247 (15)	0.75 (48)
Eigen-value	2.395	0.478	0.125
Percent variability explained	80	16	4

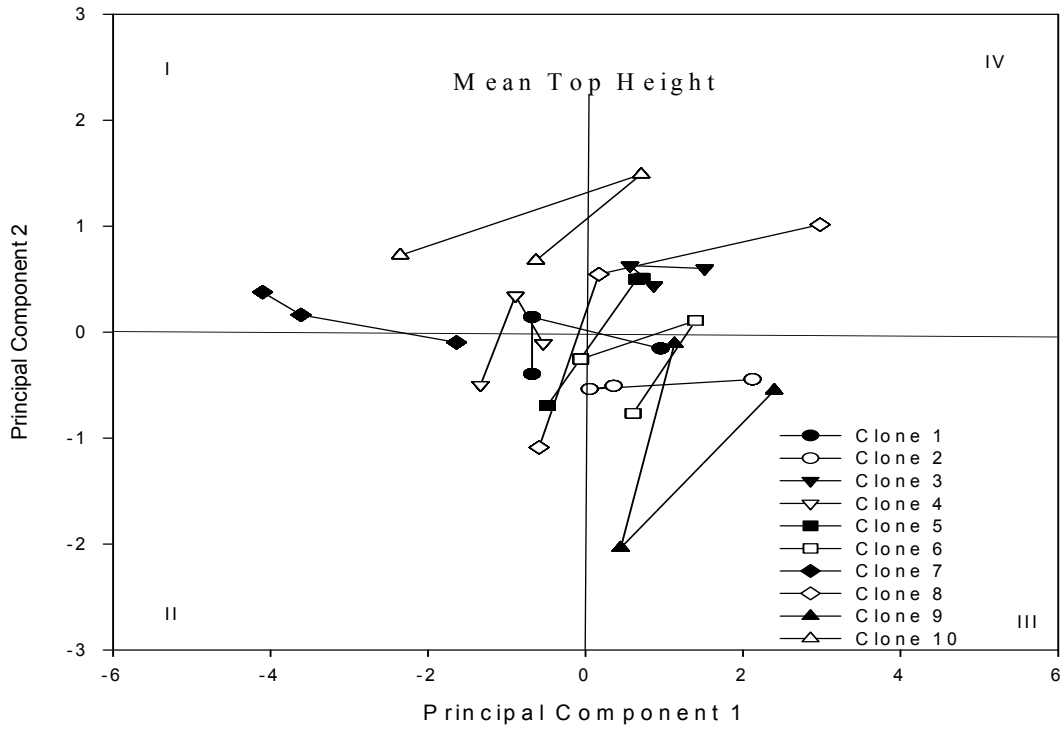


Figure 6.2: Groups of clones formed based on values of principal component 1 and 2 of mean top height models parameters. Three values for each clone represent three plots of each clone.

Simulations of mean top heights from parameters of fitted models to data up to ages 7 and 10 years exhibited greater deviations from observed mean top heights at age 13 years (Figures 6.3, 6.4) than the simulations from parameters of models fitted using data up to age 12 years (Figure 6.5). Although simulations from parameters of models fitted using data up to age 12 years were more precise than models fitted using data up to ages 7 and 10 years, they

remained biased, with a majority of individual models under-predicted mean top heights at age 13 years (Figure 6.5).

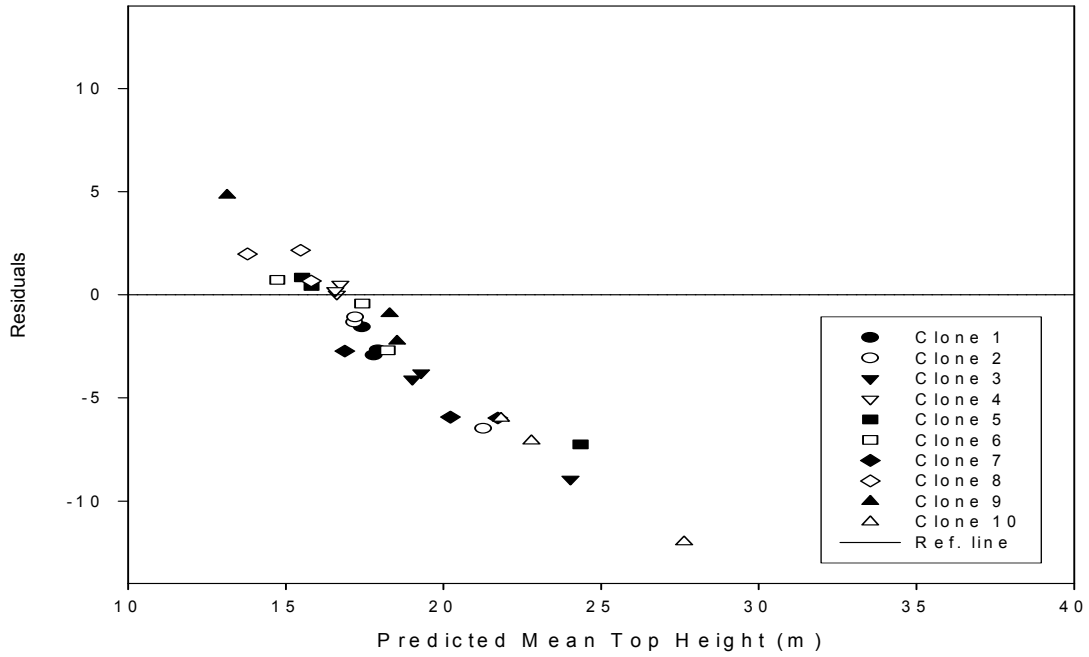


Figure 6.3: Plot of residuals versus predicted mean top heights at age 13 years. The mean top heights were predicted from parameters of models fitted using data up to age 7 years.

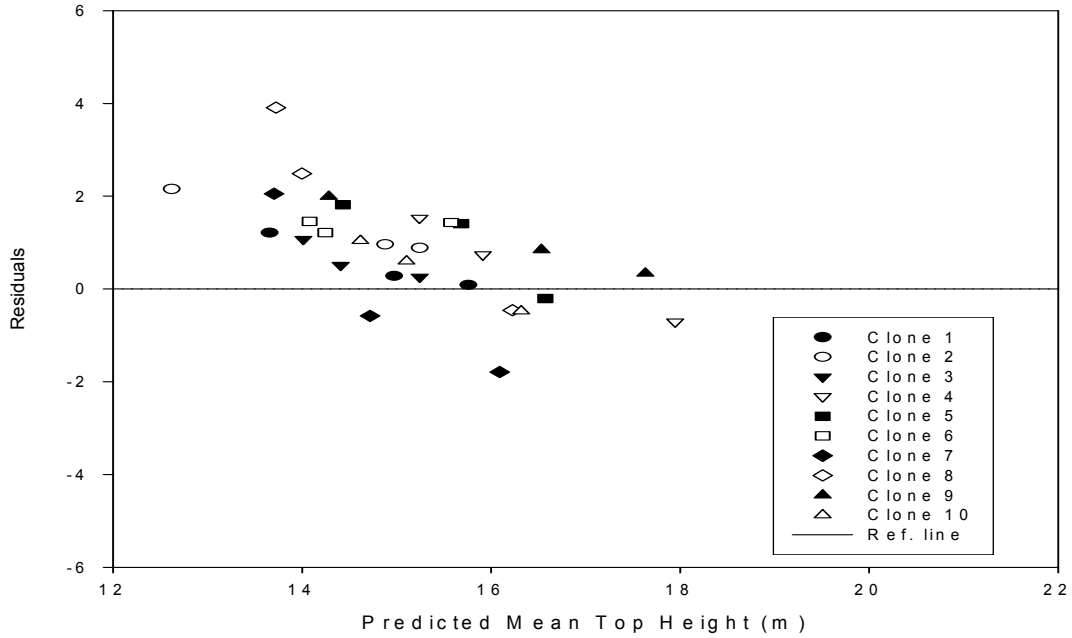


Figure 6.4: Plot of residuals versus predicted mean top heights at age 13 years. The mean top heights were predicted from parameters of models fitted using data up to age 10 years.

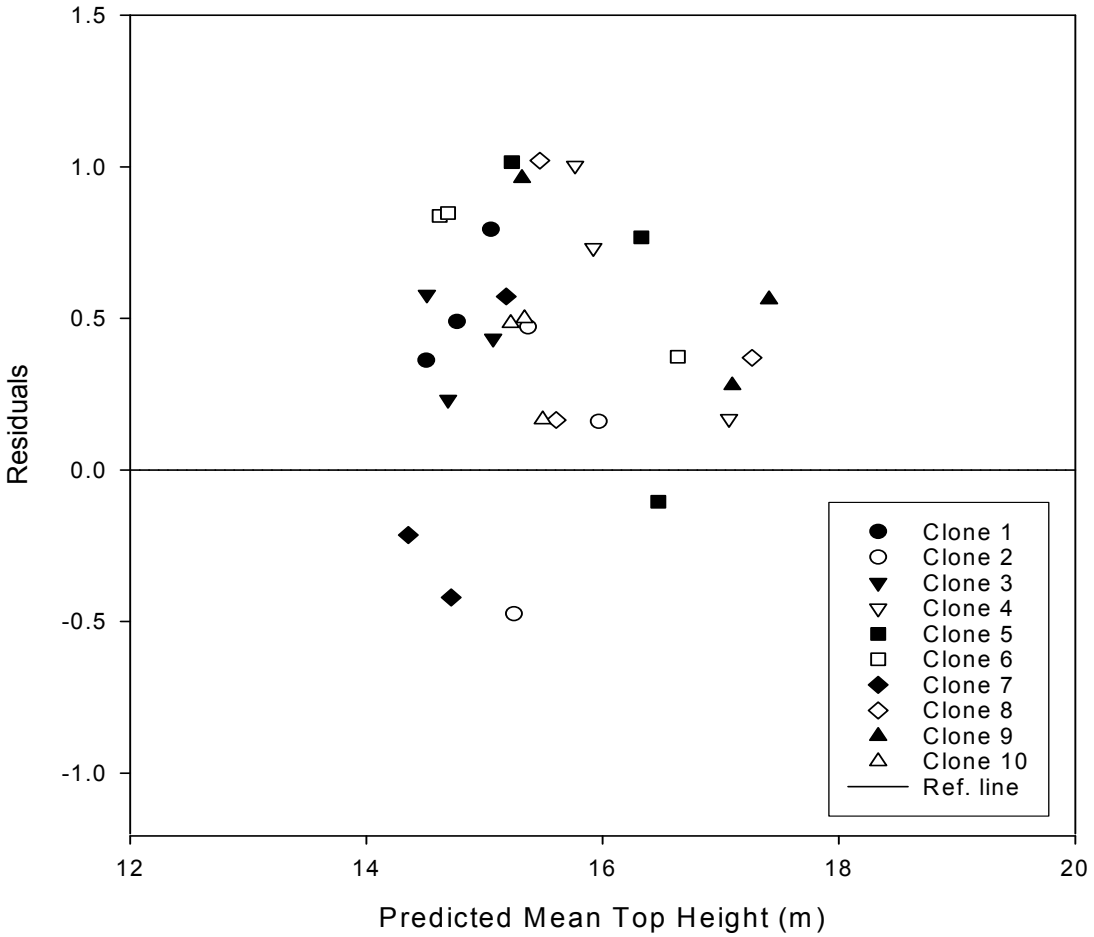


Figure 6.5: Plot of residuals versus predicted mean top heights at age 13 years. Mean top heights were predicted from parameters of models fitted using data up to age 12 years.

6.4.2 Stand Basal Area

Clones did not exhibit significant differences in stand basal areas from age 10 years onwards except at age 12 years (Table 6.5, Figure 6.6).

Table 6.5: Stand basal areas of clones from age 4 to age 13 years. Values followed by the same letter are not significantly different according to smallest critical value of the SNK (Student-Newman-Keuls) multiple range test ($P<0.05$). 18 trees per plot were measured to calculate stand basal area for each plot. Stand basal area for each clone were calculated from plot values.

Stand Basal Areas (m^2/ha)								
	Age (Years)							
Clone	4	5	6	7	10	11	12	13
1	1.93 cde	6.38 d	14.15 d	23.09 cd	50.12 a	57.93 a	67.02 ab	72.96 a
2	2.37 bcd	7.15 cd	14.16 d	23.58 cd	43.05 a	49.72 a	56.87 ab	62.93 a
3	1.63 de	5.8 d	13.79 bd	23.45 cd	46.9 a	53.89 a	60.35 ab	66.56 a
4	2.87 b	8.84 bc	18.19 b	26.66 abc	46.37 a	51.63 a	56.68 ab	62.34 a
5	2.6 bc	9.06 b	18.01 bc	28.61 ab	53.54 a	60.89 a	70.71 ab	76.27 a
6	1.64 de	5.52 d	12.32 d	20.16 d	46.54 a	54.36 a	65.03 ab	70.15 a
7	1.93 bcd	7.01 d	14.98 cd	24.18 bcd	51.61 a	59.39 a	67.37 ab	73.37 a
8	2.08 cde	6.75 d	15.17 bcd	24.64 abcd	48.74 a	58.64 a	66.37 ab	72.41 a
9	4.35 a	12.8 a	21.53 a	29.36 a	43.63 a	47.88 a	54.34 b	59.46 a
10	1.37 e	5.72 d	13.63 d	22.02 cd	45.36 a	52.95 a	61.39 ab	65.06 a
SNK critical range	0.74-1.27	1.72-2.94	3.18-5.42	4.86-8.30	12.46-21.27	14.39-24.56	15.76-26.90	17.40-29.70

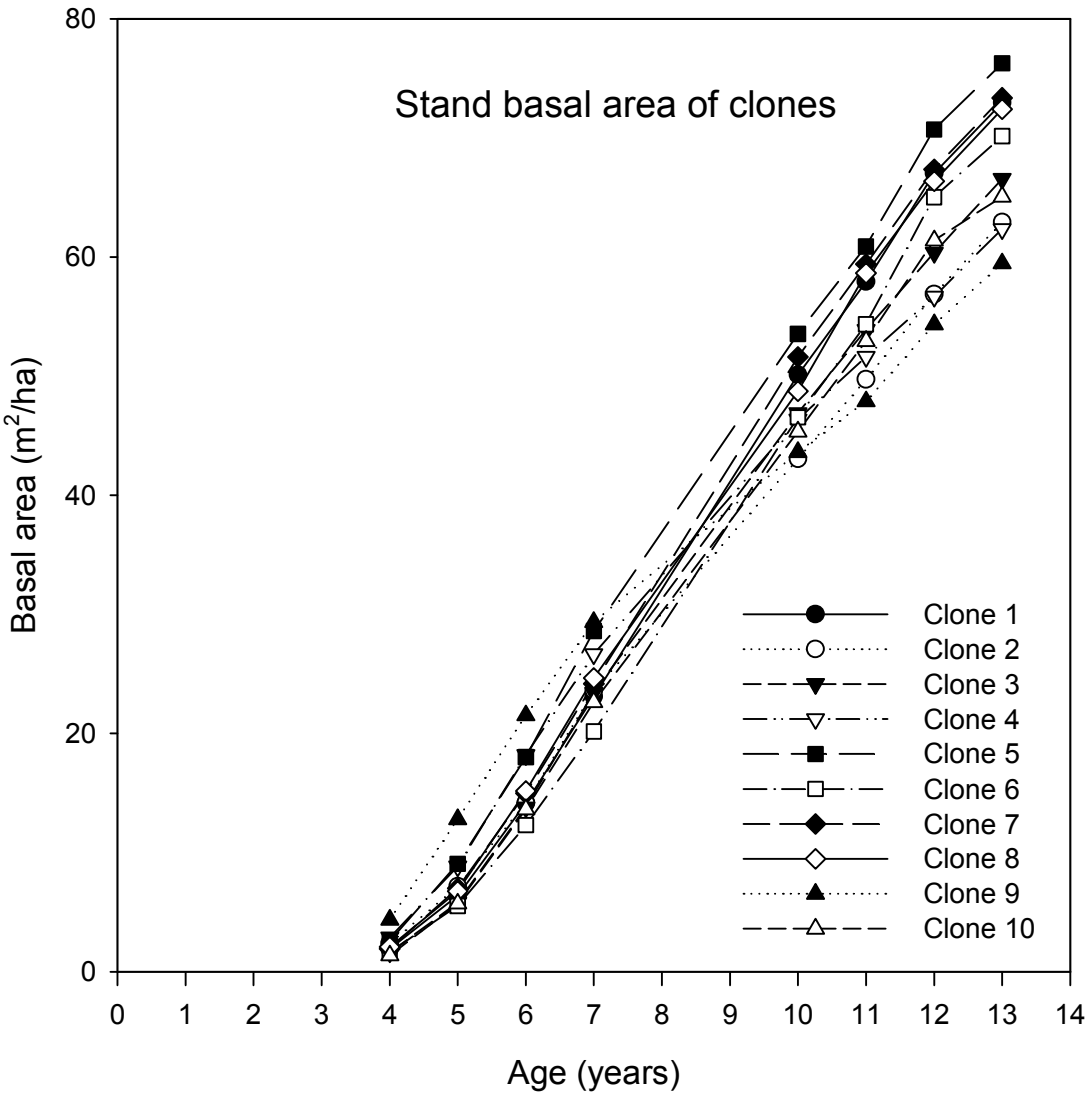


Figure 6.6: Stand basal area growth of clones in monoclonal plots from age 4 years to age 13 years.

The best equation fitted to stand basal areas was the Schumacher yield equation (5), and the parameters representing asymptotes and yield pattern to each plot and mean for each clone are given in Table 6.6.

Table 6.6: Parameters of models fitted to monoclones for stand basal area. Values in each column followed by the same letter are not significantly different according to the smallest critical value of the SNK (Student-Newman-Keuls) multiple range test ($P<0.05$).

Individual plot Parameters				Mean values of Parameters		
Block	Clone	α	β	Clone	α	β
1	1	5.771	19.291			
2	1	5.807	18.868	1	5.768 a	18.705 a
3	1	5.725	17.957			
1	2	5.229	15.569			
2	2	5.400	16.933	2	5.397 ab	16.364 ab
3	2	5.563	16.591			
1	3	5.613	17.835			
2	3	5.626	17.968	3	5.585 a	17.600 ab
3	3	5.516	16.997			
1	4	5.430	15.738			
2	4	5.418	15.035	4	5.240 ab	14.295 b
3	4	4.871	12.111			
1	5	5.634	16.464			
2	5	5.678	16.833	5	5.619 a	16.399 ab
3	5	5.543	15.900			
1	6	5.749	19.963			
2	6	5.861	19.806	6	5.837 a	20.065 a
3	6	5.903	20.426			
1	7	5.708	18.379			
2	7	5.804	17.362	7	5.729 a	18.144 ab
3	7	5.676	18.692			
1	8	5.648	17.393			
2	8	5.650	19.148	8	5.694 a	18.009 ab
3	8	5.784	17.487			
1	9	4.974	11.531			
2	9	4.069	7.589	9	4.862 b	11.240 c
3	9	5.543	14.600			
1	10	5.599	17.816			
2	10	5.749	19.705	10	5.635 a	18.222 ab
3	10	5.558	17.146			
SNK critical range					0.48-0.82	2.60-4.44

Individual analyses of the parameters of stand basal area models indicated that there were differences in the yield models of monoclones as they showed distinct groupings for stand basal area (Table 6.6). Principal component analyses of parameters showed that principal component 1 and 2 explained 97 and 3 percent variation between the parameters of stand basal area models (Table 6.7). Eigen-vectors (coefficients) of principal components 1 and 2 indicated that differences between clones were both due to the yield pattern and asymptotes of yield models of clones. Both parameters contributed equally (50 %) to respective principal components. Stand basal area models of clones 4, 6 and 9 significantly differed from each other (Figure 6.7) that confirmed that stand basal area of clone 9 was significantly lower compared to other clones at age 12 years (Table 6.5).

Table 6.7: Eigen-values and eigenvectors of principal components of stand basal area models parameters. Principal components 1 and 2 abbreviated as PC1 and PC2. Values in parenthesis are % contribution of parameters in respective principal components.

Stand Basal Area

Parameters	Eigen-vectors of PC1	Eigen-vectors of PC2
α	0.707 (50)	0.707 (50)
β	0.707 (50)	-0.707 (50)
Eigen-values	1.932	0.067
Variation explained (%)	97	3

Principal component analyses of stand basal area parameters revealed that models of clones 4 and 9 significantly differed from those of other clones (Figures 6.7 and 6.8) and formed distinct groups. The greater negative values of principal component 1 for these clones indicated that they were growing slowly. A steep dip in stand basal area growth of clones 4 and 9 (Figure 6.9) was due to greater mortality due to windthrow damage (Chapter 4).

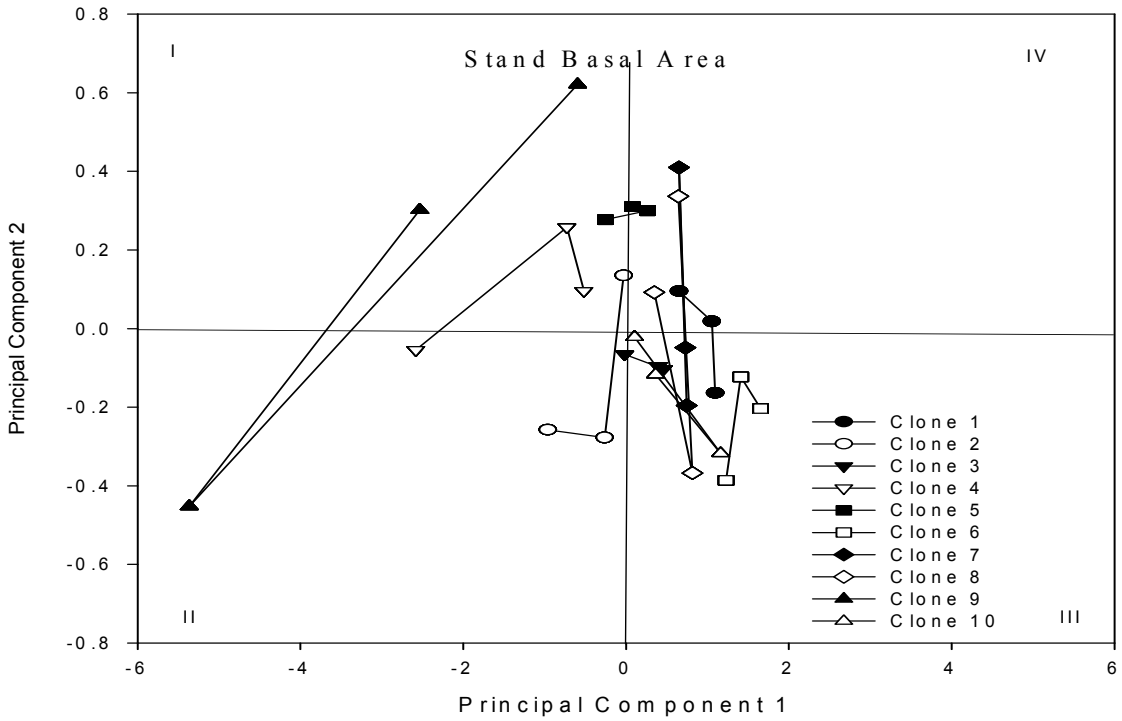


Figure 6.7: Groups of monoclones formed based on values of principal component 1 and 2 of stand basal area models parameters. Three values for each clone represent three plots (models) of each clone.

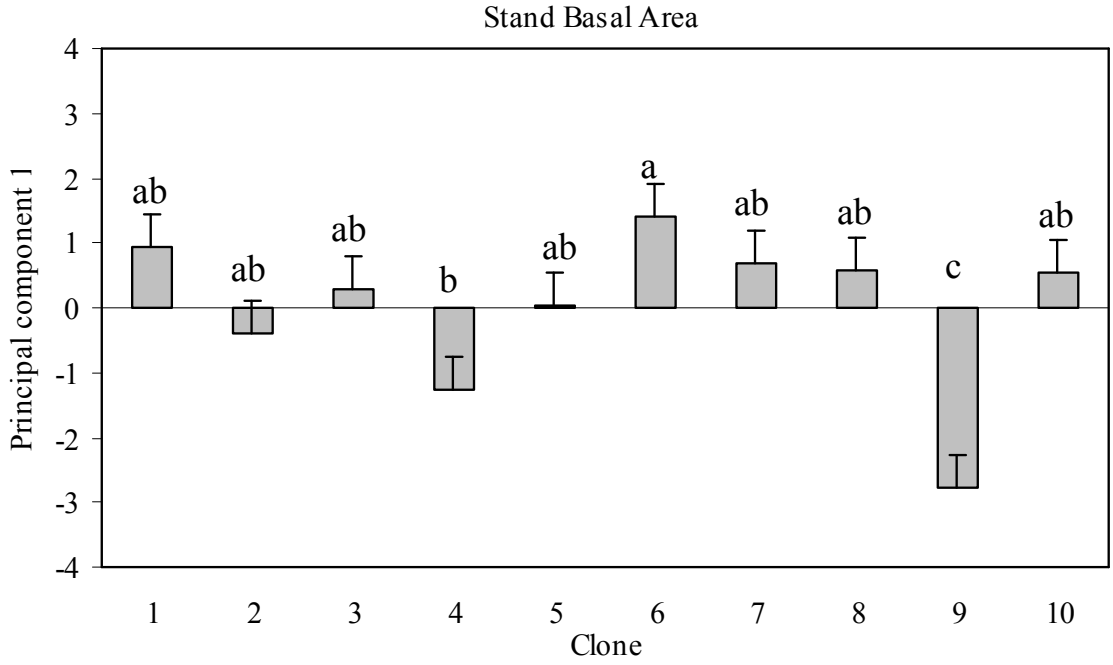


Figure 6.8: Statistical groupings of clones for stand basal area based on values of principal component 1.

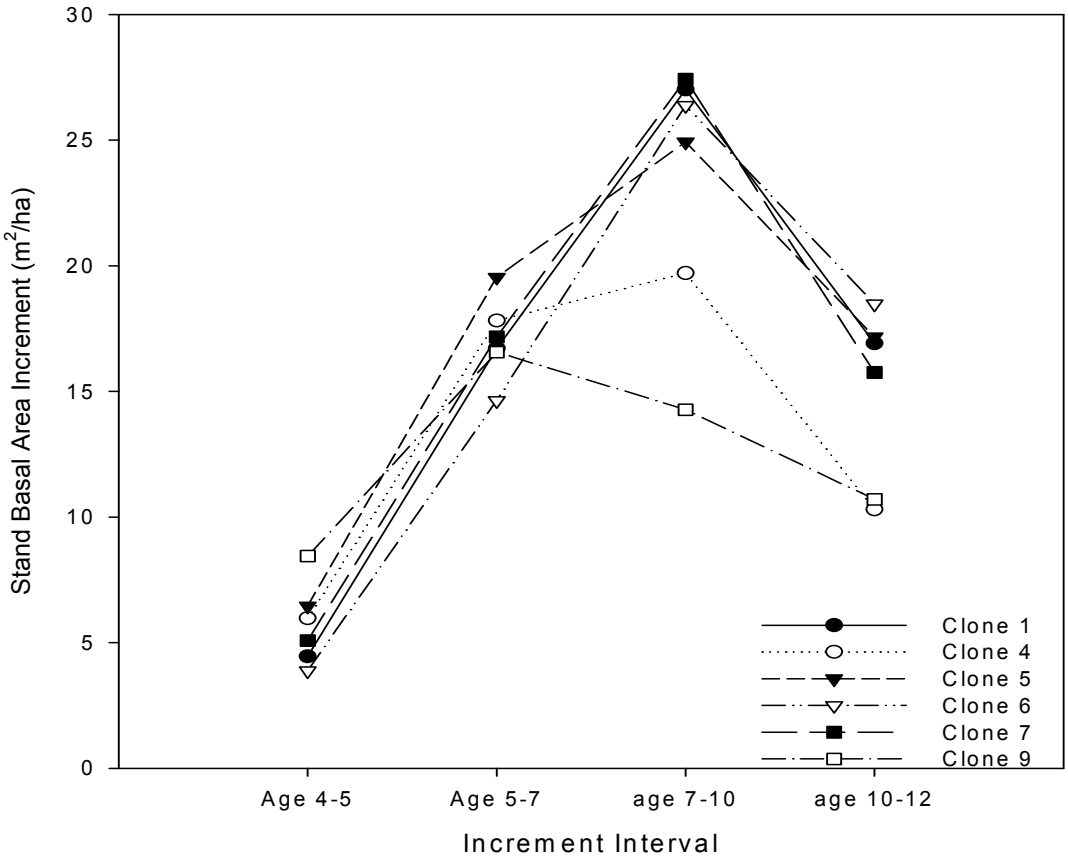


Figure 6.9: Stand basal area increments of clones at ages 5, 7, 10 and 12 years.

Simulations of stand basal area from parameters of fitted models to data up to ages 7 and 10 years exhibited greater deviations from observed stand basal areas at age 13 years (Figures 6.10, 6.11) than the simulations from parameters of models fitted using data up to age 12 years (Figure 6.12). Although simulations from parameters of models fitted using data up to age 12 years were more precise than models fitted using data up to ages 7 and 10 years, they remained biased with a majority of individual models over-predicted stand basal areas at age 13 years (Figure 6.12).

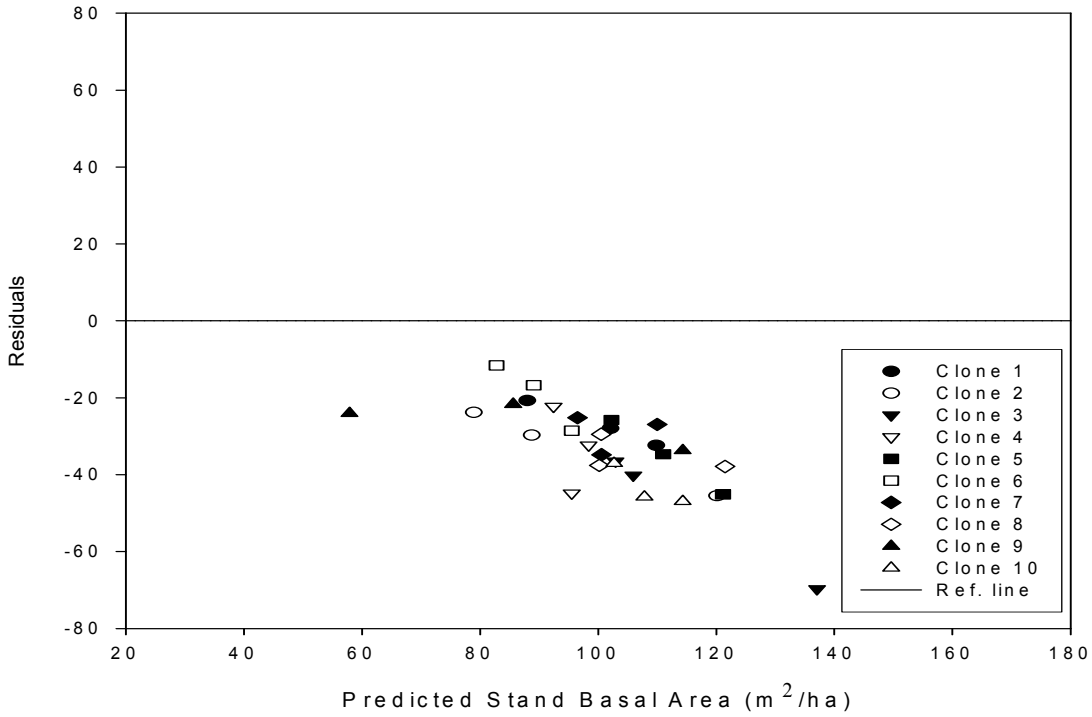


Figure 6.10: Plot of residuals versus predicted stand basal areas at age 13 years. The stand basal areas were predicted from parameters of models fitted using data up to age 7 years.

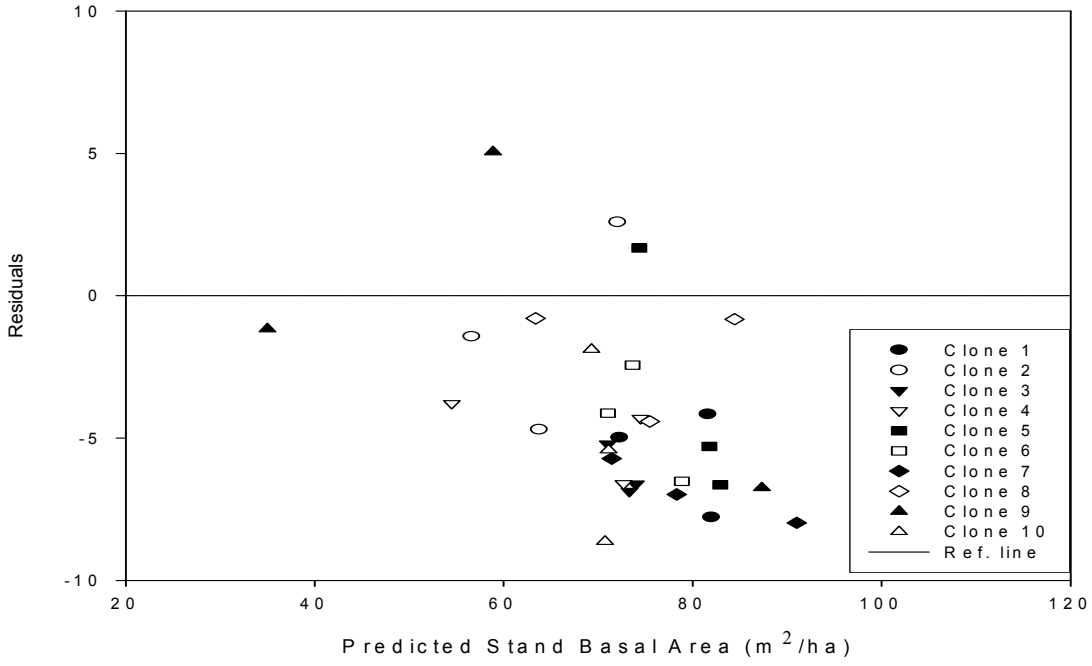


Figure 6.11: Plot of residuals versus predicted stand basal areas at age 13 years. The stand basal areas were predicted from parameters of models fitted using data up to age 10 years.

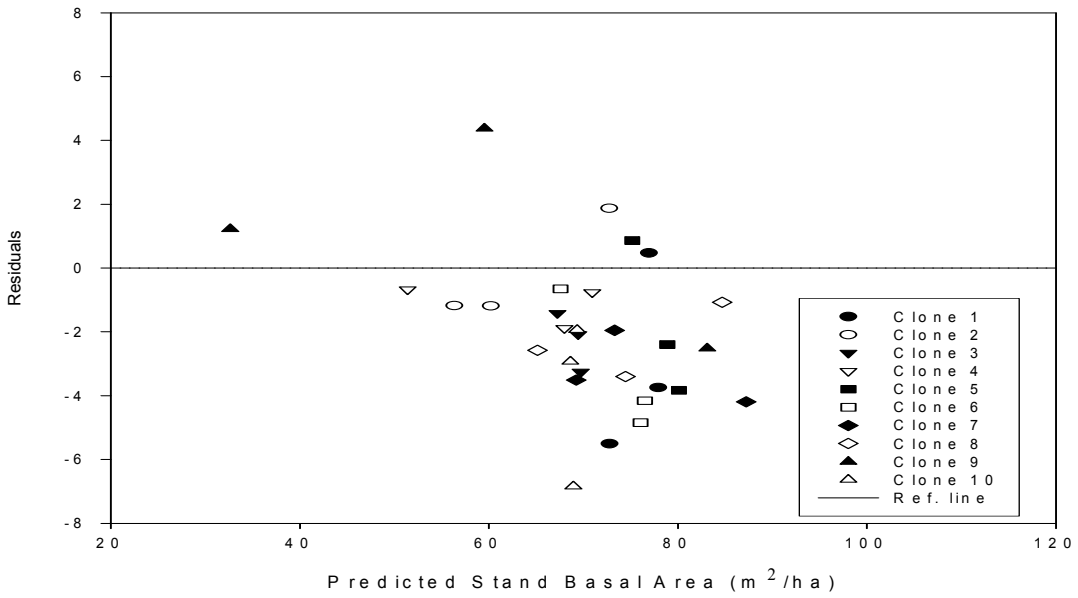


Figure 6.12: Plot of residuals versus predicted stand basal areas at age 13 years. The stand basal areas were predicted from parameters of models fitted using data up to age 12 years.

6.4.3 Nonlinear model analysis

SAS output confirmed two distinct groupings of clones. The parameters of two groups differed significantly (Table 6.8). Clone 9 had bigger residuals than other clones (Figure 6.13), an effect caused by windthrow-related mortality.

Table 6.8: Parameters of fitted nonlinear stand basal area model for two different groups of clones.

Group	Clone	Parameters	Estimate	Standard Error	95 % Confidence Limits	
A	1, 2, 3, 5, 6, 7, 8, 10	α_0	5.6554	0.0528	5.5514	5.7595
		β_0	17.858	0.5459	16.7816	18.9343
B	4	α_1	-0.405	0.1425	-0.6858	-0.1241
		β_2	-3.523	1.4189	-6.3206	-0.7254
B	9	α_3	-0.6919	0.1305	-0.9491	-0.4347
		β_4	-6.1136	1.2529	-8.5839	-3.6433

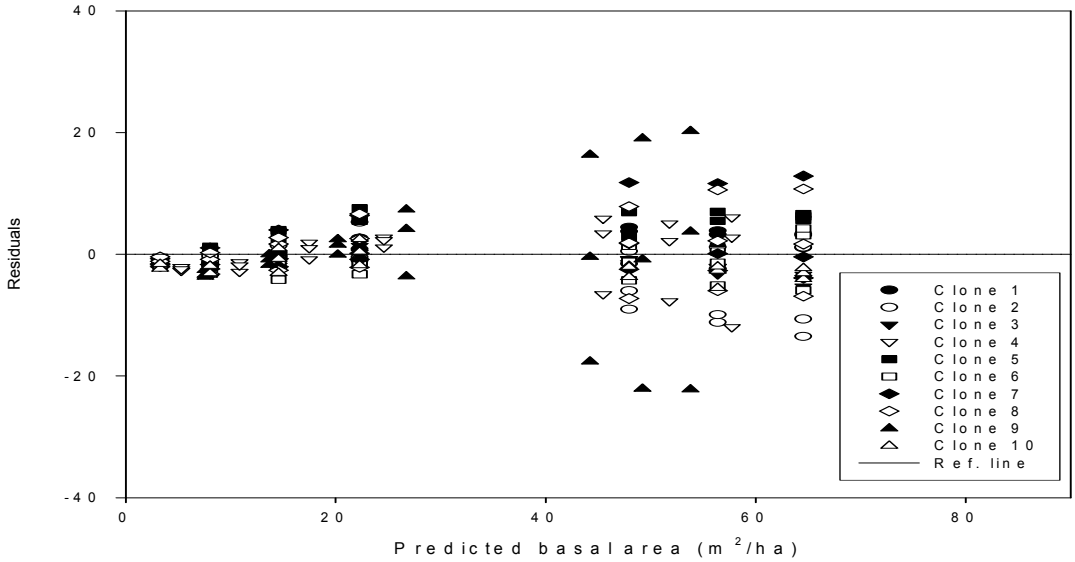


Figure 6.13: Residuals versus predicted stand basal area plot of the nonlinear model (5).

6.4.4. Predictions from existing models

Existing stand basal area model (10) under predicted the stand basal area of majority of the clones (Figure 6.14) and over predicted for clones 4 and 9. Clones 4 and 9 had lower observed stand basal area compared to other clones due to windthrow damage. Mean top height model also under predicted the mean top heights of majority of clones (Figure 6.15) except clone 7.

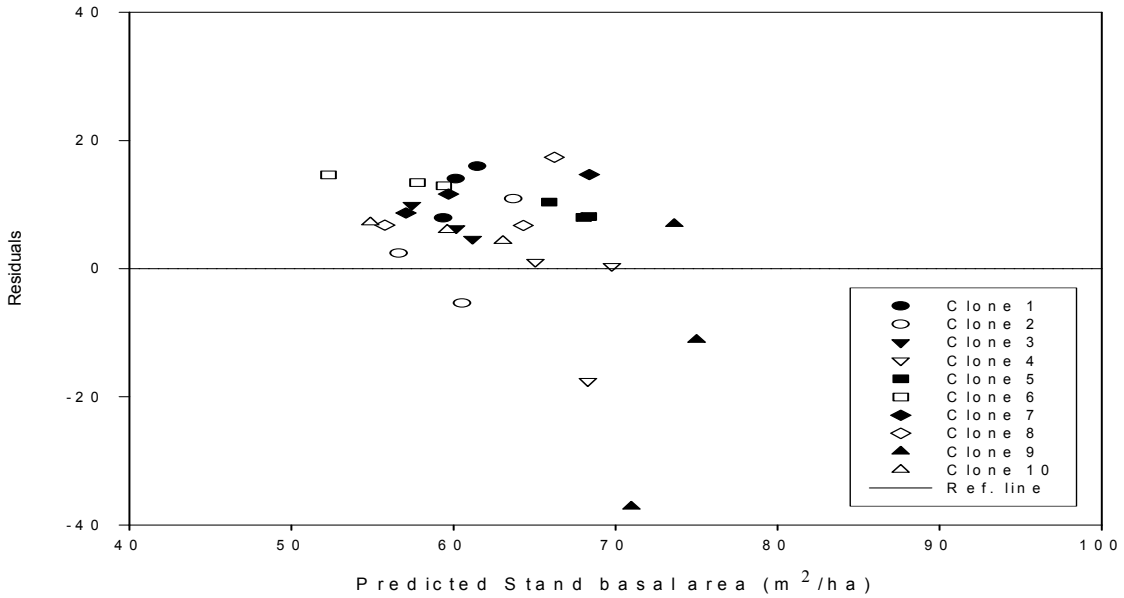


Figure 6.14: Residuals versus predicted stand basal area plot of the existing stand basal area model (10).

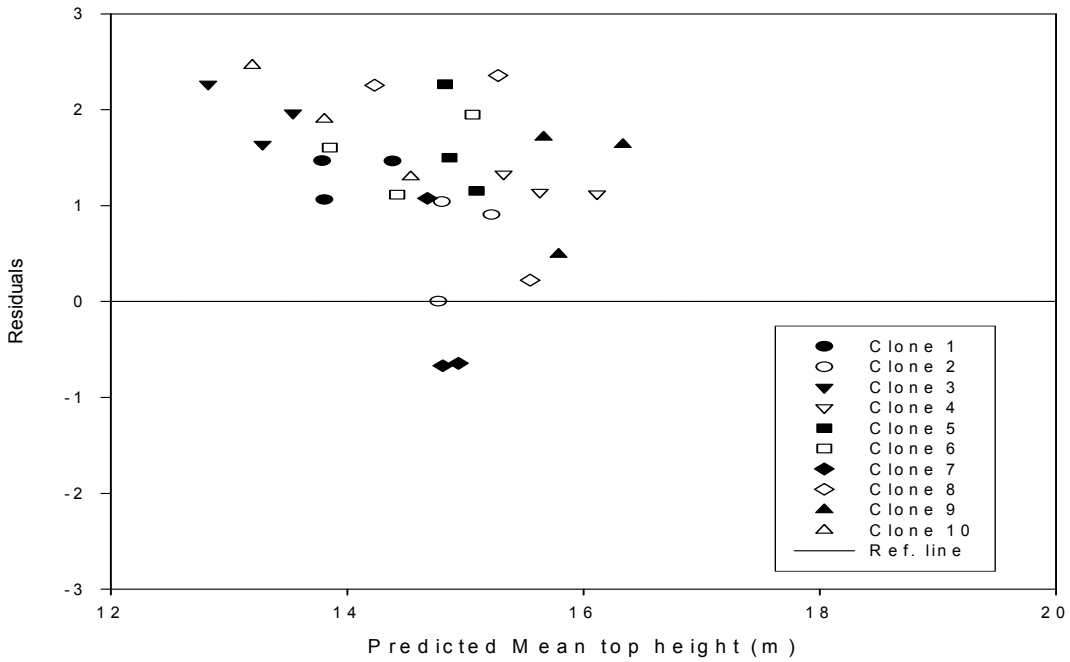


Figure 6.15: Residuals versus predicted stand basal area plot of the existing mean top height model (11).

6.5 Discussion

Stand growth modelling and principal component analyses of parameters of fitted models in this study revealed that some monoclones differed in their modelled yield pattern. Although clones did not exhibit significant differences in stand basal areas from age 10 years onwards except at age 12 years, the analysis of variance of fitted model parameters and principal component analysis suggested clones differed in their growth pattern. This either indicates that type II errors occurred for analyses of basal areas after age 10 years, or that clones converged towards a common basal area through different growth patterns. If the latter is true, then the implications for tree breeding a clonal forestry using radiata pine are profound, because genetic selections are commonly made prior to age 8 years.

Non-linear modelling and multivariate analyses of parameters both generated similar, distinct groupings of clones, based on similarities in their modelled asymptotes and yield patterns. Calegario *et al.* (2005) have also used nonlinear mixed-effect modelling to study height growth pattern of eucalyptus clonal stands in Brazil and found this modelling methodology to be flexible, precise and accurate. Whyte and Woollons (1990)

demonstrated the usefulness of discrininant analysis to evaluate the performance of stand growth of radiata pine at varying densities. This suggests that multivariate analyses might be useful to analyse the growth or yield pattern of clones at particular sites.

Clones 4 and 9 had significantly poorer stand yield from all other clones. These clones grew very rapidly during establishment period (Chapter 3), but windthrow-related mortality at age 7 years stunted the stand basal area growth of these clones, even up to age 12 years (Figure 6.9).

Predictions of mean top heights and stand basal areas at age 13 years from the fitted models using data up to ages 7, 10 and even 12 years were biased, particularly for certain clones. This implies that mensuration-based growth and yield might result in biased predictions of future performances of monoclones when only initial few years growth and yield data are used to fit the models. The main drawback of the mensurational models is that extrapolations from these models are based on weakly understood conditions or mechanisms (Sun *et al.* 2007). The stand conditions and the mechanisms controlling growth of clones change over time and the interactions of these mechanisms with genotype may result in differences in their growth patterns that can only be modelled using mensurational techniques when we have data from PSPs at a range of ages greater than half the rotation age containing the clones and deployment options chosen by practitioners.

Models are generally used to predict the rotation age productivity of stands. Different genotypes grow differently, some grow fast in the beginning and some grow moderately during initial establishment period and then start growing rapidly. Therefore, it is not appropriate for foresters to merely depend upon mensurational models developed using initial few years' data to make decisions about the long term states of their clonal stands. The improvement in precision of estimation of stand level values exhibited in this study when more data was incorporated to fit the models suggest that the mensurational models to be used for production planning should be developed using adequate number of years growth or yield data for long term predictions especially in long rotation species. There is a need to further test the effectiveness of models fitted to data around mid rotation (age 12 years) by comparing predicted values with observed values near rotation age.

The existing yield models also failed to accurately predict stand basal area and mean top height of clonal stands. This supports the assertion that traditional mensuration-based yield modelling might result in biased predictions of future performances of monoclonal stands of clones having different growth patterns.

6.6 Conclusions

Clones differed significantly in modelled yield patterns and/or model asymptotes.

Ten clones were reduced to two distinct groups having significantly different yield models. These differences were due to differences in parameters that represented yield patterns and asymptotes.

Parameters of models fitted to mean top heights and stand basal area data up to age 12 years gave more close predictions to observed values than parameters of models fitted to data up to ages 7 and 10 years and extrapolation from yield models fitted to individual clones were biased indicators of their relative future performances.

Existing stand basal area and mean top height yield models failed to accurately predict stand basal area and mean top height of clones.

CHAPTER 7

EFFECTIVNESS OF 3-PG (A HYBRID PHYSIOLOGICAL GROWTH MODEL) IN EXPLAINING DIFFERING PRODUCTIVITIES OF RADIATA PINE CLONES

7.1 Abstract

The effectiveness of 3-PG (Physiological Principles Predicting Growth) hybrid model was evaluated for representing and explaining differential productivity of four clones of radiata pine in a clonal experiment established at Dalethorpe, Canterbury, New Zealand in Sept. 1993. The effectiveness of the model was determined by comparing the simulated values with measured values of stand basal area, DBH (diameter at breast height over bark) and LAI (leaf area index) from age 5 to age 13 years. Allometric relationships of foliage:stem biomass and DBH were determined from destructive sampling data at ages 5 and 11 years. Some species-specific values from other studies were also used. Biomass estimates of four clones at age 5 years provided starting values for the simulation. Clones significantly differed in foliage and stem biomass at age 5 years. Differences in final productivity of clones were concluded to be due to differences in biomass partitioning and specific leaf areas. The 3-PG model gave better fits to the observed values of stand basal areas and DBH when quantum efficiency was raised from 0.050 to 0.063 molC/molPAR or minimum fraction of biomass allocated to roots was decreased from 0.25 to 0.13 at quantum efficiency of 0.05 molC/molPAR.

7.2 Introduction

Clonal forestry allows managers to capture more genetic gain in rapid growth and better wood quality, and they would benefit from access to growth & yield models customisable to genotype, to critically explore the relative benefits of candidate commercial clones. In the absence of rotation-length clonal PSP data for each production clone, models that incorporate key eco-physiological differences between clones could provide the required level of detail and predictive accuracy.

Foresters have long used growth and yield models for predicting the future states of their forests. There are three approaches to forest simulation modelling, mensuration-based growth and yield models, physiological models, and hybrid models (Kimmins *et al.,* 1990; Landsberg, 2003). Standard mensuration-based growth and yield models are the simplest and most believable methods for predicting future forest growth and productivity over which future growing conditions are not expected to change significantly (Kimmins *et al.,* 1990; Korzukhin *et al.,* 1996), and can be tested rigorously through statistical analysis (Mohren and Burkhart, 1994; Korzukhin *et al.,* 1996). Their disadvantages are that these models are region specific, and it is difficult to analyse the consequences of climatic changes or environmental stresses (Kimmins, 1990; Mohren and Burkhart, 1994).

Models that represent physiological processes offer the potential to represent how productivity will vary with environmental conditions (Landsberg and Gower, 1997) and are developed to understand forest behaviour from a description of plant-soil and carbon-nutrient-water interactions. They can make long-term predictions for changing climate and management conditions (Tome *et al.,* 2004). These models can also be parameterised to make predictions of plant growth on sites where a given community has not been grown before and effects of silvicultural activities such as weed control or fertilisation, or the impacts of pests and diseases on productivity could not be directly observed (Landsberg, 2003). These models have not been used much by foresters because of the number of sub-models involved, compounding of errors associated with sub-models, the large numbers of parameter values that may not be readily available to forest managers (Mohren and Burkhart, 1994; Landsberg and Gower, 1997; Johnsen *et al.,* 2001; Sands *et al.*, 2000; Mäkelä *et al.*, 2000; Landsberg, 2003), less accuracy in prediction of forest yield observed

during comparisons (Pinjuv *et al.,* 2006), and challenges in rigorously testing them versus standard mensuration-based growth and yield models developed from historical data (Mohren and Burkhart, 1994; Battaglia and Sands, 1998).

Global warming and climate change may influence the growth patterns of forest trees. There is therefore a need for models that could provide better predictions based on deep understandings of biological phenomena. This need led to new approaches to modelling *i.e.* Hybrid models, which are intermediate between physiological and empirical models. At present the 3-PG hybrid model (Landsberg and Waring, 1997) is a popular process-based hybrid model and has been evaluated using data from experiments and commercial plantations in Australia, New Zealand, the UK, the United States, South Africa (Landsberg *et al.,* 2001); Portugal (Tome *et al*.,2004) and Brazil (Almeida *et al.,* 2004).

Tome *et al.* (2004) tested the effectiveness of 3-PG in predicting productivities of *Eucalyptus globulus* plantations in Portugal. They concluded that it was possible to use 3-PG for simulation of the growth and productivity of their plantations, although the preliminary results were un-satisfactory. Almeida *et al.* (2004) tested the effectiveness of 3-PG in predicting productivities of *Eucalyptus grandis* clones in Brazil and concluded that it is possible to detect differences in the parameter values applicable to different clones if high quality, detailed data are available for calibration.

The study described here was undertaken in order to evaluate the effectiveness of the 3-PG hybrid model at representing the productivity of radiata pine clones, and to identify reasons for observed differences in productivities of clones.

7.3 Materials and Methods

7.3.1 Site

An experiment was established with radiata pine (*Pinus radiata* D. Don) on a site at Dalethorpe (latitude 42°-45'S, longitude 171°-55'E, elevation 520 m above sea level), 70 km west of Christchurch, Canterbury, New Zealand in September 1993. The soil at the site was well-developed silt-loam (NZ Soil Bureau, 1968). Mean annual precipitation was 1058

mm from 1993 to 2006 (NIWA, 2006). Precipitation was distributed fairly evenly throughout the year, although a marked dry period can occur during February and March (McCracken, 1980).

7.3.2 Design of the experiment

Ten clones were deployed in monoclonal plots in a randomised complete block design with three blocks. Each block had ten monoclonal treatments. Plots were rectangular (16 x 20 m) and contained 40 trees (5 x 8). Trees were spaced at 2 m within rows, and rows were spaced at 4 m (1250 stems/ha). Total size of the experiment was 9600 sq m. No pruning or thinning treatments were applied to the experiment from 0-6 years. At age 7 years all trees were pruned to a height of 2.5 m.

7.3.3 Planting material

Ten clones (1-10) were used. All were propagated by organogenesis from controlled pollinated mature seeds that were surface sterilised and germinated into sterile tissue cultures. After propagation they were hardened off in a nursery in the North Island (Fletcher Challenge Forests Ltd. Biotechnology Centre, TeTeko), conditioned with an undercutting and wrenching regime, and then were transplanted as bare-root plants. Clones 3, 7 and 10 were propagated from different seeds of same control-pollinated cross and are "full-sibs". Clones 1 & 9 and clones 6 & 8 were also propagated from different seeds of each of two crosses. Clones 2, 4 and 5 were from three additional crosses. Clones deployed in this experiment therefore represented six different families. The exact pedigrees of the clones were not revealed by the organization that provided the clones for this experiment, although they were said to have growth and form ratings (Sorensson, personal communication) between 25 and 30.

7.3.4 Establishment practices

All the plants were planted in pits of 30 cm depth in ripped lines with ripping at a depth of 30 cm. Each planting spot was further cultivated with a spade. Each randomised complete block was planted by only one person. All the plots were kept completely weed free using

initially a mixture of Hexazinone and Turbuthylazine, and subsequently a mixture of Turbuthylazine, Clopyralid and Haloxyfop herbicides for 5 years following planting.

7.3.5 Assessments

Stem heights and diameters at breast height over bark (DBH) were recorded from 1997 to 2006 for all live interior trees (*i.e.* excluding a single buffer row around each plot). At age 5 years (1998), three trees each of four clones (clone 4, 6, 9 and 10) having different growth patterns were destructively sampled and foliage, branch, and stem oven-dry biomasses were recorded. At age 11 years (2004), 30 clonal trees (4 of clone 1, 5 of clone 2, 5 of clone 3, 6 of clone 6, 4 of clone 7, 5 of clone 8 and 1 of clone 10) of genetically identical clones were destructively sampled *in an adjoining experiment* established on the same date, but at stockings of 833 and 2500 stems/ha. The foliage, branch and stem oven-dry biomass were recorded. The specific leaf areas of new and old (>1 year age) needles of destructively sampled clones were also estimated at ages 5 and 11 years. Allometric models were found to not differ between stockings within clones.

Mean heights, mean diameters (DBH) and stand basal area per hectare were calculated for each plot and each clone. Leaf area index (LAI) was measured at age 13 years for each plot using a plant canopy analyser (LAI-2000) instrument, as prescribed in its instruction manual (LICOR, 1991).

7.3.6. Overview of the 3-PG model

The 3-PG model is a monthly time step model and produces at every time step, updated values of stem diameter, stand volume and many other outputs.

This model uses "Beers Law" to estimate absorbed photosynethically active radiation (APAR) given any amount of radiation and LAI as in equation (1).

$$APAR = (1 - exp^{-kL}) PAR \quad (1)$$

The model then calculates the proportion of absorbed photosynthetically active radiation (APAR) converted to GPP (gross primary productivity) as in equation (2).

$$GPP = \alpha_c \, APAR \, min(f_\theta \; f_D) f_T \; f_F \; f_S \quad (2)$$

Where α_c is quantum efficiency, and is determined by environmental factors expressed as growth modifiers. The value of these modifiers varies from 0 to 1. In equation (2): f_θ is the soil water modifier (0-1), f_D is the vapour pressure deficit modifier (0-1), f_T is the temperature modifier (0-1), f_F is the frost modifier (0-1), and f_S is the senility modifier (0-1).

Then NPP (net primary productivity) is calculated as fixed proportion of GPP.

$$NPP = Y \, GPP$$

Y is constant proportion (0.47) in 3-PG.

The model then partitions NPP in to foliage, stem and roots. Partitioning to roots is influenced by soil nutrition and available soil water, and partitioning to foliage and stem is based on the observed allometric relationships (3 and 4) between foliage or stem biomass and DBH (Landsberg and Waring, 1997).

$$W_S = a_s \, DBH^{n_s} \quad (3)$$

$$W_F = a_F \, DBH^{n_F} \quad (4)$$

Where W_S and W_F are stem and foliage mass respectively, and a_s and a_f are coefficients and n_s and n_f are powers.

Species specific values of litter-fall and root-turnover are used to determine net biomass of foliage and roots.

The 3-PG model then uses well established mathematical formulae to determine the variables DBH, LAI, stand volume, stem number (calculated using -3/2 self-thinning law) and MAI (mean annual increment) from the biomass pools of foliage and stem.

7.3.7 Calibration of the 3-PG Model

The following are the minimum data required to run 3-PG:

Climate data

Monthly mean temperature (Ta), solar radiation, rainfall, vapour deficit and frost days are required. If only maximum (Tx), and minimum (Tn) air temperature are known, then Ta = ½(Tx +Tn). Vapour pressure deficit can also be estimated as half the difference between saturated vapour pressures at Tx and Tn. The 3-PG model can be run using either actual monthly weather data or long term monthly averages. The daily data of above mentioned climate variables were obtained from NIWA (2006) from January 1993 to December 2006. Monthly averages or sums were calculated in order to run 3-PG using monthly estimates of climatic variables.

Site factors

Site latitude, maximum available water stored in the soil, and a soil fertility rating were required. The latitude of the site was 42^{o} 45' S. Available soil water levels and initial available soil water, soil class and site fertility input (which is unit-less value ranging from 0 to 1) were taken from Pinjuv (2006) for this site. Pinjuv calibrated 3-PG for use with radiata pine throughout the forest estate within which the experiment was established.

Initial conditions

Initial stem, root and foliage biomass and stocking were required in order to start the simulation. Clones had significantly different foliage and stem dry mass at age 5 years (Table 7.1). Above-ground initial biomass levels (t/ha) were calculated for four clones (4, 6, 9 and 10) from oven dry weights calculated from destructive sampling and stocking at

age 5 years, and the averages of four clones were used as estimate of the overall values for the species for an initial, average simulation (Table 7.2) although average of four contrasting clones do not represent a species. Following Beets *et al*. (1999), root biomass was assumed fixed at 30 % of the total biomass of each tree.

Table 7.1 Foliage and stem dry mass of four clones at age 5 years. Values followed by different letters are significantly different according to minimum value of critical range of SNK test. These values were calculated from three trees of each clone destructively sampled at age 5 years.

Clone Species	Foliage Biomass (Kg/tree)	Stem biomass (Kg/tree)	Foliage:Stem Ratio
4	9.9 b	19.4 b	0.51 b
6	7.7 b	12.5 c	0.61 a
9	15.5 a	26.9 a	0.58 ab
10	10.3 b	21.2 ab	0.49 b
SNK Critical Range	3.8-5.4	5.9-8.3	0.09-0.13

Table 7.2 Initial values of foliage, root and stem biomasses at age 5 years used in 3-PG for simulations. Individual tree biomass calculated in table 7.1 and actual stockings at age 5 years were used to calculate biomasses per hectare.

Clone / Species	Foliage Biomass (t/ha)	Root biomass (t/ha)	Stem biomass (t/ha)
4	10.5	14.6	23.7
6	9.6	10.8	15.6
9	19.4	22.7	33.6
10	11.7	15.3	23.9
Species	12.8	15.8	24.2

Parameters of allometric relationships

To determine foliage-stem partitioning ratios at DBHs of 2 and 20 cm (pFS2 and pFS20 in the 3-PG software) the parameters of DBH and pFS ratio relationship were estimated from destructive sampling data at age 5 and 11 years for clones 4, 6, 9, 10 and overall for the species using a nonlinear allometric relationship (5).

$$pFS = ap * DBH^{np} \tag{5}$$

Where pFS is foliage: stem ratio, and ap and np are constants (parameters of relationship).

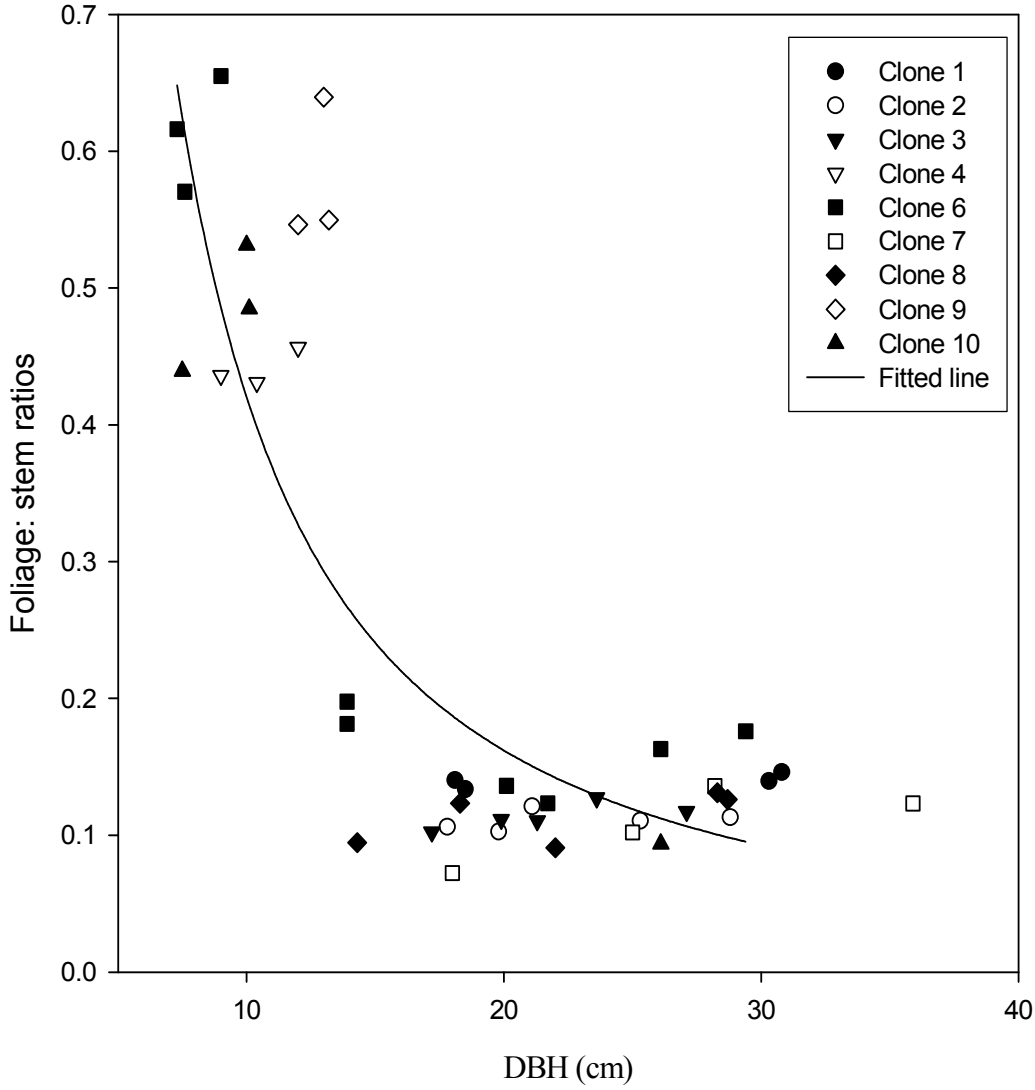


Figure 7.1 Observed relationship between pFS (foliage: stem biomass ratios) and DBH. Foliage and stem biomass data from destructive sampling at age 5 and 11 years were used to develop this relationship.

Figure 7.1 shows the allometric relationship between pFS ratio and DBH. This fit gave reasonable values of pFS at DBH 2 and 20 cm for clone 6 and for the overall species. Clones 4, 9 and 10 were not destructively sampled at age 11 years, but destructive sampling at age 5 years indicated that these clones had quite similar pFS ratios at age 5 years, so for these clones pFS ratios at DBH=20 cm were assumed 0.15 (Figure 7.1) and pFS ratios at DBH=2 cm were estimated (Table 7.3) using the nonlinear model (5).

Table 7.3: Values of foliage: stem ratios at DBH=2 and DBH=20 and parameters of stem mass and DBH allometric relationship. Foliage and stem biomass data from destructive sampling at age 5 and 11 years were used to estimate these values.

Clone	Specific leaf area (m^2/kg)	Foliage: stem ratio		Parameters of stem mass and DBH relationship	
		DBH=2 cm	DBH=20 cm	a	b
4	3.79 b	4.99	0.15	0.218	1.962
6	4.35 a	3.84	0.16	0.218	1.962
9	4.15 ab	4.99	0.15	0.218	1.962
10	3.79 b	1.69	0.23	0.218	1.962
Overall	4.02	3.56	0.17	0.218	1.962

The parameters of allometric relationships (6) between stem mass and DBH were estimated for the species (Figure 7.2) from destructive sampling data of all clones at ages 5 years and 11 years. Wood basic density was not measured at the time of destructive sampling. Just as basic density of all clones was assumed similar, so the same parameter values of relationship (6) were used for simulating growth and productivity of clones and the overall species (Table 7.3).

$$M = a*DBH^{b} \quad (6)$$

Where M is stem mass of tree, a and b are constants.

Specific leaf areas

A default value of 6 for specific leaf area at age 0 (Landsberg *et al*., 2001) was used. Specific leaf areas at maturity were estimated as the mean of proportionate specific leaf areas of new and old live needles calculated from destructive sampling at ages 5 and 11 years. The mean of the specific leaf areas of four clones was used as the specific leaf area for the species.

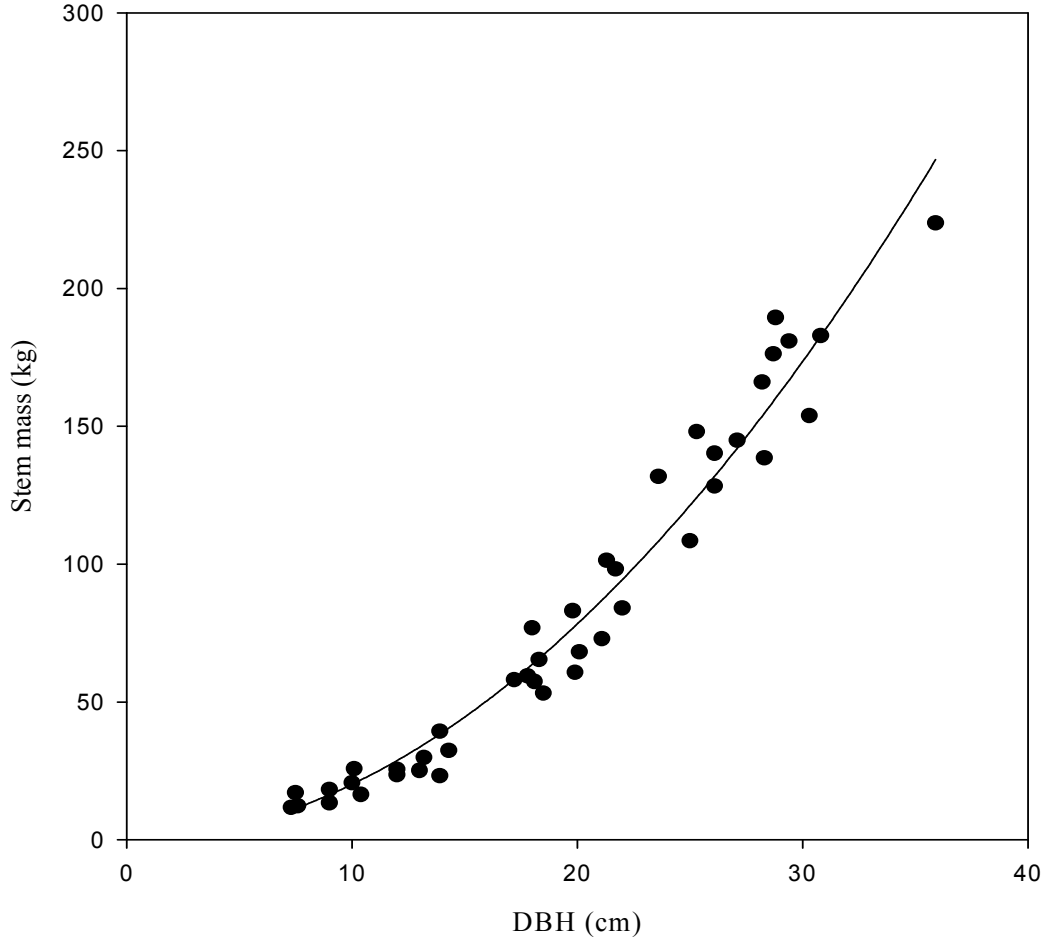


Figure 7.2 Relationship between measured stem mass (Oven Dry) and DBH. Stem biomass data from destructive sampling at ages 5 and 11 years were used to estimate these values.

Thinning

To match the stocking over the time course of simulations, thinnings were simulated according to the observed trend of mortality in respective clones and overall.

Basic density

The basic density of clones was not measured at the time of destructive sampling at ages 5 and 11 years. A minimum basic density of 350 (kg/m^3) for young trees and a maximum basic density of 450 (kg/m^3) for older trees of radiata pine have been reported by Cown *et*

al. (1991) and Cown (1992) in the Canterbury region. An average basic density of 400 (kg/m^3) was used in the models for simulations. The age at which average density =

(Minimum density + Maximum density)/2 was 11 years (Cown *et al.,* 1991). The parameters for maximum litter-fall rate and age at which litter-fall has median value were taken from Raison *et al.* (1992).

Canopy quantum efficiency

Canopy quantum efficiency was fitted to match the model output to mean observed values of stand basal area, mean DBH and mean LAI for the species.

Once a fertility parameter and maximum canopy quantum efficiency common to all clones were chosen, clone-specific biomasses were used to start simulations for each of the four clones. The final values of parameter inputs for individual clone and species simulations are listed in Tables 7.2, 7.3 and 7.4.

Sensitivity analysis

Sensitivity analysis was carried out by analysing the fits at two values of quantum efficiency (0.05 molC/molPAR and fitted value 0.063 molC/molPAR) because the maximum value of quantum efficiency for *Eucalyptus* plantations had been fitted from 0.046 molC/molPAR to 0.070 molC/molPAR (Sands and Landsberg 2002; Tome *et al*. 2004; Almeida *et al.* 2004).

Sensitivity to minimum fraction of NPP allocated to roots was also analysed for species and clones by reducing minimum fraction of biomass allocation to roots from 0.25 to 0.13 at quantum efficiency of 0.05 molC/molPAR to get best fits.

Table 7.4: Description and sources of the 3-PG model parameters used for simulation of productivity of *Pinus radiata* clones and overall of the species at Dalethorpe, Canterbury, New Zealand.

Meaning/comments	Parameter source	Units	Clone 4	Clone 6	Clone 9	Clone 10	Species
Allometric relationships & partitioning							
Foliage:stem partitioning ratio @ D=2 cm	Estimated (Table 7.1)	-	4.99	3.84	4.99	1.69	3.56
Foliage:stem partitioning ratio @ D=20 cm	Estimated (Table 7.1)	-	0.15	0.16	0.15	0.15	0.17
Constant in the stem mass v. diam. relationship	Estimated (Table 7.1)	-	0.218	0.218	0.218	0.218	0.218
Power in the stem mass v. diam. relationship	Estimated (Table 7.1)	-	1.962	1.962	1.962	1.962	1.962
Maximum fraction of NPP to roots	Default	-	0.8	0.8	0.8	0.8	0.8
Minimum fraction of NPP to roots	Default	-	0.25 or 0.13	0.25 or 0.13	0.25 or 0.13	0.25 or 0.13	0.25 or 0.13
Temperature modifier (fT)							
Minimum temperature for growth	Landsberg *et. al* (2001)	deg. C	0	0	0	0	0
Optimum temperature for growth	Landsberg *et. al* (2001)	deg. C	20	20	20	20	20
Maximum temperature for growth	Landsberg *et. al* (2001)	deg. C	35	35	35	35	35

Meaning/comments	Parameter source	Units	Clone 4	Clone 6	Clone 9	Clone 10	Species
Frost modifier (fFRost)							
Days production lost per frost day	Default	days	1	1	1	1	1
Soil water modifier (fSW)							
Moisture ratio deficit for $f_{\square}$ = 0.5	Default	-	0.7	0.7	0.7	0.7	0.7
Power of moisture ratio deficit	Default	-	9	9	9	9	9
Fertitlity effects							
Value of 'm' when FR = 0	Default	-	0	0	0	0	0
Value of 'fNutr' when FR = 0	Default	-	0.6	0.6	0.6	0.6	0.6
Age modifier (fAge)							
Maximum stand age used in age modifier	Default	years	50	50	50	50	50
Power of relative age in function for fAge	Default	-	4	4	4	4	4
Relative age to give fAge = 0.5	Default	-	0.95	0.95	0.95	0.95	0.95

Meaning/comments	Parameter source	Units	Clone 4	Clone 6	Clone 9	Clone 10	Species
Litterfall & root turnover							
Maximum litterfall rate	Raison *et al.* (1992)	1/month	0.025	0.025	0.025	0.025	0.025
Litterfall rate at t = 0	Raison *et al.* (1992)	1/month	0.001	0.001	0.001	0.001	0.001
Age at which litterfall rate has median value	Raison *et al.* (1992)	month	36	36	36	36	36
Average monthly root turnover rate	Default	1/month	0.015	0.015	0.015	0.015	0.015
Conductance							
Maximum canopy conductance	Default	m/s	0.02	0.02	0.02	0.02	0.02
LAI for maximum canopy conductance	Default	-	3.33	3.33	3.33	3.33	3.33
Defines stomatal response to VPD	Default	1/mBar	0.05	0.05	0.05	0.05	0.05
Canopy boundary layer conductance	Default	m/s	0.2	0.2	0.2	0.2	0.2
Stem numbers	Default						
Max. stem mass per tree @ 1000 trees/hectare	Pinjuv, (2006)	kg/tree	250	250	250	250	250
Power in self-thinning rule	Default	-	1.5	1.5	1.5	1.5	1.5

Meaning/comments	Parameter source	Units	Clone 4	Clone 6	Clone 9	Clone 10	Species
Fraction mean single-tree foliage biomass lost per dead tree	Default	-	1	1	1	1	1
Fraction mean single-tree root biomass lost per dead tree	Default	-	0.2	0.2	0.2	0.2	0.2
Fraction mean single-tree stem biomass lost per dead tree	Default	-	1	1	1	1	1
Canopy structure and processes							
Specific leaf area at age 0	Landsberg *et al.* 2001	m^2/kg	6	6	6	6	6
Specific leaf area for mature leaves	Observed	m^2/kg	3.79	4.35	4.15	3.79	4.02
Age at which specific leaf area = (SLA0+SLA1)/2	Default	years	1	1	1	1	1
Extinction coefficient for absorption of PAR by canopy	Default	-	0.5	0.5	0.5	0.5	0.5
Age at canopy cover	Default	years	3	3	3	3	3
Maximum proportion of rainfall evaporated from canopy	Default	-	0.15	0.15	0.15	0.15	0.15
LAI for maximum rainfall interception	Default	-	4	4	4	4	4
Canopy quantum efficiency	Fitted	molC/ molPAR	0.063	0.063	0.063	0.063	0.063

Meaning/comments	Parameter source	Units	Clone 4	Clone 6	Clone 9	Clone 10	Species
Branch and bark fraction (fracBB)							
Branch and bark fraction at age 0	Default	-	0.75	0.75	0.75	0.75	0.75
Branch and bark fraction for mature stands	Default	-	0.15	0.15	0.15	0.15	0.15
Age at which fracBB = (fracBB0+fracBB1)/2	Default	years	1.5	1.5	1.5	1.5	1.5
Various							
Ratio NPP/GPP	Default	-	0.47	0.47	0.47	0.47	0.47
Basic density	Cown *et. al* (1991)	t/m^3	0.4	0.4	0.4	0.4	0.4
Conversion factors							
Intercept of net v. solar radiation relationship	Default	W/m^2	-90	-90	-90	-90	-90
Slope of net v. solar radiation relationship	Default	-	0.8	0.8	0.8	0.8	0.8
Molecular weight of dry matter	Default	gDM/mol	24	24	24	24	24
Conversion of solar radiation to PAR	Default	mol/MJ	2.3	2.3	2.3	2.3	2.3

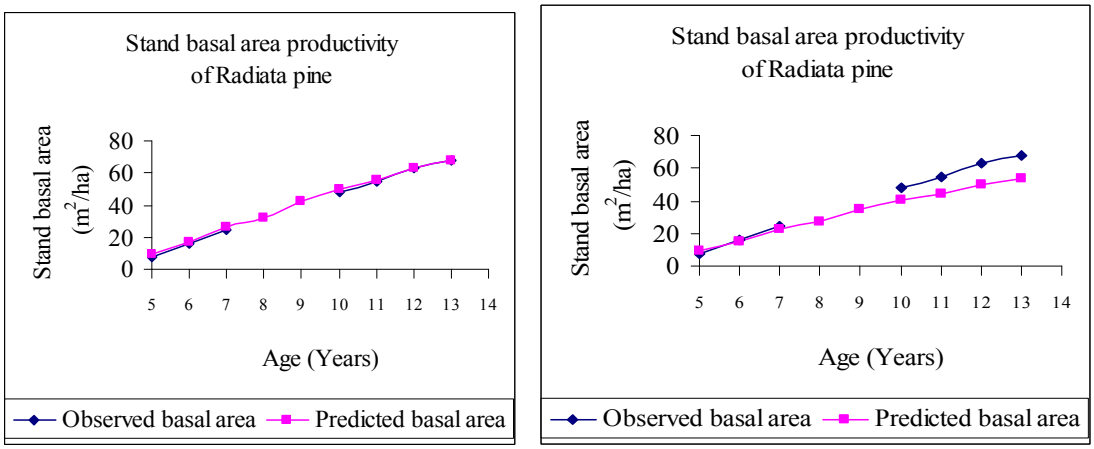
7.4 Results

Observed and species-specific values of various parameters reported in literature were used to simulate productivity of clones and of the overall species. Observed stand basal area, DBH and LAI were compared with values predicted by 3-PG for these variables to evaluate the effectiveness of the 3-PG model.

Clones differed in foliage biomass, stem biomass, foliage-stem partitioning ratios (Table 7.1) and specific leaf areas (Table 7.3). Clones 6 and 9 had greater specific leaf areas than clones 4 and 10.

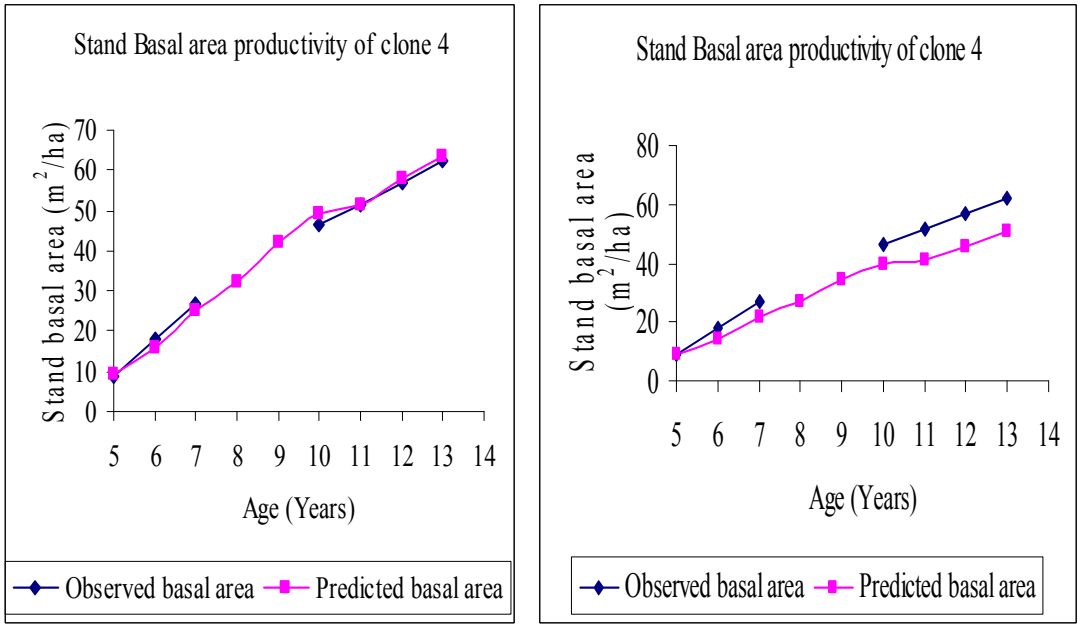
7.4.1 Stand basal area predictions

Figures 7.3-7.7 show the observed and predicted values of stand basal area of the species and clones over time. Better fits were obtained with fitted values of quantum efficiency (0.063 molC/molPAR, Figures 7.3 a1, 7.4 a1, 7.5 a1, 7.6 a1 and 7.7 a1) compared to quantum efficiency of 0.05 molC/molPAR (Figures 7.3 a2, 7.4 a2, 7.5 a2, 7.6 a2 and 7.7 a2). Good fits were obtained for the overall species and clones 4, 6 and 9 at the fitted quantum efficiency (0.063 molC/molPAR), but over predicted for clone 10. At quantum efficiency of 0.05 molC/molPAR, 3-PG consistently under predicted, *i.e.* for the species and all the four clones.



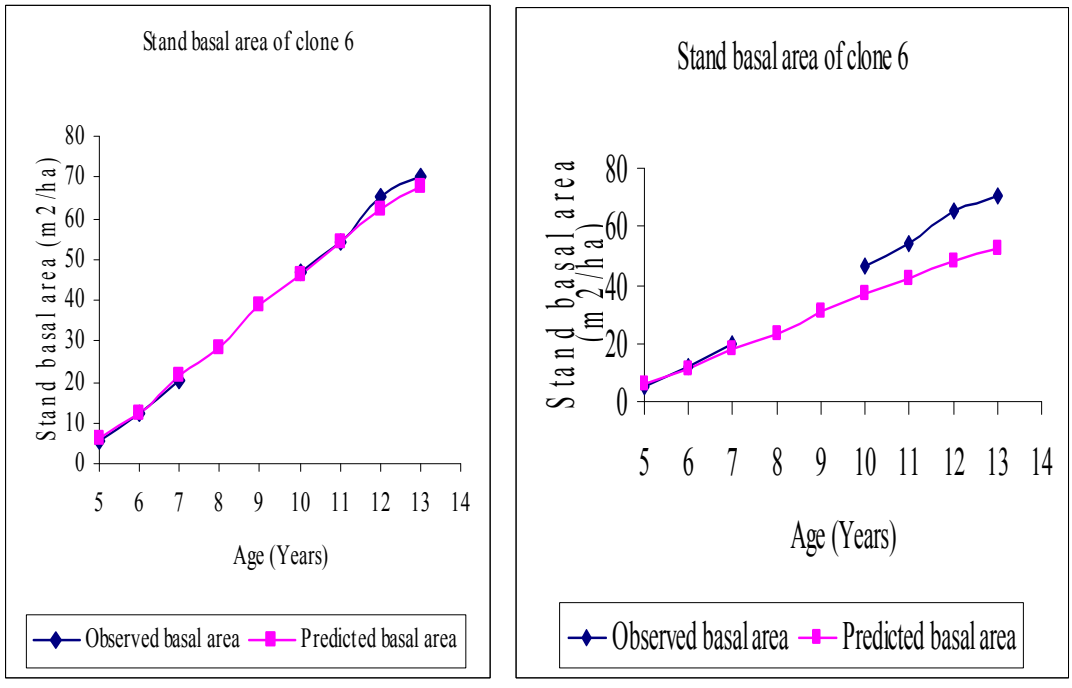
a1) a2)

Figure 7.3 Comparison of observed and predicted stand basal area (m^2/ha) over time of radiata pine (species) at quantum efficiency of 0.063 molC/molPAR (a1), and at quantum efficiency of 0.05 molC/molPAR (a2).



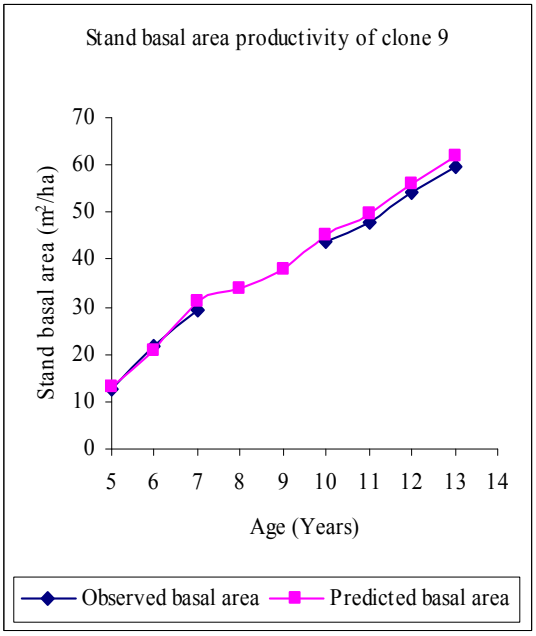
a1) a2)

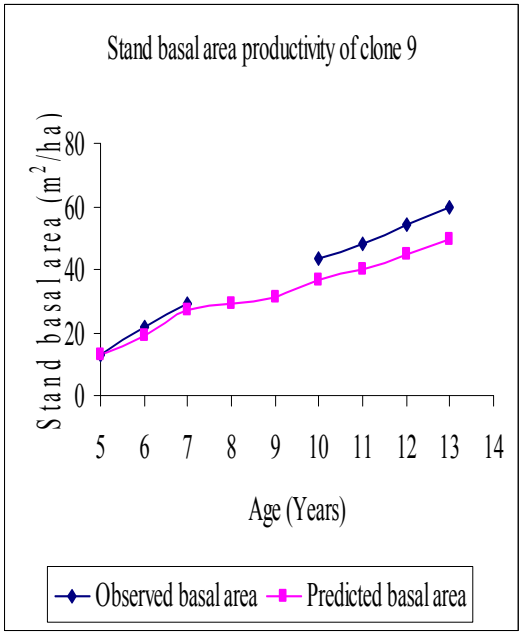
Figure 7.4 Comparison of observed and predicted stand basal area (m^2/ha) over time of clone 4 at quantum efficiency of 0.063 molC/molPAR (a1), and at quantum efficiency of 0.05 molC/molPAR (a2).



a1) a2)

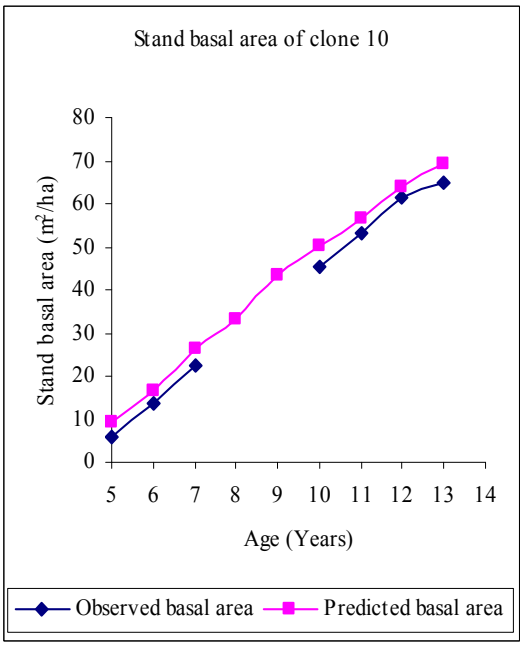
Figure 7.5 Comparison of observed and predicted stand basal area (m^2/ha) over time of clone 6 at quantum efficiency of 0.063 molC/molPAR (a1), and at quantum efficiency of 0.05 molC/molPAR (a2).

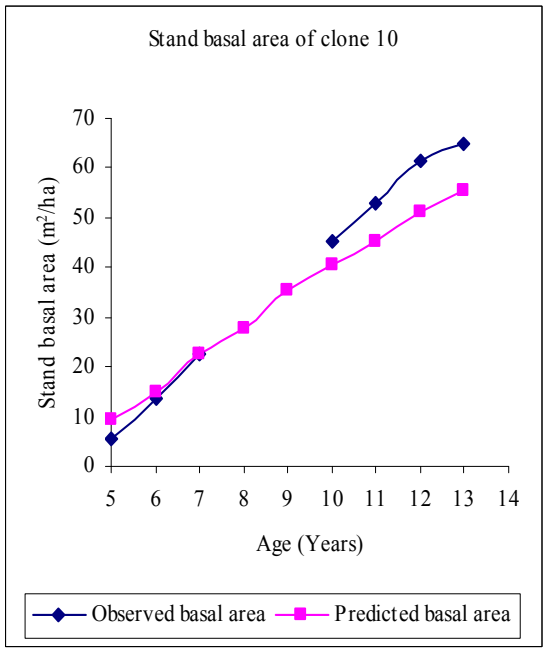




d1) d2)

Figure 7.6 Comparison of observed and predicted stand basal area (m^2/ha) over time of clone 9 at quantum efficiency of 0.063 molC/molPAR (a1), and at quantum efficiency of 0.05 molC/molPAR (a2).



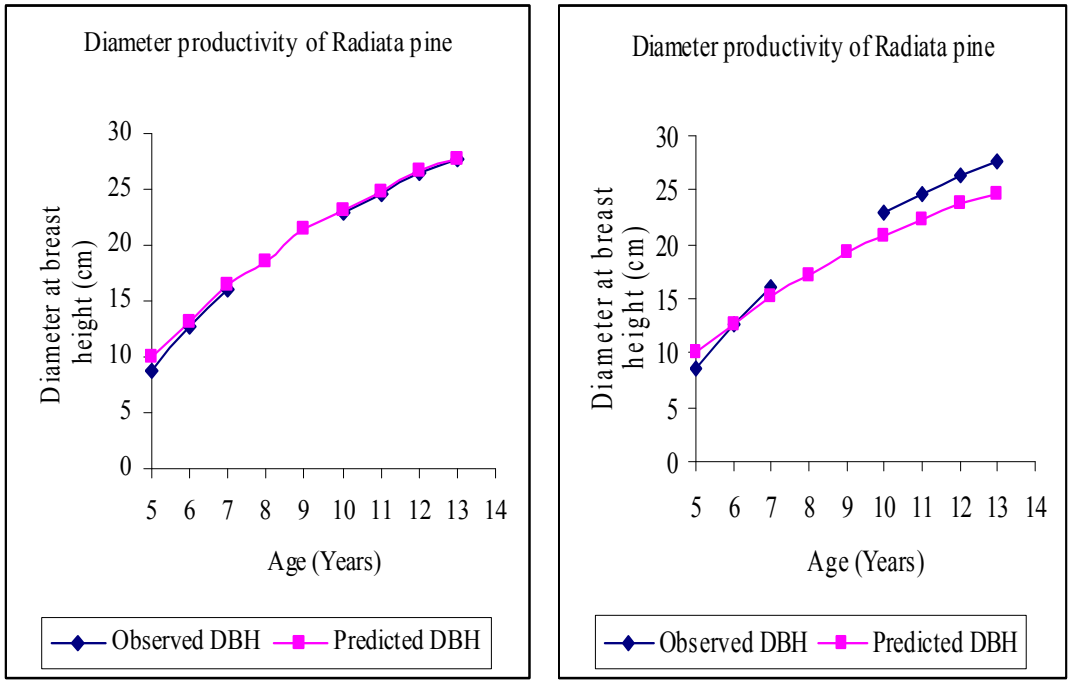


a1) a2)

Figure 7.7 Comparison of observed and predicted stand basal area (m^2/ha) over time of clone 10 at quantum efficiency of 0.063 molC/molPAR (a1), and at quantum efficiency of 0.05 molC/molPAR (a2).

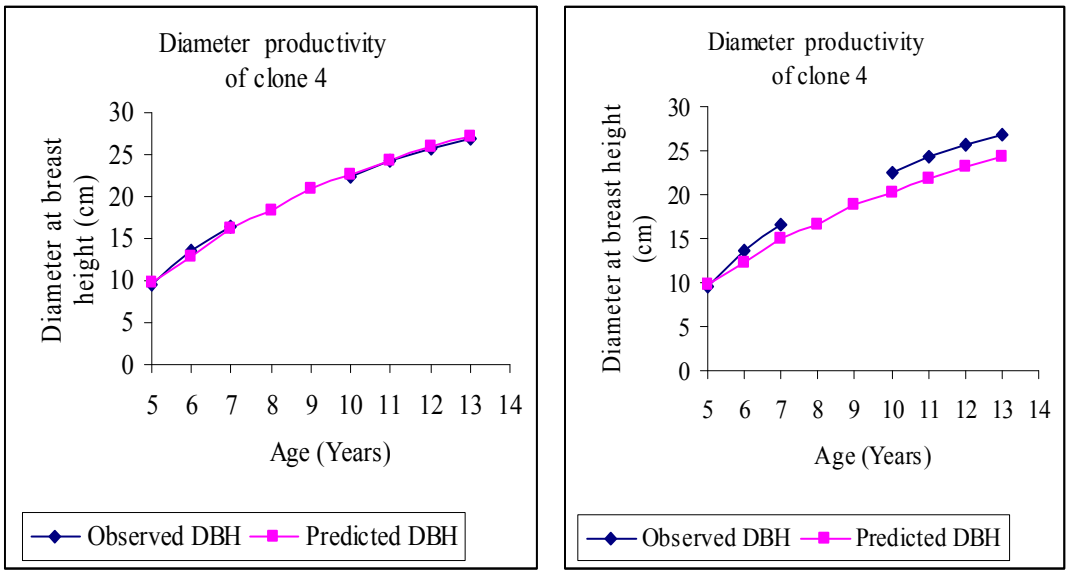
7.4.2 Diameter at breast height predictions

Figures 7.8-7.12 show observed and predicted values of average DBH and predicted DBH of clones over time. Predicted DBH for the overall species and clones were quite similar to observed DBH at fitted quantum efficiency (0.063 molC/molPAR Figures 7.8 a1, 7.9 a1, 7.10 a1, 7.11 a1 and 7.12 a1) than at value of 0.05 molC/molPAR (Figures 7.8 a2, 7.9 a2, 7.10 a2, 7.11 a2 and 7.12 a2).



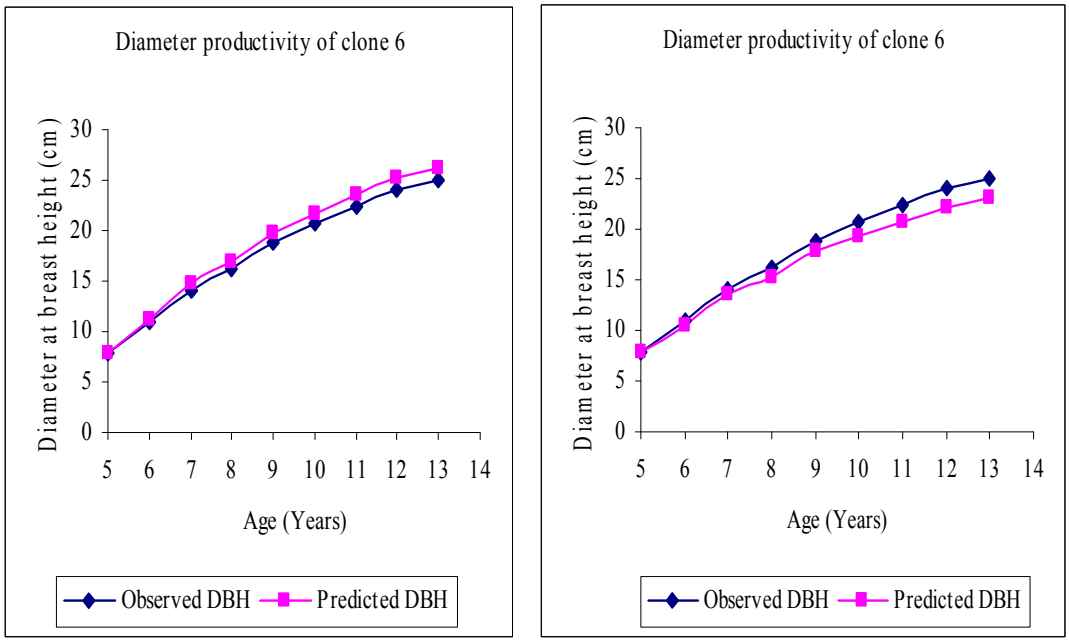
a1) a2)

Figure 7.8 Comparison of observed and predicted DBH over time of radiata pine (species) at quantum efficiency of 0.063 molC/molPAR (a1), and at quantum efficiency of 0.05 molC/molPAR (a2).



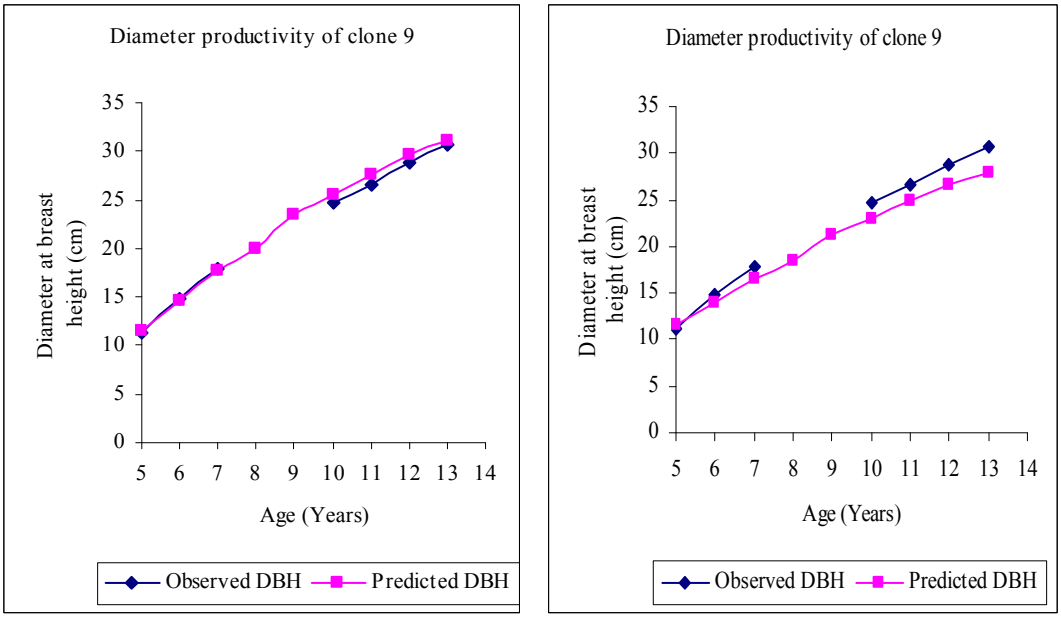
a1) a2)

Figure 7.9 Comparison of observed and predicted DBH over time of clone 4 at quantum efficiency of 0.063 molC/molPAR (a1), and at quantum efficiency of 0.05 molC/molPAR (a2).



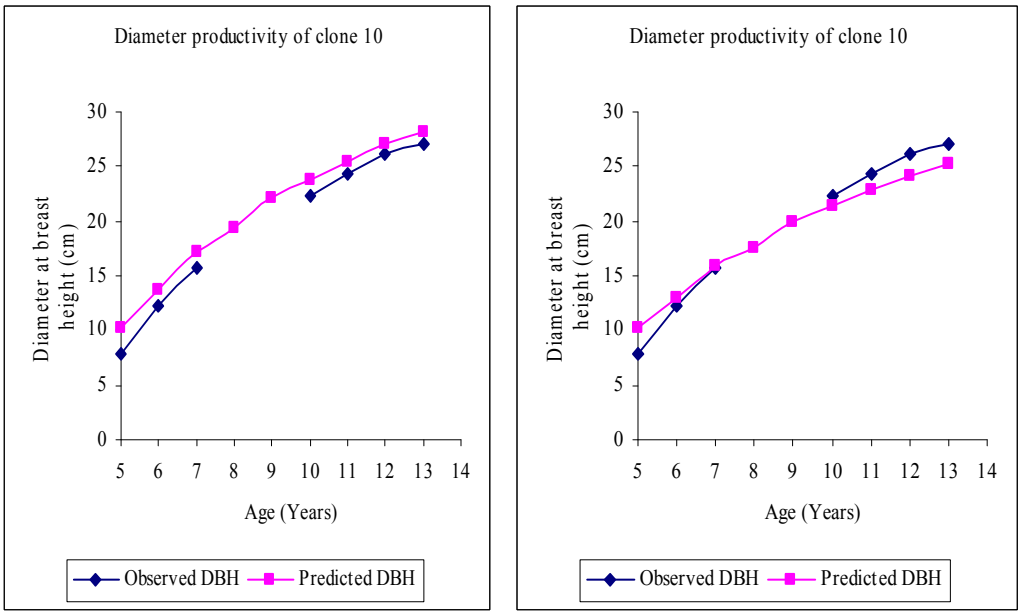
a1) a2)

Figure 7.10 Comparison of observed and predicted DBH over time of clone 6 at quantum efficiency of 0.063 molC/molPAR (a1), and at quantum efficiency of 0.05 molC/molPAR (a2).



a1) a2)

Figure 7.11 Comparison of observed and predicted DBH over time of clone 9 at quantum efficiency of 0.063 molC/molPAR (a1), and at quantum efficiency of 0.05 molC/molPAR (a2).



a1) a2)

Figure 7.12 Comparison of observed and predicted DBH over time of clone 10 at quantum efficiency of 0.063 molC/molPAR (a1), and at quantum efficiency of 0.05 molC/molPAR (a2).

7.4.3 Leaf area index (LAI) predictions

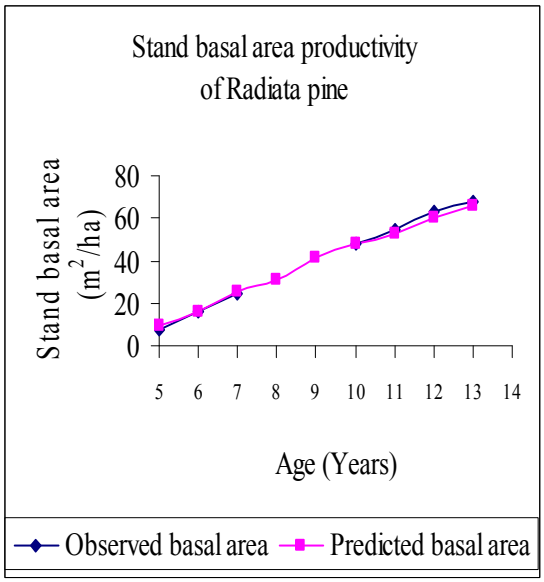
Table 7.5 shows the predicted values of LAI of clones obtained using fitted value of quantum efficiency (0.063 molC/molPAR) over time and mean observed values of LAI at age 13 years. The predicted LAI for species as well as for clones at age 13 years were lower than actual measured LAI.

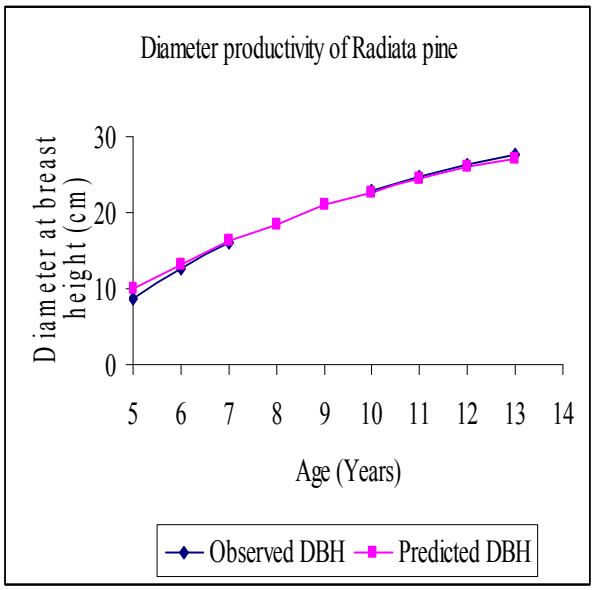
Table 7.5 Observed LAI versus predicted LAI of radiata pine and clones 4, 6, 9 and 10. PLAI and OLAI represent predicted and observed LAI respectively. OLAI values for each clone were calculated from LAI measured in three plots of each clone at age 13 years.

Age	Species		Clone 4		Clone 6		Clone 9		Clone 10	
(Years)	PLAI	OLAI	PLAI	OLAI	PLAI	OLAI	PLAI	OLAI	PLAI	OLAI
5	5.3		4.1		4.3		8.3		4.6	
6	6.1		4.9		5.6		9.4		5.0	
7	6.7		5.5		6.9		9.8		5.3	
8	6.4		5.3		6.9		7.9		5.1	
9	6.1		5.1		6.7		5.8		4.8	
10	5.7		4.7		6.3		5.1		4.7	
11	5.1		4.2		5.6		4.3		4.0	
12	4.5		3.5		5.1		3.9		3.6	
13	3.8	4.4	3.0	3.8	4.4	4.7	2.75	3.9	3.1	4.4

7.4.4 Sensitivity to biomass allocation to roots

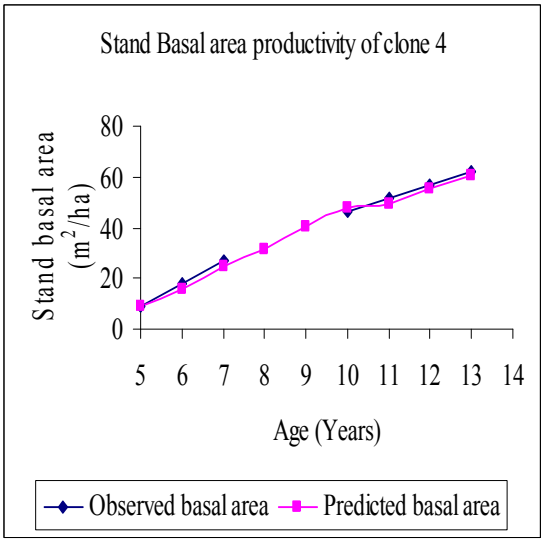
The reduction of minimum fraction of biomass allocation to roots from 0.25 to 0.13 at quantum efficiency of 0.05 molC/molPAR allowed the productivity of these clones to match observed values (Figure 7.13), but at fitted value of quantum efficiency of 0.063 molC/molPAR 3-PG over predicted stand basal areas and DBH for the species as well as for clones (Figures 7.13 – 7.17).

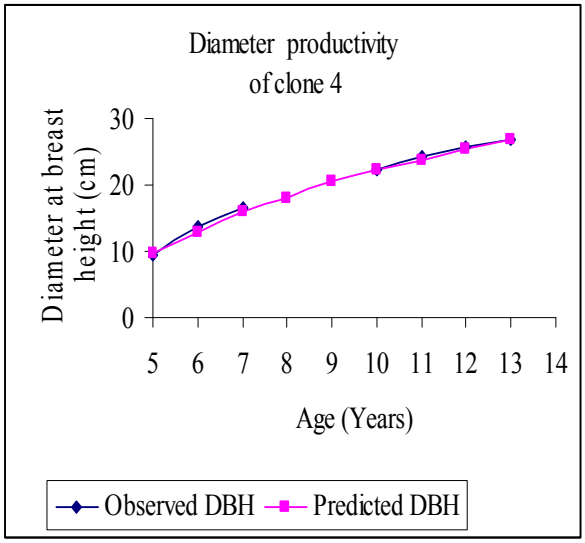




a1) a2)

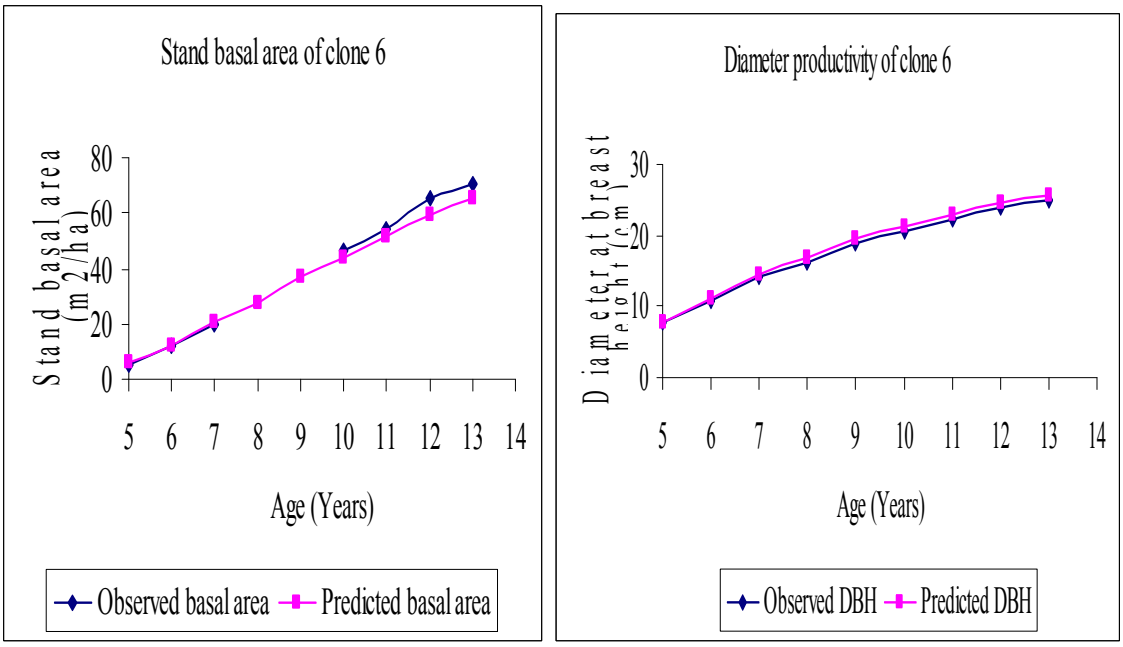
Figure 7.13 Comparison of observed and predicted stand basal area (a1) and DBH (a2) over time of radiata pine (species) at quantum efficiency of 0.05 molC/molPAR and minimum fraction of biomass allocation to roots of 0.13.





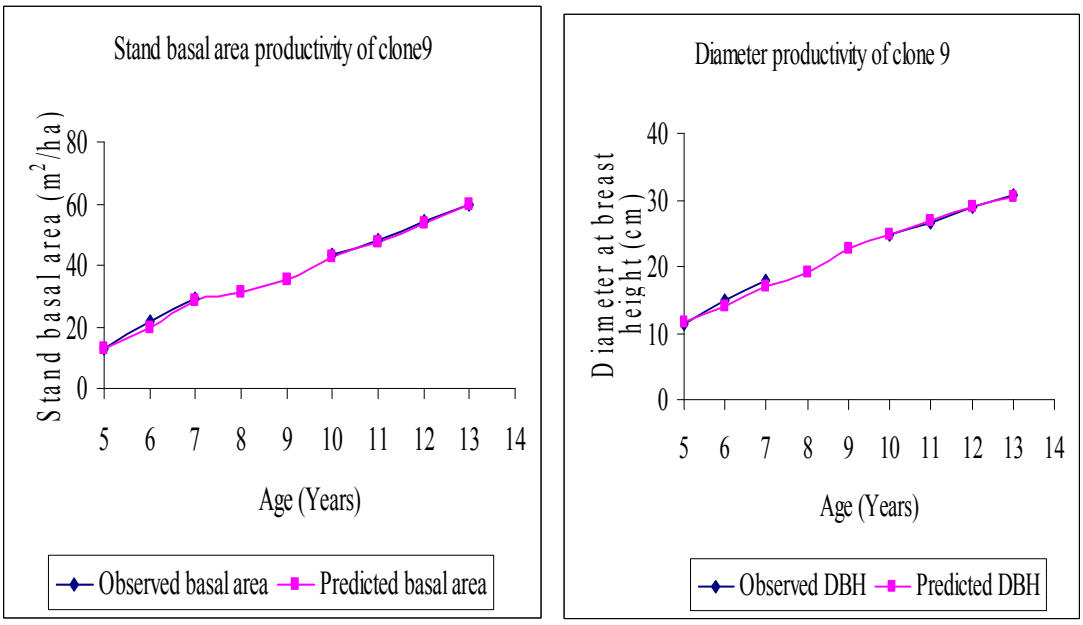
a1) a2)

Figure 7.14 Comparison of observed and predicted stand basal area (a1) and DBH (a2) over time of clone 4 at quantum efficiency of 0.05 molC/molPAR and minimum fraction of biomass allocation to roots of 0.13.



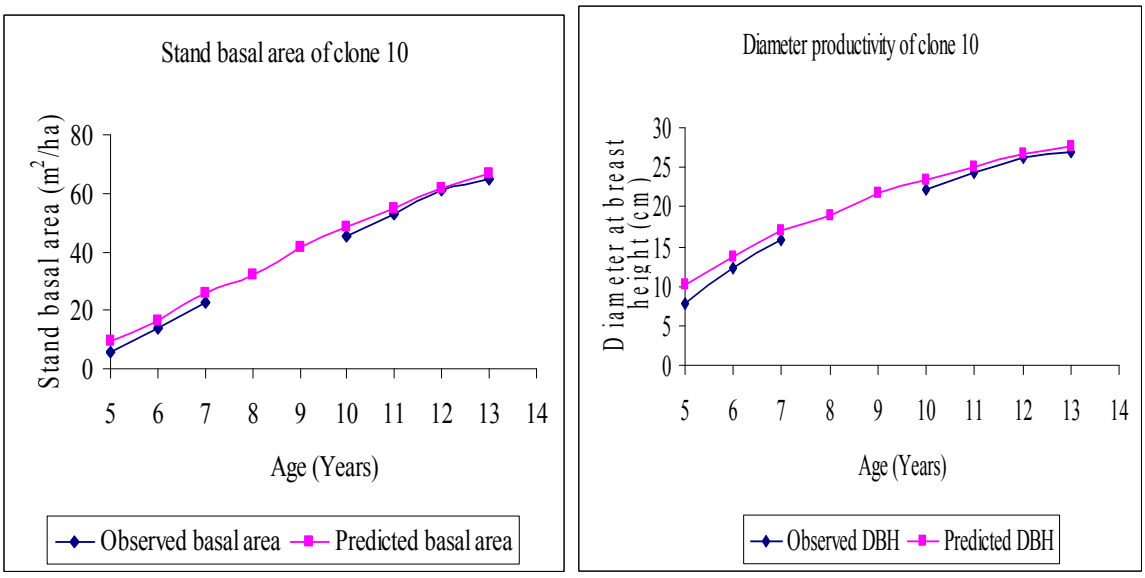
a1) a2)

Figure 7.15 Comparison of observed and predicted stand basal area (a1) and DBH (a2) over time of clone 6 at quantum efficiency of 0.05 molC/molPAR and minimum fraction of biomass allocation to roots of 0.13.



a1) a2)

Figure 7.16 Comparison of observed and predicted stand basal area (a1) and DBH (a2) over time of clone 9 at quantum efficiency of 0.05 molC/molPAR and minimum fraction of biomass allocation to roots of 0.13.



a1) a2)

Figure 7.17 Comparison of observed and predicted stand basal area (a1) and DBH (a2) over time of clone 10 at quantum efficiency of 0.05 molC/molPAR and minimum fraction of biomass allocation to roots of 0.13.

7.5 Discussion

The close prediction of stand basal areas and diameters at breast height over time by the 3-PG model using variables and parameters calculated from destructive sampling data, and by varying quantum efficiency or minimum fraction of NPP to roots indicated that it is possible to determine parameters needed to calibrate the 3-PG model for clones. In this study maximum quantum efficiency was not measured and it was assumed that fast growing clones might have allocated more carbon to stems at the expense to roots. Therefore, measurements of biomass allocation patterns, particularly those to roots, and measurement of quantum efficiency may be required before simulations could be employed for predictions, however. Differences in productivity of clones appeared due to their observed differences in biomass partitioning and specific leaf areas. Differences in foliage: stem ratios at early ages resulted in corresponding later differences in stem biomass, foliage biomass, and leaf area. Differences in specific leaf area resulted in differences in productivity and growth. Clones exhibited greater inter-change of ranks in monoclonal plots than in clonal mixture plots (Chapter 4, Figures 4.3-4.6). The growth rates of clones relative to one another changed with age. Some clones grew rapidly during the first few years. Others grew more moderately at the beginning, but outperformed the early fast-growers (e. g. clone 6). Destructive sampling information at age 5 years revealed

that trees of clone 6 had lower overall biomass (foliage biomass + stem biomass, Table, 7.1), but allocated more photosynthate to its foliage and had greater foliage: stem biomass ratios (Table 7.1) and specific leaf areas (Table 7.3). The greater foliage mass and specific leaf areas enhanced the growth of this clone. Enhanced growth combined with greater survival of this clone resulted in greater overall stand basal area productivity that improved its ranking relative to other clones in monoclonal plots. Although, this clone got suppressed in clonal mixtures but emerged as strong competitor (Chapter 5). The greater allocation to foliage may explain its enhanced competitiveness in clonal mixture plots.

The ratio of net primary productivity to gross primary productivity (NPP/GPP) and quantum efficiency was not varied among clones because it is normally assumed to be constant within a species (Landsberg and Waring, 1997; Landsberg *et al*., 2001; Sands and Landberg, 2002; Almeida *et al*., 2004). Differences in observed and predicted performance of clones could be due to parameters not measured, *e.g.* wood density, maximum canopy conductance, and/or maximum and minimum allocation to roots.

Almeida *et al.* (2004) parameterised the 3-PG model for fast-growing *Eucalyptus grandis* clones in Brazil and reported that parameters of biomass partitioning to roots, ratios of foliage to stem biomass partitioning, coefficients of stem allometric relationships with DBH, maximum canopy conductance and stem-wood basic densities differed between clones. They attributed differences in production between genotypes primarily to differences in biomass partitioning and differences in stomatal conductance. In this study default values were used for maximum canopy conductance, but we cannot rule out the possibility of differences in conductance between clones. Landsberg *et al.* (2003) demonstrated through sensitivity analysis that increasing stomatal conductance decreased net primary productivity of *Eucalyptus globulus.* Almeida *et al.* (2004) reported variation in stomatal conductance between *Eucalyptus* clones was one of the main causes of productivity differences between clones.

Poor matching of predicted and observed LAI in this study might be due to lack of precision in estimating the values of foliage stem mass ratios. Landsberg *et al.* (2003) suggested that the gap between observed and predicted LAI can be narrowed by further adjusting the foliage allometric parameters.

Model validation is important for evaluating the effectiveness of models. Unfortunately the lack of other experimental plots of the same genetic material at other sites or destructive sampling data proved limiting for testing the effectiveness of the parameter values used. Therefore, it is difficult to comment with confidence on the usefulness of the 3-PG model for prediction of productivities of clonal stands because there are many parameters that could be adjusted to match the model outputs with actual productivities. Further detailed studies would be required to estimate and validation of the model to evaluate its effectiveness. But successful calibration of radiata pine clones in this study and *Eucalyptus grandis* clones considered by Almeida *et al.* (2004), and *Eucalyptus globulus* by Sands *et al.* (2002); Landsberg *et al.* (2003) and Tome *et al.* (2004) indicates that 3-PG can at least partially explain differences in observed clonal productivities. The extent to which it is useful for this purpose will depend on several factors, including knowledge of input parameters unique to each study site. The accuracy in predictions depends upon accuracy of estimating parameter values from measured variables and destructive sampling data, and the absence of unusual, harsh stresses.

7.6 Conclusions

Clones significantly differed in foliage biomass, stem biomass and specific leaf areas at age 5 years.

Better fits of stand basal area and DBH for species and clones were obtained by increasing quantum efficiency or decreasing minimum fraction of biomass allocation to roots. At a quantum efficiency of 0.05 molC/molPAR, the 3-PG model regularly under predicted both stand basal areas and DBH. This bias disappeared when quantum efficiency was raised to 0.063 molC/molPAR or minimum fraction of biomass allocated to roots was decreased from 0.25 to 0.13.

The 3-PG model showed that the differences in foliage: stem ratios at early ages resulted in corresponding later differences in stem biomass, foliage biomass, and leaf areas. Modelled differences in final productivity of clones were due to differences in biomass partitioning and specific leaf areas.

CHAPTER 8

INFLUENCE OF MODE OF DEPLOYMENT ON STEM SLENDERNESS, BRANCHING AND WOOD STIFFNESS OF 13-YEAR- OLD RADIATA PINE CLONES AT DALETHORPE, CANTERBURY

8.1 Abstract

The influence of mode of deployment (*i.e.* monoclonal or clonal mixture deployment to forest) on wood stiffness and stem form was evaluated at age 13 years in an experiment established with ten radiata pine clones at Dalethorpe, Canterbury. Stiffness of stems was defined as velocity-squared, using un-adjusted velocities from the time-of-flight sonic tool TreeTap. The influence of mode of deployment on stiffness and stem slenderness of clones was evaluated only at an initial stocking of 1250 stems/ha. Branch diameter and angle over the basal 3.5-m stem was evaluated in four contrasting clones across three stockings: 833 stems/ha, 1250 stems/ha and 2500 stems/ha.

Clones significantly differed in stem-wood stiffness (P=0.004), stem slenderness (P=0.0008), branch angle (P=0.0043), branch diameter (P<0.05, SNK test) and branch index (P<0.05, SNK test) at a stocking of 1250 stems/ha. Variability in stem stiffness was 25% greater (P=0.040) in clonal mixture plots than monoclonal plots. Variability in stem slenderness was also greater (15 %) in clonal mixture plots, but not significantly so (P=0.2901).

Greater stem slenderness was correlated to live-crown height ($P<0.0001$), and exerted a positive ($P<0.0001$) influence on stiffness, but mode of deployment only significantly altered the stem slenderness of one of the ten clones. Two clones of the same family significantly differed in branch diameter and branch angle when they were competing with other genotypes at a stocking of 1250 stems/ha. Increasing stocking from 833 stems/ha to 2500 stems/ha lowered the branch diameter by 56 %, but increased the branch insertion angle by 17 %.

8.2 Introduction

Stiffness is one of the most important wood properties for structural timber of radiata pine. Plantation-grown *Pinus radiata* timber has relatively poor stiffness and stability compared to other internationally traded structural lumber species (Walford, 1991; Cave and Walker 1994). The emphasis of breeding has recently shifted to improving stiffness of radiata pine rather than wood density (Jayawickarama, 2000).

Several studies of contrasting *Pinus radiata* genotypes concluded that wood properties were under moderate to high genetic control. Lindstrom *et al.* (2004) reported high (80-90 %) clonal heritabilities of stiffness, microfibril angle and wood density. Dungey *et al.* (2006) reported high to moderate genetic control of microfibril angle, density and stiffness using SilviScan, in core-wood and outer-wood respectively.

Several studies have identified significant impacts on dynamic stiffness of either genotype (clone) or initial stocking on dynamic stiffness, but not their interaction. Waghorn *et al*. (2007a) studied the influence of initial stand stocking and genotype on dynamic modulus of elasticity (stiffness) of 17-year-old radiata pine logs using the sonic resonance tool Hitman, and reported significantly greater influence of initial stand stocking (37 % increase in dynamic modulus of elasticity at stocking of 2551 stems ha^{-1} over 275 stems ha^{-1}), and genotype (18 % increase in modulus of elasticity of stiffest genotype over least stiff genotype). They also discovered marginally significant influences from the interaction of initial stand stocking and genotype on stiffness. Waghorn *et al.* (2007b) also studied the influence of initial stand stocking and genotype on stiffness on 17-year-old standing trees using TreeTap (a Time-of Flight (ToF) sonic tool) and reported a significant influence of

initial stand stocking and genotype on stiffness, but not for their interaction on stiffness. Lasserre *et al*. (2004, 2005) studied influence of initial stocking and genotype on corewood stiffness of 11-year-old radiata pine using TreeTap. They reported a 34 % increase in stiffness at a stocking of 2500 stems ha^{-1} compared to stocking of 833 stems ha^{-1}, and 15 % gains in stiffness were attributed to genetic material. They found no significant influence of interaction between initial stocking and genotype. Roth *et al.* (2007) also reported 31 % increase in dynamic stiffness at initial stocking of 2990 stems/ha over stocking of 1334 stems/ha and attributed 22 % gains to genetic material in a 6 years old plantations of loblolly pine (*Pinus taeda*). They reported non-significant interaction of genotype and stocking. These studies suggest consistently that genotype and stocking do not interact with respect to their impacts on stiffness. Mason (2006) reported significant influences of genotype, slenderness and pruned height on stiffness in a study conducted to analyse the effect of weed control on wood stiffness.

Silvicultural practices also influence wood quality through their effects on the growing environment of the tree's crown and roots (Zobel and van Buijtenen, 1989; Punches, 2004). Spacing between trees and stocking level can both affect stem form, with tighter spacings and higher stockings resulting in more slender stems (Punches, 2004). Waghorn *et al.* (2007b) reported significant increase ($P<0.0001$) in stem slenderness with increasing stand stocking. They found no influence of the interaction between genotype and stocking on stem slenderness.

Measuring stiffness of standing trees might be of benefit to forest managers to segregate young trees when deciding which trees to cull during thinning operations (Tsehaya and Walker, 1995). Some companies are attempting to use sonic testing of standing trees to map velocity, especially in pre-harvest inventories (PHI), and such testing necessarily must be done using time-of-flight tools, since resonance tools require cut log ends. ToF tools used in NZ include Fakopp (Chauhan *et al.,* 2005; Lindstrom *et al*., 2004), Director ST-300TM (Carter *et al.,* 2005), and TreeTap (Lasserre *et al.,* 2004, Grabianowski *et al.,* 2005, Mason, 2006, Waghorn *et al*., 2007b). Use of these tools has enabled researchers to study impacts of management practices on wood properties. Foresters use sonic resonance (Joe *et al.,* 2004) to segregate or audit the structural quality of harvested logs, and only some routinely use ToF sonic tools on standing trees for stand characterisation.

Stem form and branching are critically important to structural log value. Stem slenderness and branch habit are important tree morphological characteristics that affect the quality of timber and product recovery at the end of the rotation (Grace, 1992). Slender trees typically produce wood with higher stiffness, apparently as a response to withstand higher compressive stress, possibly by manipulating the microfibril angle in the secondary cell wall (Watt *et al*., 2006). Large branches lead to large defects (knots, wider occlusion scars, more compression wood and included bark, more top breakout) and are costly to prune and slow to occlude, leading to large defect cores in pruned logs. According to the New Zealand Forest Service (1984), the ideal branching habit for production would be small diameter branches growing at right angles to the main stem.

Genotype, site conditions (latitude, altitude, slope, windiness, soil fertility), and silvicultural practices (thinning, pruning, irrigation, fertilization, weed control) influence growth rate. Growth rate can also affect wood characteristics that determine the quality of timber (Macdonald and Hubert, 2002; Punches, 2004; Gartner, 2005). Mode of deployment (*i.e.* monoclonal or clonal mixture deployment to forest) may affect growth rate and stem form of some clones in clonal mixture plots as reported by Debell and Harrington (1997) and Benbrahim *et al*. (2000).

Monoclonal deployment or deployment of sets of clones with known, similar wood properties might be a more efficient way to produce logs and wood that are uniformly suitable for structural applications.

The study described here was undertaken with the following objectives:

- To evaluate effects of mode of clonal deployment on stem-wood stiffness and stem slenderness of clones.
- To determine if mode of clonal deployment affects the variability of stem stiffness.
- To identify morphological characteristics that influenced stiffness development of clones and determine whether or not these morphological differences fully explained observed differences in wood properties between clones.
- To evaluate the effect of genotype, DBH and stocking on branch diameter and branch angle.

8.3 Materials and Methods

8.3.1 Site

An experiment was established with radiata pine (*Pinus radiata* D. Don) on a site at Dalethorpe (latitude 42^0-45'S, longitude 171^0-55'E, elevation 520 m above sea level), 70 km west of Christchurch, Canterbury, New Zealand in September 1993. The soil at the site was well-developed silt-loam (NZ Soil Bureau, 1968). Mean annual precipitation was 1058 mm from 1993-2006 (NIWA, 2006). Precipitation was distributed fairly evenly throughout the year, although a marked dry period can occur during February and March (McCracken, 1980).

8.3.2 Planting material

Clones were propagated by organogenesis from controlled pollinated mature seeds that were surface sterilised and germinated into sterile tissue cultures. After propagation they were hardened off in a nursery, conditioned with an undercutting and wrenching regime, and field-transplanted as bare-root plants. Ten clones (1 to 10) were planted in this experiment, derived from control-pollinated crosses. Clones 3, 7 and 10 were propagated from different seeds of same control-pollinated cross and are "full-sibs". Clones 1 & 9 and clones 6 & 8 were propagated from different seeds of each of two crosses. Clones 2, 4 and 5 were from three additional crosses. Clones deployed in this experiment therefore represented six different families. The exact pedigrees of the clones were not revealed by the organization that provided the clones for this experiment, although they were said to have growth and form ratings (Sorensson, personal communication) between 25 and 30.

8.3.3 Design of the experiment

The ten clones were deployed in two modes of deployment (monoclonal and clonal mixture) in a complete randomised block design with three replications. Each block thus comprised eleven treatments: Each monoclone and the clonal mix contained all ten clones randomised in equal proportions. All plots were of rectangular shape (16 x 20 m) and

contained 40 trees (5 x 8), except for one larger clonal mixture plot (64 x 20 m) that contained 160 trees (5 x 32). Trees were spaced 2 m within rows and 4 m between. The total area of the experiment was 1.15 hectares, which comprised 9600 sq m of monoclonal plots and 1920 sq m of clonal mixture plots. The only tending applied to the trial was a lift-pruning to 2.5 m at age 7 years. A common silivicultural regime in Canterbury is an initial stocking of 1250 stems per hectare thinned to 600 stems per hectare at ages 6-7 years (MAF, 2005; SPBL, 2006). Thinning was not carried out in this experiment and a stocking of 1250 stems/ha was maintained unless mortality reduced it.

8.3.4. Establishment practices

All the plants were planted in pits of 30 cm depth in ripped lines with ripping at a depth of 30 cm. Each planting spot was further cultivated with a spade. Each randomised complete block was planted by only one person. All the plots were kept completely weed free using initially a mixture of Hexazinone and Turbuthylazine, and subsequently a mixture of Turbuthylazine, Clopyralid and Haloxyfop herbicides for 5 years following planting.

8.3.5. Assessments

Tree and crown heights (height of live crown from ground) were measured using vertex hypsometer, and diameters at breast height over bark (DBH) were recorded using diameter tapes for all live interior trees (*i.e.* excluding buffer trees in monoclonal as well as in clonal mixture plots) of all plots during September 2006 (age 13 years). Time-of-flights were recorded using the non-destructive acoustic wood quality measurement tool TREETAP version 4, developed at the University of Canterbury, Christchurch, New Zealand (www.cant.canterbury.ac.nz/showcase/trends.shtml), over a 1.300-m path length, with start and stop probes placed at 0.3 and 1.6 m above the base of each tree. Eight repeated sonic measurements on each side (windward and leeward) of the standing trees were made through bark on each stem at age 13 years. In total, 467 trees in monoclonal and 105 in clonal mixture plots were “tapped”.

8.3.6 Determination of stiffness

Unadjusted stem-average velocity was calculated from mean time-of-flight as in (1).

$$V = l/t \quad (1)$$

where V= velocity of sound in m/sec, *l*= 1.300 m (distance between two probes), and *t* = mean time of flight between two probes in micro-seconds.

Green dynamic modulus of elasticity (E_d; Pa) was estimated for all trees as in (2). This equation assumes that V is composed entirely of the plane wave, and is unaffected by the faster dilatational wave. This high bias of time-of-flight-derived velocity has been observed, and ranges from about 107% to 130% or more (Andrews, 2003; Wang *et al.,* (2007) but is less serious with the TreeTap tool due to its 3-probe design, and is less serious in younger age and small-diameter stems (Wang *et al*. 2007), such as that in this study (mean DBH of 27.7 cm at age 13 years).

$$E_d = \rho V^2 \quad (2)$$

Where V = velocity of sound (m/s) and ρ is green density (Kg/m^3).

The density of sapwood under-bark in live, young pine trees is typically assumed to be identical amongst trees, at 1000 Kg/m^3 (Huang *et al.,* 2003; Lindstorm *et al.,* 2004; Grabianowski *et al.,* 2005; Mason, 2006). It should be noted that standing tree time of flight sonics do not sample equally all wood of a stem, as they primarily travel 20-60 mm below bark (E.G. Mason unpubl. data).

Branch habits (branch diameter, branch angle and branch index) of four clones 4, 6, 8, and 10 having different growth patterns and morphology were compared in clonal mixture plots at three stockings 833 stems/ha, 1250 stems/ha and 2500 stems/ha using data collected by Samia Pelletier (personal communication) at age 13 years in an adjoining experiment established at same time.

Branch diameter (over bark) and branch insertion angle of two trees of these clones in three blocks were measured to ladder height (3.90 m). Trees with double leaders or any sort of malformation, close to border or gap created by mortality were avoided. Branch diameters were measured with a calliper to the nearest millimetre, less than 5 cm from the branch collar. Branches smaller than 0.5 cm were only counted for each whorl. Branch angle was measured with a clinometer to the nearest 5 degrees. The branch angle in this study refers to the angle made by the axis of the base of the branch with the line outside of the trunk above the branch, 0 degree angle represent the branches at right angle to the stem. The compass quarter (N S E W) in which each branch was positioned was noted, as it is required to calculate branch index. Branch index was calculated as the average diameter of one largest branch diameter taken from each quarter of the tree over a short 3.5-m stem from about 0.5 to 3.9 m.

8.3.7 Variables calculated

Mean stiffness and slenderness were calculated for each clone in every plot. Coefficients of variation of stiffness and slenderness were calculated for each clone both in monoclonal and clonal mixture plots. Overall coefficients of variation in monoclonal and clonal mixture modes of deployment were also calculated. Stem Slenderness (mm^{-1}) and Live-Crown length (length of live crown in meters) were calculated as:

$$Slenderness = \frac{Height * 100}{DBH} \quad (3)$$

$$Crown\ Length = Total\ Tree\ height - Live\ Crown\ height \quad (4)$$

Where live crown height is the height from the base of tree to the base of the live crown. Mean branch diameter, branch angle and branch index were calculated for each tree measured.

8.3.8. Data analysis

Correlation and regression analyses were carried out between the following variables: stiffness, DBH, stem slenderness, live-crown height and crown length.

Some trees with broken stem tops were considered outliers and their heights treated as missing data (Figure 8.1). In Total, 555 trees (453 in monoclonal and 102 in clonal mixture plots) were used for regression analyses.

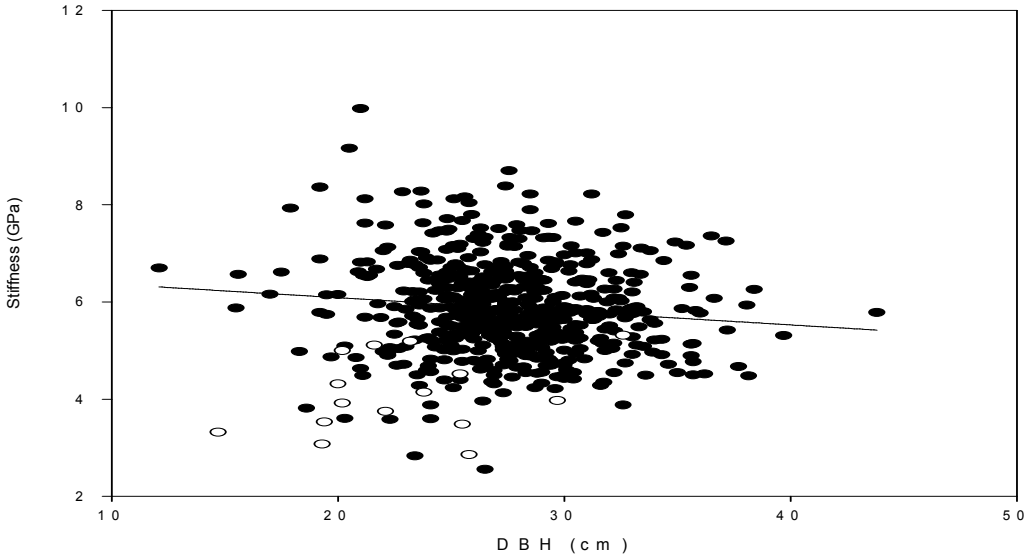


Figure 8.1: Scatter plot of DBH and stiffness. Black circles represent normal tress and blank circles represent trees with broken stem tops (outliers).

Procedure GLM (General linear models) of SAS (SAS Institute Inc. 2000) was used to examine the effects of block, genotype, mode of deployment, and interactions between genotype and mode of deployment on stiffness and slenderness, and on the coefficient of variation (CV) in stiffness and slenderness. The following model (5) was used for analysis of variance:

$$Y_{ijk} = \mu + g_i + b_j + d_k + (gd)_{ik} + e_{ijk} \qquad (5)$$

Where Y_{ijk} is mean dynamic stiffness or stem slenderness or CV of dynamic stiffness or CV of stem slenderness of i^{th} clone, j^{th} block and k^{th} mode of deployment, μ is overall

mean, g_i is i^{th} clone, b_j is j^{th} block, d_k is k^{th} mode of deployment, $(gd)_{ik}$ is interaction of i^{th} clone and k^{th} mode of deployment and e_{ijk} is error.

Student-Newman-Keuls multiple range test was used to distinguish differences in mean stiffness between clones. The smallest critical range of SNK test was used as measure of statistical power for each variable.

Covariance analysis was conducted using model (6) on individual tree data. Stiffness was the dependent variable; block and clone were class variables; and slenderness or crown height or crown length were covariates to evaluate the influence of morphological characteristics on dynamic stiffness.

$$Y_{ij} = \mu + g_i + b_j + s_{ij} + (gb)_{ij} + (gs)_{ij} + e_{ij} \quad (6)$$

Where Yij is dynamic stiffness of i^{th} clone and j^{th} block, μ is overall mean, g_i is i^{th} clone, b_j is j^{th} block, $(gb)_{ij}$ is interaction of i^{th} clone and j^{th} block, $(gs)_{ij}$ is interaction of i^{th} clone and stem slenderness of i^{th} clone and j^{th} block and e_{ij} is error.

Analysis of variance was carried out on branch diameter, branch angle and branch index to analyse differences in branching habit of clones at stocking of 1250 stems/ha. Analysis of covariance using DBH and stocking as covariates were carried out to evaluate the impacts of DBH, stocking and their interactions on branch diameters and branch angles of four clones deployed at stockings of 833 stems/ha, 1250 stems/ha and 2500 stems/ha.

8.4 Results

Mode of deployment significantly influenced stem slenderness but did not significantly affect stiffness. Clones significantly differed in stem slenderness (P=0.0004) and stiffness (P=0.0048) in monoclonal plots, but did not differ in clonal mixture plots (Table 8.1 and 8.2). When data of monoclonal and clonal mixture plots were analysed together, clones significantly differed in stiffness (P=0.0040) and stem slenderness (P=0.0008).

Table 8.1: Stiffness (GPa) and slenderness (m m^{-1}) exhibited by clones in monoclonal plots, clonal mixture plots, and when all plots taken together as one experimental unit in the experiment at initial stocking of 1250 stems/ha at age 13 years. Values followed by same letter were not significantly different according to smallest critical range of SNK (Student-Newman-Keuls) multiple range test.

Clone	Monoclonal Plots		Clonal Mixture Plots		All Plots Together	
	Stiffness	Slenderness	Stiffness	Slenderness	Stiffness	Slenderness
1	6.5 ab	54.9 ab	6.3 a	52.0 a	6.4 a	54.3 abc
2	6.6 a	55.4 ab	6.1 a	58.6 a	6.4 a	55.8 ab
3	5.8 abc	57.1 ab	5.8 a	56.4 a	5.8 abc	57.2 ab
4	6.2 ab	60.3 a	5.6 a	53.6 a	6 abc	60.4 a
5	6.2 ab	54.1 ab	5.7 a	51.4 a	6.1 ab	54.1 abc
6	6 abc	56.4 ab	6.2 a	57.4 a	5.9 abc	56.3 ab
7	5.6 abc	46.7 c	6.1 a	59.9 a	5.7 abc	49.3 c
8	5.1 c	56.7 ab	6 a	51.8 a	5.1 c	55.8 ab
9	5.9abc	52.1 b	5.4 a	51.2 a	5.8 abc	51.82 bc
10	5.4 bc	56.5 ab	5.5 a	60.6 a	5.4 bc	57.4 ab
Overall	5.9	55.0	5.9	55.4	5.9	55.0
SNK critical range	0.7-1.2	4.2-7.2	1.3-2.2	9.7-16.5	0.6-1.0	3.8-6.4

Table 8.2: Analysis of variance of stem-wood stiffness and stem-slenderness in monoclonal and clonal mixture plots at age 13 years.

Sources of variation	Degrees of freedom	Stiffness			Slenderness		
		Mono-clonal	Clonal Mixture	All Plots together	Mono-clonal	Clonal Mixture	All Plots together
		Pr > F	Pr > F		Pr > F	Pr > F	Pr > F
Clone	9	0.0048	0.7733	0.004	0.0004	0.2744	0.0008
Block	2	0.0154	0.0213	0.0191	0.0954	0.465	0.0815

Analysis of variance revealed that mode of deployment did not affect stiffness of clones (*P*=0.3865), but stem slenderness of clones was significantly (*P*=0.015) affected by mode of deployment (Table 8.3). Clone 7 exhibited significantly greater stem slenderness in clonal mixture plots compared to monoclonal plots.

Table 8.3: Analysis of variance carried out on: mean values of stem-wood stiffness and stem-slenderness, and mean values of coefficient of variation of stem-wood stiffness and stem-slenderness of clones at age 13 years.

Source of variation	Degrees of freedom	Mean		Coefficient of variation	
		Stiffness	Slenderness	Stiffness	Slenderness
		Pr > F	Pr > F	Pr > F	Pr > F
Clone	9	0.1282	0.0776	0.3763	0.0013
Block	2	0.0063	0.1226	0.0399	0.004
Mode of deployment	1	0.5601	0.7758	0.0404	0.2901
Clone*Mode of deployment	9	0.3865	0.0155	0.2842	0.068

Variability (Table 8.4) in stiffness was 25 % greater in clonal mixture plots (*P*=0.0404). Variability in stem slenderness was 15 % greater in clonal mixture plots, but not significant statistically (*P*=0.2901).

Analysis of covariance (Table 8.5) using stem slenderness as a covariate in model (6) showed that stiffness was significantly related to stem slenderness ($P < 0.0001$).

Stiffness was weakly positively correlated with stem slenderness ($P<0.0001$, $r^2=0.03$). Live-crown height was weakly positively correlated with stem slenderness ($P<0.0001$, $r^2=0.06$).

Clones significantly differed in branch angle (*P*=0.0043, Table 8.6), branch diameter and branch index (according to smallest critical range value to SNK multi range test at $P<0.05$ level) at the initial stocking of 1250 stems ha^{-1}. Clone 6 exhibited significantly greater branch diameters, branch index and angle compared to clone 8 of same family and the two other clones measured at stocking of 1250 stems ha^{-1} (Table 8.7).

Table 8.4: Variation (coefficient of variation %) in dynamic stiffness (GPa) and slenderness (mm^{-1}) of clones in monoclonal and clonal mixture plots at age 13 years. Values followed by same letter were not significantly different according to smallest critical range of SNK (Student-Newman-Keuls) multiple range test.

Clone	Monoclonal Plots		Clonal Mixture Plots	
	Stiffness	Slenderness	Stiffness	Slenderness
1	10.5 a	10.1 a	16.8 a	6.6 c
2	13.6 a	11.1 a	17.3 a	19.6a
3	13.2 a	8.5 a	13.4 a	5.4 bc
4	10.9 a	8.3 a	15.6 a	8.9 abc
5	9.8 b	11.6 a	26.8 a	11.9 abc
6	14.2 a	9.9 a	18.6 a	5.4 bc
7	13.5 a	11.5 a	9.1 a	18.0 ab
8	12.2 a	9.7 a	13.8 a	7.7 bc
9	10.0 a	9.2 a	4.9 b	3.4 c
10	12.7 a	12.3 a	16.2 a	17.4 abc
Overall	12.1	10.2	15.2	11.7
SNK critical range	4.1-6.9	4.0-6.9	20.4-37.0	6.6-11.7

Table 8.5: Analysis of covariance: block and clone as class variables; stiffness as dependent variable; and slenderness as covariates.

Source	Degrees of freedom	Pr > F
Block	2	<.0001
Clone	9	0.1101
Slenderness	1	<.0001
Block*Clone	18	<.0001
Clone*slenderness	9	0.0910

Table 8.6: Analysis of variance of branch diameter, branch index and branch angle at stocking of 1250 stems ha^{-1}at age 13 years.

Source of variation	Degree of freedom	Branch Diameter	Branch Angle	Branch Index
		Pr>F	Pr>F	Pr>F
Block	2	0.0085	0.1403	0.0459
Clone	3	0.1009	0.0043	0.1032

Table 8.7: Branch diameter, branch angle and branch index of selected clones in clonal mixture plots at a stocking of 1250 stems ha^{-1} at age 13 years. Values followed by same letter were not significantly different according to smallest critical range value of SNK (Student-Newman-Keuls) multiple range test.

Clone	Branch Diameter (cm)	Branch Angle (deg)	Branch Index (cm)
4	2.0 b	21 b	3.1 b
6	2.6 a	30 a	4.2 a
8	2.2 ab	23 b	3.9 ab
10	2.3 ab	23 b	3.4 ab
SNK critical range	0.5-0.6	4.8-6.4	1-1.3

Effect of genotype and stocking on branch diameter and branch angle

Clones did not differ in branch diameter when data of all stockings (833 stems ha^{-1}, 1250 stems ha^{-1} and 2500 stems ha^{-1}) were analysed together but, differed in branch angle according to Student-Newman-Keuls multiple-range test (Table 8.8). Stocking influenced both branch diameter and branch angle. Branch angle exhibited a positive (P<0.0001) and branch diameter inverse (P<0.0001) relationships with stocking (Table 8.8). Branch diameter was 56 % greater (2.5 cm versus 1.6 cm) at stocking of 833 stems ha^{-1} compared to 2500 stems ha^{-1}. Branch angle was lower by 17 % (23 degree versus 27 degree) at stocking of 833 stems ha^{-1} compared to 2500 stems ha^{-1}. DBH exhibited significant positive (P<0.0001) influence on branch diameter (Table 8.9). Clones did not interact with DBH and stocking in their effects on branch diameter and branch angle (Table 8.9 and 8.10).

Table 8.8: Results of analysis of variance carried out on branch diameter and branch angle and influence of genotype and stocking on branch diameter and branch angle.

	Clone					Stocking	
Variable	4	6	8	10	833	1250	2500
Branch diameter	2.2 a	2.1 a	2.2 a	2.4 a	2.5 a	2.5 a	1.6 b
	SNK (0.4 - 0.5)					SNK (0.27 - 0.3)	
Branch angle	22 c	30 a	24 bc	26 b	23 b	26 ab	27 a
	SNK (3.1 – 4.1)					SNK (3.1 – 3.7)	

Table 8.9: Results of analysis of covariance carried out on branch diameter and branch angle using DBH as covariate.

		Branch diameter	Branch angle
	DF	Pr>F	Pr>F
Clone	3	0.14	0.575
DBH	1	<0.0001	0.051
Clone*dbh	3	<0.057	0.186

Table 8.10: Results of analysis of covariance carried out on branch diameter and branch angle using stocking as covariate.

		Branch diameter	Branch angle
	DF	Pr>F	Pr>F
Clone	3	0.205	0.056
Stocking	1	<0.0001	0.003
Clone*Stocking	3	0.299	0.498

8.5 Discussion

8.5.1 Stiffness

The focus in this study was the under-bark wood stiffness. Clonal stiffness significantly varied from 5.1 GPa to 6.6 GPa in monoclonal plots and averaged about 6 GPa at age 13 years (about one half of rotation age). The deployment of clones in clonal mixture plots did not affect stiffness of clones which varied from 5.4 GPa to 6.3 GPa. Dynamic MOE involves unadjusted velocity calculated from time-of-flight, and true stiffness in clearwood could be somewhat lower. The minimum target value of two lowest structural timber grade MSG 6 and MSG 8 (machine stress graded timber) in New Zealand are 6 GPa and 8 GPa respectively (http://www.verified timber.co.nz/timbergrades.php). The differences in stiffness of clones were only of 0.7 GPa in clonal mixture to 1.5 GPa in monoclonal plots and overall stiffness was similar about 6 GPa in both modes of deployment. Therefore the

wood produced at this site in Canterbury up to half the rotation age would not be suitable for structural timber.

Several studies have demonstrated significant affects of genotype and stocking on dynamic stiffness (Lasserre *et al.,* 2004, 2005; Waghorn *et al.,* 2007b; Roth *et al.,* 2007). Lindstorm *et al.,* (2004) reported two fold (2.2 – 4.7 GPa) variation in static stiffness and high (80-90 %) broad sense heritability of stiffness, microfibril angle and wood density in a *Pinus radiata* clonal trial at age 3 years in New Zealand. All these studies suggest that there is potential to produce stiffer structural radiata pine timber by selecting stiffer genotypes at early age through rigorous selection criteria and deploy them at higher initial stockings.

8.5.2. Slenderness

Deployment in clonal mixtures resulted in dominance and suppression of clones (Chapter 5). Stems of suppressed trees became more slender compared to dominant ones due to their slow radial growth. The significant effect of mode of deployment on stem slenderness in this study resulted from these canopy dynamics. Clone 7 was growth-suppressed in clonal mixture plots (Chapter 5) and was significantly less slender (P<0.0001) when deployed in monoclonal plots (Table 8.1). Benbrahim *et al.* (2000) also reported that stem slenderness of some *Populus* clones was significantly affected by clonal deployment, *i.e.* that clones were generally more slender in monoclonal plots than in clonal mixtures.

8.5.3. Influence of stem slenderness on stiffness

Analysis of covariance using stem slenderness as a covariate in individual tree stiffness model (6) revealed that stem slenderness was the primary trait affecting tree stiffness. Mode of deployment significantly increased stem slenderness of trees of clone 7 in clonal mixture plots. Slight increases in stiffness of this clone (about 0.5 Gpa) in clonal mixture plots suggests that modes of deployment might have indirectly influenced stiffness through their influence on stem slenderness. Waghorn *et al.* (2007b) reported a strong relationship between stem slenderness and stiffness (r^2=0.49) at age 17 years. They reported an increase in stem slenderness from 43 mm^{-1} at a stocking of 209 stems ha^{-1} to 103 mm^{-1} at a stocking of 2551 stems ha^{-1} and corresponding increase in stiffness from 5.4 GPa to 7.5 GPa in

Canterbury. A strong relationship between stem-slenderness and stiffness was also reported in juvenile *Pinus radiata* (Watt *et al.,* 2006) and *Pinus taeda* (Roth *et al*., 2007). Stocking significantly affected stem slenderness and stiffness (an increase in stocking led to increases in both stem slenderness and stiffness). In this study all the trees were at one stocking of 1250 stems ha^{-1} which might explain the weak relationship between stem stiffness and stem slenderness.

One likely explanation for the relationship between slenderness and higher stiffness of trees of clone 7 in clonal mixtures plots observed in this study might be that growth suppression led to an early transition of earlywood to latewood in suppressed trees, which resulted in a higher proportion of high-density latewood in more slender trees. Grotta *et al.* (2005) reported an early transition of earlywood to latewood in slow growing (suppressed) trees of Douglas fir growing in a mixture with red alder trees (dominant). Johnson *et al*. (2003) also found that latewood proportion increased in slow-growing trees of Douglas-fir infested with Swiss needle cast. Wood density and microfibril angle both affect stiffness of wood; the latter particularly in the young wood which this study sampled (roughly rings 8 to 11 from the pith). Greater wood density and lower microfibril angle are features of latewood tracheids of radiata pine (Cave and Walker, 1994), and both these characteristics enhance wood stiffness. The significant influence of mode of deployment on stem slenderness and of stem slenderness on stiffness exhibited by clones in this study and studies reported suggest that the non-significant influence of mode of deployment on stiffness might have been masked due to fewer trees per clone and non-significant variability in stiffness exhibited by clones in clonal mixture plots. The chances of committing a type II statistical error in accepting the false hypothesis were reasonably high with such small numbers of trees. Therefore, there is need to further investigate the influence of mode of deployment on stiffness in bigger experiments with greater number of trees per clone in clonal mixture plots. At that time it would be imperative to use the latest production clones, which are now propagated using the somatic embryogenesis pathway, and are much more intensely screened at multi-site screening trials and block plot trials than the clones sampled in our study.

8.5.4 Variability

Greater variability in stem-wood stiffness and stem slenderness exhibited in clonal mixture plots suggest that greater stem uniformity could be achieved by deploying clones in monoclonal plots.

8.5.5. Influence of stocking on stiffness and stem form

Clonal branch index was attractively low, and ranged from 3.1 to 4.9 cm at an initial stocking of 1250 stems/ha. Clonal branch diameter was lower at higher initial stockings and branch angle was slightly greater. Waghorn *et al.* (2007b) reported increases in both stem slenderness and stem-stiffness with increase in initial stocking. This suggests that higher initial stocking have potential to enhance stem stiffness and greater product recovery due to small diameter branches.

8.6 Conclusions

Clones significantly differed in stem-wood stiffness, stem slenderness, branch diameter, branch index and branch angle at a stocking of 1250 stems/ha. Mode of deployment significantly affected stem slenderness (P=0.015) but did not affect stem-wood stiffness of clones (P=0.386). Variability in stem stiffness and stem slenderness were 25 % and 15 % more in clonal mixture plots compared to monoclonal plots.

Stem slenderness was weakly correlated with stem-wood stiffness (P<0.0001, r^2=0.03) and live-crown height. (P<0.0001, r^2=0.06).

DBH exhibited a significant influence on branch diameter (increase in branch diameter with increase in DBH). Clones did not interact with DBH or stocking in their effects on branch diameter and branch angle. Increase in stocking from 833 stem ha^{-1} to 2500 stems ha^{-1} resulted in 56 % decrease in branch diameter (2.5 cm to 1.6 cm), whereas branch angle increased by 17 % (23 degrees to 27 degrees). Trees of clone 6 exhibited significantly greater branch diameters and branch angles compared to other clones including clone 8 of same family at stocking of 1250 stems ha^{-1}.

CHAPTER 9

DISCUSSION AND CONCLUSIONS

The aim of this thesis was to study: growth behaviour of clones; influence of initial morphology on establishment success (initial growth and survival); clonal interactions (competition); influence of mode of deployment on stand structure development and wood properties; comparison of crop uniformity and productivity in two modes of deployment; risks associated with two modes of deployment; and some other important clonal forestry issues: clonal selection field test design; effectiveness of mensuration-based as well as process-based hybrid modelling in prediction of growth and productivity of clones. This chapter will discuss these aspects/issues covered in this thesis, some general conclusions, limitations of the study and future research aspects.

9.1 General discussion and conclusions

9.1.1 Quality of planting stock versus establishment success

Initial management (from planting to before canopy closure) is very crucial for the success of every plantation. Initial management practices include seedling lifting, packaging, transporting, seedlings placement and after care (weeding, irrigation, fertilization and gap filling). Quality of planting stock, initial management practices, and site conditions (edaphic and climatic) determine initial growth and survival. Slow initial growth and lower initial survival result in lower final productivity. Lower initial survival also enhances initial cost of plantation establishment due to extra costs of gap filling. Standard values of morphological indicators of radiata pine seedlings and cuttings have been developed and it is essential that when using of micro-propagated planting stock to establish plantations necessitate these morphological indicators are not ignored.

This study concluded that clones significantly differed in morphological characteristics, despite essentially the same propagation techniques. Initial height was found to be the best predictor of transplant stress. Sturdiness and initial heights were the best predictors of initial survival. The production of quality planting stock using important morphological predictors would benefit both nursery growers in terms of greater premium for quality stock as well as plantation managers in terms of rapid initial growth and greater survival of out-planted quality planting stock. Moreover rapid initial growth and greater survival of out-planted clones can allow managers to use lower selection ratios and ensure early site occupancy by tree crops. This implies that different genotypes may require different nursery techniques in order to produce morphological traits that promote successful establishment.

Use of poor planting stock in progeny tests might result in transplant stress and slower initial growth of some clones. In single tree plot selections slow initial growth might result in suppression of slow growing clones and such clones might miss selections which otherwise if deployed monoclonally could perform better. Early selection even in block plot progeny tests might miss out some clones which grow slowly due to initial transplant stress during establishment period when nursery techniques tailored to those genotypes may have allowed them to grow well after outplanting. This selection bias can be avoided if quality stock is used in progeny tests in the breeding programs. The nursery managers need to use different conditioning techniques, such as root-cutting, lateral root pruning, wrenching and top pruning, for each clone in order to produce uniform nursery planting stock of different clones to be deployed in the plantations.

9.1.2. Choice of mode of deployment

There are mainly two modes of clonal deployment: monoclonal and clonal mixtures. Several factors such as planting stock available, cost of planting stock, objectives of plantations, legal bindings if any, such as the use of minimum number of clones, operational efficiency, ease of management, productivity and biotic or abiotic risks affect the choices between the modes of clonal deployment. It is believed that mixtures of species or genotypes are generally more productive than monocultures. The very few studies conducted in short rotation hardwood species that compared the productivity of

monoclonal and clonal mixture plots have exhibited mixed results, however. Moreover, paucity of such studies in long rotation tree species has left forest managers in a quandary regarding the choice of mode of deployment. This study concluded that mode of deployment did not affect overall productivity although individual clone performances differed with mode of deployment.

The main limitation of this study was lack of replication of this experiment at different sites. Although the results of this study do not represent genotype x site interaction effects, still they corroborate similar conclusions reported by Debell and Harrington (1997) and Benbrahim *et al* (2000) in short rotation *Populus* clonal studies.

Presently plantation forestry is governed by demands of processors of wood and end users of the products. Wood processing industries require uniform raw materials for production of uniform products to ensure quality of their products, and cost effectiveness in handling of raw materials. Therefore requirements of uniform raw materials and ease in operational efficiency in carrying out various silvicultural operations have emerged as important factors affecting choice of mode of deployment.

Long term investment also emphasises the need of risk evaluation. The opinions of researchers differ regarding the principle of ecological stability which states that stability depends upon the diversity. Monoclonal plantations are perceived to have greater risk from insect-pests and diseases compared to clonal mixtures.

Therefore, managers need to select their preferred mode of deployment based on other factors such as crop uniformity, risk management, and operational efficiency in tending, harvest, log segregation, and subsequent processing and marketing rather than productivity only.

9.1.3. Single tree plot versus block plot selections

In New Zealand tree genotypes are selected in single tree plots. Large numbers of entries can be evaluated at a number of sites at one time, and dominant characteristics of genotypes can also be identified while they are competing with other genotypes. However, this study has demonstrated that some clones that grew slowly in the beginning can reach

their maximum potential in a monoclonal mode of deployment, whereas these clones might get suppressed by fast growing neighbors in clonal mixture plots and fail to express their full potentials. This sort of selection bias can be overcome with block plot selection methods. The drawback of block plot methods is the greater cost involved in testing and greater environmental variances that result in lower precision in estimating heritability and genetic gains, therefore block plots have lower efficiency compared to single tree plots. The predictions of genetic gain are more likely to be accurate when the conditions in the test design closely resemble the conditions in which the selected clones will be deployed, however. The issue of reduction in precision can be overcome by increasing replications per site. The ultimate choice of method of selection would depend on trade offs between selection gains, cost of testing and the choice of mode of deployment. If the selections are to be deployed in monoclonal mode then block plot selection methods would be more effective, and if they are to be deployed as clonal mixtures then single tree plot selection methods might be more effective.

The other important factor to be considered in clonal testing is the number of test sites required which would depend upon the purpose of selection. If one wants to select for generally adaptable clones then one needs to increase number of different site conditions tested, and if one wants to select site specific clones then precision can be enhanced by increasing the number of ramets per entry and decreasing the number of test sites. Therefore, selection of clones in single tree plots in initial stages of selection programs when the number of clones to be tested is large, and later block plot evaluations of selected clones might be more effective, and besides this would reduce bias in estimation of gains before deployment in commercial plantations.

9.1.4. Timings of selections

In New Zealand the selections are made at age 8 years in single tree plots. This study also corroborated that the growth patterns of genotypes stabilized around age 8 years in clonal mixture plots. The interchange of ranks exhibited in these studies suggests that the probability of wrong selections is higher if selections are carried out earlier than this age. Clones have exhibited greater interchange of ranks in monoclonal plots which suggest that selections in single tree plots can be done earlier if the selections are to be deployed in clonal mixtures.

9.1.5 Clonal modelling and its effectiveness in clonal selections

This study showed that mensurational stand modelling can be used for prediction of short term productivities of clones, but may be biased if they are extrapolated. The effectiveness of 3-PG as a predictor of clonal performance could not be evaluated because there were too many degrees of freedom in parameters that could be adjusted to make the model fit, and so more detailed studies would be required to estimate these parameters (particularly allocation of C to roots and maximum quantum efficiency of the species) in order to properly evaluate the model, however, if clonal performance is differentiated by either differences in carbon allocation or specific leaf area, then the 3-PG model has potential to represent differences in productivity between clones.

9.1.6 Mode of deployment versus wood quality

Inter-genotypic competition influences growth rate of interacting genotypes. Some slow starting genotypes were suppressed in clonal mixtures that further slowed down their growth and resulted in lower productivity. Growth rate affected stem form (stem slenderness) and formation of wood. Generally slow growth resulted in greater stem slenderness. In this study slow growth due to suppression and enhanced stiffness of one clone might have resulted from early transition to latewood and that might have resulted in greater wood density and lower microfibril angle. Greater wood density and lower microfibril angle enhance wood stiffness. Slender stems should produce stiffer wood.

This study and some earlier studies have reported influence of mode of deployment on stem form (stem slenderness). Although mode of deployment did not show direct influences on stem wood stiffness but indicated that mode of deployment might have indirectly influenced stem wood stiffness of clones, as one clone that exhibited greater slenderness in clonal mixture plots also exhibited slightly enhanced stiffness in clonal mixture plots. The lower power of clonal mixture plots analysis might have contributed to non-significant differences in stem stiffness and stem slenderness.

9.1.7 Uniformity

Uniform crops and raw materials for processing are important for ease of management, operational efficiency, and greater consistency in quality of end products. Foresters are more interested in ease of management and greater operational efficiencies, whereas wood-processors need uniform raw materials to ensure the quality of their end products. Greater uniformity can be achieved by deploying clones in monoclonal plots because all the trees grow almost equally due to their similar morphologies, growth patterns and growth potentials (asymptotes). This study has exhibited significantly greater variability in tree sizes, wood qualities (stiffness and stem slenderness), and competition experienced by clones in clonal mixture plots which suggests that the monoclonal mode of deployment would benefit plantation growers, processors and consumers. The monoclonal mode of deployment would be the right choice for greater gains in terms of ease in management, operational efficiency, greater premiums for uniform raw material (quantity and wood quality), ease in sorting and allocation of raw material for different end uses and maintaining consistency in quality of end products. The uniformity in clonal mixtures might be enhanced by deploying sets of clones that have similar growth patterns and morphologies, but this hypothesis needs to be investigated through research trials.

9.1.8 Risks versus mode of deployment

Lower genetic diversity in monoclonal plantations is perceived to make this form of silviculture more prone to insect-pest and disease outbreak risks. This study has also indicated that deployment of single susceptible clone over a large area monoclonally might pose greater risks to the viability of a plantation than would a clonal mixture. However, many researchers believe that proper management of monocultures can minimize such risks. Genetic diversity can be maintained by deploying certain numbers of clones (15-30) in mosaics of monoclonal plots for greater uniformity while minimizing biological risks. The risks to monoclonal plantations can also be minimized by strict quarantine measures, choosing suitable locations, genotypes, regimes, minimizing injuries during thinning and pruning operations, and removal of debris in plantations.

9.2 Limitations of the study design

- This study compared the development of clones in monoclonal and clonal mixture modes of deployment in an experiment established with three replications at one site that was representative of a narrow range of New Zealand site conditions, and with a limited number of onsite replications. Therefore, results of this study don't include effects of clone x site interactions.
- The experiment has greater stocking (1250 stems/ha) at age 12 years than a normal stocking regime of 600 stems/ ha at this age in the Selwyn Plantation Board Ltd.'s estate.
- Plots, particularly those of clonal mixtures, were small therefore type II errors might have contributed to some of the non-significant results.
- Clones not generated from SE (somatic embryogenesis), thus not representative of "multiclonal varietal forestry", and not reproducible.
- Plant (stock) quality was variable at the time of planting.
- The study lacked seedling controls.

9.3 Future research

- There is need to evaluate the influence of genotype x site interactions on productivities of clones.
- There is a need to further investigate the influence of mode of deployment on stiffness in bigger experimental plots with greater numbers of trees of each clone in clonal mixture plots.
- Further parameterization and evaluation of 3-PG model for simulating growth of clones by measuring maximum quantum efficiency of the radiata pine, stomatal conductance of clones and actual allocation of biomass to roots by fast growing and slow growing clones would indicate whether or not 3-PG has a useful function in clonal forestry.

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APPENDIX I

Foliar nutrient status of clones at age 4 years

Salient findings

- The analysis of foliar nutrition status of one year old needles of 4 years old radiata pine clones revealed that clones significantly differed in level of Phosphorous (*P*=0.0016), Potassium (*P*=0.0002), Calcium (*P*=0.0009), Magnesium (*P*<0.0001), Boron (*P*=0.0004), Zinc (*P*=0.0009), Copper (*P*<0.0001), Potassium: Magnesium ratio (*P*<0.0001) except Nitrogen (*P*=0.24) and Manganese (*P*=0.3683) (Tables AI.1-AI.10).

- Almost all the clones had lower than marginal level (0.07-0.10 %) of Magnesium (Table AI.11a) in their one year old foliage. Will (1985) has reported that Magnesium level <0.07 % affects the growth of radiata pine trees and further decrease <0.04 % results in severely stunted growth. Clone 3 grew slowly during establishment period and had lowest level of Magnesium compared to other clones. Clone 3 also had lower than critical level (<8 ppm) of Boron (Table AI.11b) but did not show deficiency symptoms. Boron deficiency below critical level results in dieback of shoot. In South island of New Zealand radiata trees with Boron level even <6 ppm don't show dieback (Will, 1985). This indicated that lower level of these nutrients might have resulted in slower growth of clone 3.

TableAI.1: Analysis of variance of Nitrogen in one year old needles for radiata pine clones at age 4 years at Dalethorpe.

Source	DF	Sum of squares	Mean square	F	Pr>F
Blk	2	0.05748667	0.02874333	15.11	0.0001
clone	9	0.02481333	0.00275704	1.45	0.24

Table AI.2: Analysis of variance of Phosphorous in one year old needles for radiata pine clones at age 4 years at Dalethorpe.

Source	DF	Sum of squares	Mean square	F	Pr>F
Blk	2	0.0002616	0.0001308	0.82	0.4549
clone	9	0.0073503	0.0008167	5.14	0.0016

Table AI.3: Analysis of variance of Potassium in one year old needles for radiata pine clones at age 4 years at Dalethorpe.

Source	DF	Sum of squares	Mean square	F	Pr>F
Blk	2	0.082205	0.041102	37.59	<.0001
clone	9	0.071563	0.007951	7.27	0.0002

Table AI.4: Analysis of variance of Calcium in one year old needles for radiata pine clones at age 4 years at Dalethorpe.

Source	DF	Sum of squares	Mean square	F	Pr>F
Blk	2	0.016167	0.008084	11.75	0.0005
clone	9	0.035107	0.003901	5.67	0.0009

Table AI.5: Analysis of variance of Magnesium in one year old needles for radiata pine clones at age 4 years at Dalethorpe.

Source	DF	Sum of squares	Mean square	F	Pr>F
Blk	2	1.63E-05	8.13E-06	0.55	0.5858
clone	9	0.001977	0.00022	14.88	<.0001

Table AI.6: Analysis of variance of Boron in one year old needles for radiata pine clones at age 4 years at Dalethorpe.

Source	DF	Sum of squares	Mean square	F	Pr>F
Blk	2	87.8	43.9	40.45	<.0001
clone	9	62.96667	6.996296	6.45	0.0004

Table AI.7: Analysis of variance of Manganese in one year old needles for radiata pine clones at age 4 years at Dalethorpe.

Source	DF	Sum of squares	Mean square	F	Pr>F
Blk	2	1911.667	955.8333	3.63	0.0474
clone	9	2778.033	308.6704	1.17	0.3683

Table AI.8: Analysis of variance of Zinc in one year old needles for radiata pine clones at age 4 years at Dalethorpe.

Source	DF	Sum of squares	Mean square	F	Pr>F
Blk	2	132.0667	66.03333	6.44	0.0078
clone	9	518.3	57.58889	5.62	0.0009

Table AI.9: Analysis of variance of Copper in one year old needles for radiata pine clones at age 4 years at Dalethorpe.

Source	DF	Sum of squares	Mean square	F	Pr>F
Blk	2	0.144667	0.072333	1.01	0.3856
clone	9	5.369667	0.59663	8.29	<.0001

Table AI.10: Analysis of variance of Potassium: Magnesium ratio in one year old needles for radiata pine clones at age 4 years at Dalethorpe.

Source	DF	Sum of squares	Mean square	F	Pr>F
Blk	2	33.45774	16.72887	23.22	<.0001
clone	9	123.1383	13.68204	18.99	<.0001

Table AI.11 a, b: Average foliar nutrient status of clones at age 4 years.

(a)

Clone	Nitrogen (N)	Phosphorus (P)	Potassium (K)	Calcium (Ca)	Magnesium (mg)
1	1.54 a	0.18 a	0.71 b	0.3 ab	0.07 a
2	1.47 a	0.15 abc	0.75 ab	0.29 ab	0.05 c
3	1.51 a	0.14 bc	0.74 ab	0.24 b	0.05 c
4	1.45 a	0.17 ab	0.8 ab	0.23 b	0.07 ab
5	1.49 a	0.17 ab	0.81 a	0.33 a	0.06 ab
6	1.45 a	0.13 c	0.63 c	0.27 ab	0.06 ab
7	1.48 a	0.15 abc	0.77 ab	0.31 a	0.07 a
8	1.52 a	0.17 a	0.71 b	0.32 a	0.06 ab
9	1.46 a	0.16 abc	0.72 b	0.26 ab	0.07 a
10	1.49 a	0.17 a	0.73 ab	0.32 a	0.06 b

(b)

Clone	Boron (b)	Manganese (mn)	Zinc (zn)	Copper (cu)	Potassium-magnesium ratio (k: mg)
1	7.67 bc	102 a	27.33 b	3.93 a	10.65 cd
2	11.33 a	107 a	29 b	3.17 bc	15.95 a
3	6.67 c	74 a	31.67 ab	2.5 c	15.96 a
4	9 abc	99 a	26.33 b	2.66 c	12.24 bcd
5	8.67 abc	90 a	32.67 ab	3.5 ab	12.97 b
6	10.67 a	89 a	35 ab	3.1 bc	10.14 d
7	7 bc	93.67 a	29.67 b	2.6 c	10.66 cd
8	9.67 ab	103 a	39 a	3.17 bc	11.41 bcd
9	7.67 bc	105.67 a	38.33 a	3.43 ab	10.66 cd
10	8.67 abc	89 a	34.67 ab	2.97 bc	12.85 bc

APPENDIX II

DATE	MIN TEMP	MAX TEMP	SOIL TEMP	RH (%)	RAIN (mm)
01.09. 1993	-3	11.8	3.6	83.3	0
02.09. 1993	0.8	16.6	4.2	62.3	0
03.09. 1993	8.8	20.9	6	61.6	0
04.09. 1993	4.7	14.3	5.8	96.5	13.5
05.09. 1993	0.8	7	5.1	96.2	31.2
06.09. 1993	-0.4	6.4	3.4	87.4	16.4
07.09. 1993	-2.5	8.5	3.5	85.6	0
08.09. 1993	-2.3	10.5	3.7	92.2	0
09.09. 1993	-2.1	12	4.1	76.5	0
10.09. 1993	1	16.5	5.3	71.7	0
11.09. 1993	5.4	13.8	6.2	76.5	0
12.09. 1993	4.7	14.1	6.8	75.2	0
13.09. 1993	0.4	17.4	5.9	77.8	4.2
14.09. 1993	5.5	16.7	6.4	52.3	0
15.09. 1993	7.1	17.7	6.1	53.2	0
16.09. 1993	1.3	16.1	6.3	69.9	0
17.09. 1993	-0.3	15.4	6.2	66.5	0
18.09. 1993	2.4	13.3	6.6	88.7	1.4
19.09. 1993	0	4.8	6.3	82.2	0
20.09. 1993	-4.5	7.3	4.8	72.2	0
21.09. 1993	-0.3	10.6	5.8	69.3	0
22.09. 1993	3.9	13.3	6.8	68.3	0
23.09. 1993	4.7	15.3	7.6	90.5	0
24.09. 1993	3.8	9	7.2	95.4	18.6
25.09. 1993	2.6	6.4	6.6	93.7	40.6
26.09. 1993	0.4	6.9	6.5	82.6	12.1
27.09. 1993	-2.7	14.8	5.5	70	13
28.09. 1993	-2.9	7.5	4.8	60.2	0
29.09. 1993	0.3	12.7	5.9	57.1	0
30.09. 1993	4.4	16.1	8.6	65.4	0

DATE	MIN TEMP	MAX TEMP	SOIL TEMP	RH (%)	RAIN (mm)
01.10. 1993	4.5	20.9	8.8	77.1	0
02.10. 1993	4.3	18.9	10	74.8	0
03.10. 1993	5.6	23.5	10	81.1	0
04.10. 1993	4	14.9	10.2	84.6	0
05.10. 1993	8.5	20.2	10.8	70.3	0
06.10. 1993	12.3	21.6	11.6	64.7	0
07.10. 1993	10.1	23.3	12.1	64.3	0
08.10. 1993	4.3	20	10.8	84.6	0
09.10. 1993	2.2	16.7	10	67.5	0
10.10. 1993	5	19.3	10.3	42.2	0
11.10. 1993	4.9	20.5	9.9	55.9	21.5
12.10. 1993	0.7	12.3	8.6	73.6	0
13.10. 1993	1.3	16	8.7	50.3	0
14.10. 1993	7.3	17.5	9.7	49	0
15.10. 1993	6.9	20.9	9.9	55.6	0
16.10. 1993	-0.8	17	8.3	75.2	5.6
17.10. 1993	0.7	17.9	9.2	54.2	0
18.10. 1993	1.8	21.2	9.3	73.6	0
19.10. 1993	7.3	18.6	11	72.9	0
20.10. 1993	7.8	19.5	11.4	68.2	0
21.10. 1993	4	17.3	10	68.1	12.1
22.10. 1993	1.9	11	7.3	57	0
23.10. 1993	3.4	15	9.8	51.2	0
24.10. 1993	0.6	17	9.4	65.6	0
25.10. 1993	1.9	18.3	10.8	73.4	0
26.10. 1993	2.5	16.3	10.9	81.3	0
27.10. 1993	4.3	22.2	11.1	42.8	0
28.10. 1993	4.3	21.6	11.1	75.5	0
29.10. 1993	2.7	19.4	11.3	73.8	0
30.10. 1993	7.4	22.3	12.8	48.2	0
31.10. 1993	8.4	19.5	12.7	88.4	0

APPENDIX III

Mean square errors of five different functions fitted to stand basal area for individual plots.

Block	Clone	Schuy 1	Schuy 2	Vonby 1	Gompy 1	Hossfeld
1	1	1.3528	1.6863	2.5022	3.26	3.33
1	2	1.241	0.8706	1.7088	2.1565	2.3926
1	3	4.0134	1.0389	1.8214	2.101	2.9354
1	4	2.6677	0.292	0.8903	1.1743	1.6403
1	5	1.746	0.7304	1.8652	2.5108	3.0152
1	6	0.9543	0.1312	0.3603	0.5464	0.8997
1	7	1.62	0.1213	0.4133	0.6462	1.0753
1	8	1.372	0.727	1.7091	2.2979	2.277
1	9	7.1051	7.2532	9.7283	10.6403	10.4334
1	10	1.6498	0.3749	1.1723	1.5802	2.161
2	1	1.3682	0.0077	0.3207	0.5874	1.0455
2	2	1.6676	0.9343	1.4257	1.6899	2.0189
2	3	1.9192	0.2607	0.9672	1.3219	1.9349
2	4	2.2101	0.5556	1.4257	1.4307	2.2698
2	5	1.7498	0.3809	1.1871	1.6715	2.2019
2	6	0.9331	0.9577	1.5389	2.0055	2.3181
2	7	1.5247	0.2751	1.0895	1.6375	2.1874
2	8	1.5928	1.7565	2.6145	3.2016	3.5276
2	9	10.3411	3.05553	3.6268	3.6476	3.6359
2	10	1.7785	1.8301	2.8152	3.4308	3.91
3	1	1.906	0.2647	0.7154	1.0092	1.5309
3	2	3.4098	3.3284	4.8434	5.6557	6.1608
3	3	2.5473	0.2865	1.0983	1.4426	2.1073
3	4	7.6492	1.1646	1.9443	2.0657	2.4162
3	5	6.7692	8.023	10.4419	11.8944	12.0999
3	6	2.1626	2.1152	2.717	3.5618	3.3453
3	7	1.1855	0.2657	0.8126	1.1467	1.6193
3	8	2.0417	1.6313	2.7934	3.537	4.0785
3	9	3.8128	0.4319	1.0818	1.4723	1.9375
3	10	3.1038	2.6234	4.2323	5.0136	5.6799

APPENDIX IV

Mean square errors of five different functions fitted to Mean Top Heights for individual plots.

Block	Clone	Schuy 1	Schuy 2	Vonby 1	Gompy 1	Hossfeld
1	1	0.3882	0.1136	0.1123	0.1316	0.1125
1	2	0.6333	0.2712	0.2734	0.3461	0.274
1	3	0.3605	0.0664	0.0628	0.0435	0.0615
1	4	0.2966	0.082	0.0586	0.0411	0.0541
1	5	0.5652	0.3264	0.3251	0.3519	0.3258
1	6	0.2635	0.0369	0.0264	0.0197	0.0242
1	7	0.3259	0.2194	0.1944	0.1785	0.1897
1	8	0.6681	0.2409	0.2454	0.363	0.2462
1	9	0.7595	0.2558	0.2567	0.311	0.2572
1	10	0.2665	0.0979	0.0704	0.0249	0.0623
2	1	0.2533	0.067	0.0451	0.0137	0.0393
2	2	0.3073	0.0676	0.0554	0.0504	0.0531
2	3	0.319	0.0753	0.0594	0.0143	0.054
2	4	0.3263	0.1373	0.0942	0.0586	0.0866
2	5	0.342	0.0599	0.0447	0.0281	0.412
2	6	0.4011	0.0399	0.0334	0.0417	0.0324
2	7	0.2651	0.2441	0.1161	0.1002	0.1525
2	8	0.2934	0.0858	0.0887	0.1277	0.0908
2	9	0.4862	0.1659	0.1635	0.1966	0.163
2	10	0.3751	0.1697	0.1669	0.1771	0.1671
3	1	0.297	0.1028	0.0745	0.035	0.0682
3	2	0.3477	0.0485	0.038	0.0438	0.0362
3	3	0.316	0.0505	0.0421	0.018	0.0394
3	4	0.2395	0.0763	0.0638	0.0783	0.0623
3	5	0.2645	0.045	0.0355	0.0466	0.0341
3	6	0.3883	0.1151	0.1101	0.1163	0.1093
3	7	0.1527	0.1293	0.0715	0.0316	0.062
3	8	0.3844	0.1857	0.1709	0.1765	0.169
3	9	0.4865	0.1116	0.1061	0.136	0.1057
3	10	0.2597	0.1775	0.1158	0.0492	0.1067