SIMULATING THE GROWTH AND YIELD OF REGROWTH KARRI (*Eucalyptus diversicolor* F. Muell.) STANDS

Martin Eugene Rayner

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DECLARATION

I declare that the work reported in this thesis is the result of my own original efforts unless indicated otherwise.

This thesis or any version thereof has not been submitted to another University.

M.E. Rayner ---------- 28 JULY 92

M.E. Rayner

Date

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ABSTRACT

The lack of a model to simulate the growth and productive potential of regrowth karri stands has seriously constrained forest management planning in south–western Australia. Experimental and inventory data from even–aged, relatively pure karri stands were used to develop a recursive system of mathematical models for predicting future stand variables under varying conditions of site, density and stand management. Nonlinear least squares methodology was used extensively for parameter estimation.

A single–tree, distance–independent simulator called KARSIM was constructed by incorporating these new models into a shell derived from Victoria's STANDSIM model. The integrated modules predict the development of stand and tree attributes on an annual time step, with all growth, mortality and treatment processes adjusting an individual tree list. Whole–model validation and sensitivity analyses indicated the model conformed to biological principles of stand development and that any bias in projected stand variables was of limited practical consequence. Model precision was acceptable for inventory update, harvest scheduling and certain stand treatment simulations. Several preliminary applications, including the assignment and scheduling of first thinnings and the preparation of management regimes for forest yield regulation demonstrated the utility of the model. Data acquisition strategies necessary to monitor model performance and improve model generality were outlined.

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CHAPTER 1 INTRODUCTION

The capacity to predict the growth and yield of species within the forest estate is fundamental to the proper management planning of forests. This thesis describes the development of a model to simulate the timber growth and yield of even-aged regrowth karri (*Eucalyptus diversicolor* F. Muell.) stands.

1.1 The karri forest

1.1.1 Location and extent

The karri forests of south-western Australia occupy almost 170,000 hectares in a restricted geographical zone between latitudes 34 and 35° S and longitudes 115 and 118° E (Boland *et al.* 1984). The main occurrence of these wet sclerophyll, high open forests is bounded by the 900 millimetre isohyet which runs approximately parallel to the coast between Albany and Cape Leeuwin (Specht 1970).

The distribution, extent, and ecology of this forest has been described by Bradshaw and Lush (1981) and Beard (1981). The forest occurs on undulating to hilly terrain which rises from sea level to approximately 350 metres altitude. The climate is temperate, with a distinct winter rainfall maximum and an annual range of 900–1300 millimetres (Boland *et al.* 1984). Karri occurs in pure stands over approximately 60% of the forest estate, with the remainder occurring in mixture with marri (*E.calophylla* R.Br.) and, to a lesser extent, W.A. blackbutt (*E.patens* Benth.), jarrah (*E.marginata* Donn ex Smith), yellow tingle (*E.guilfoylei* Maiden), red tingle (*E.jacksonii* Maiden), Rates tingle (*E.brevistylis* Brooker) and/or bullich (*E.megacarpa* F. Muell.).

These predominantly publicly-owned forests are managed by the Department of Conservation and Land Management (CALM) under a multiple-use strategy (CALM 1987a). The total area of the karri estate available for timber production in 1991 was approximately 102,000 hectares, of which 40,000 hectares are regrowth stands. The age distribution of the regrowth stands is highly skewed toward the younger ages, with almost 32,000 hectares younger than 30 years (CALM 1991).

1.1.2 Silviculture and management

Even-aged regrowth stands have been defined for management purposes as those stands of regeneration where less than 15% overstorey cover remains (Armstrong 1984). In the karri area the older regrowth stands (>100 years) regenerated from high intensity wildfires prior to the commencement of forest management. The majority of the stands, however, were regenerated prior to 1940 or after 1966 when clearfelling was used to harvest the old-growth forests (Bradshaw and Lush 1981).

Present practice within areas designated for timber production is to annually clearfell approximately 1200 hectares of old-growth forest. The predominantly monospecific regrowth stands are established by seeding from retained seed-trees following harvest of the old–growth (White and Underwood 1974), or by planting nursery–raised open–rooted seedlings at a stocking of 1600 stems per hectare. Present policy envisages that management of the resulting even–aged, vigorous regrowth stands will include multiple thinning regimes over a nominal rotation of 100 years (CALM 1987b). Fuel reduction burns are prescribed for a 7–10 year cycle, commencing when the majority of stems in the stand are of sufficient size to withstand mild fires (McCaw 1986).

Thinning of stands aged 40–60 years commenced in 1980, and averages approximately 300 hectares per annum. Products supplied from these thinnings include veneer logs, electricity poles, sawlogs and chiplogs. Commercial thinnings have recently commenced in stands aged 15–30 years, due to the availability of markets for smaller piece–sizes in chipwood and improved technology for sawing small sawlogs (to 15 cm small end diameter under bark).

1.1.3 Economic and social importance of the karri forest

Precise information on the economic importance of the karri forest to the Western Australian economy is not available. Aside from the timber products, the forest region contains major catchments for domestic and industrial water supply, and supports a rapidly expanding tourism and recreation trade largely based on forest values (CALM 1987b). The contribution of the forests to biological conservation values has been dealt with elsewhere (Christensen 1992).

The direct royalty value of wood products harvested from the karri forest in 1990 exceeded $10 million (CALM 1991), while the market value of the finished wood products from the logs is likely to be 10 to 20 times this royalty value (Campbell 1974).

The regrowth estate will provide an increasing proportion of the total annual harvest of sawlog and chiplog from the karri forest. The average size dimensions of the logs from the regrowth estate are presently smaller than the logs obtained from the traditional old–growth stands, and the major sawmilling companies have recently invested substantial capital (>$10 million) to re–equip for the processing of these smaller–sized logs. Concurrent investment in the development of processing and seasoning techniques for regrowth logs (White 1989, Brennan *et al.* 1991) is assisting the transition of the sawmilling industry from their traditional intake of large–sized old–growth logs to the increasing proportion of smaller–sized regrowth logs.

1.1.4. Strategic and management planning process in the karri forest

Comprehensive planning is required to accommodate, both temporally and spatially, the range of competing land uses and activities within the karri forest. An integral component of this process is the regulation of the yield of timber products from the forests. The Department of CALM has a legal and social responsibility to plan for a sustainable yield of forest products from public forests (CALM 1987a). Such strategic–

level planning requires information on the quantity and quality of timber produced from integrated logging operations in a range of stand structures.

Accurate prediction of future yield from the regrowth stands is critical to the planning process. The spatial and temporal scheduling of the creation of regrowth stands, and the subsequent yields generated from varying intensities of management, determine not only the future timber supply but also the capacity of these forests to provide fauna habitat, recreation opportunities and all other forest values. Present planning procedures for calculating a sustainable yield of timber products from these forests is severely limited without access to computer simulation to examine the full range of stand treatment options and yield regulation alternatives. Construction of a mathematical model to simulate the growth and consequent yield of regrowth stands would assist the application of mathematical programming techniques when developing forest–level strategies which provide an 'acceptable' combination of all forest uses.

1.2 Previous work

Very few quantitative studies of karri growth have been undertaken. Christensen (1986) and references therein provide a guide to research on karri forest biology, ecology, silviculture and management. White (1974) documented earlier observations on karri growth, while Breidahl and Hewett (1992) have recently compiled a summary of silvicultural research to date. Much of the work, however, has been based on qualitative or site–specific observations rather than quantitative analysis. The lack of a suitable site stratification for karri particularly frustrates the interpretation of stand dynamics. Grove (1987), for example, studied the development of stand biomass and nutrient cycling in an age series of regrowth stands, but extrapolation of his results was hindered by the lack of site quality stratification.

1.3 Study aims

The aim of this study was to use existing silvicultural and mensurational data to quantitatively describe the growth and productive potential of even–aged karri stands. The ultimate purpose was to develop from experimental data an integrated set of models for predicting future stand variables under varying conditions of site and stand management. Such a model would provide a framework for future research and data collection.

1.4 Study outline

This research was conducted using a systems analysis approach to model development. Jeffers (1978) defined systems analysis as "the orderly and logical organization of data and information into models, followed by the rigorous testing and exploration of these models necessary for their validation and improvement".

Accordingly, the thesis is organized into those sequential stages in model development and testing which have been summarized by Leary (1970) and Goulding (1979), *viz.* problem formulation and definition of objectives, data collection and evaluation, model formulation, parameter estimation, validation, interpretation and monitoring. In practice, many of these steps were iterative and overlapped during the course of the study.

In Chapter 2 the historical evolution of growth models developed for Australian eucalypts is reviewed, and the key factors influencing model design are identified. The choice of modelling approach is largely determined by the quantity, quality and nature of the data available for parametrization. The available karri data, it's editing, and a preliminary evaluation of the suitability of each attribute for empirical modelling purposes is described in Chapter 3.

In Chapter 4 the modelling objectives for karri are reiterated, alternative modelling philosophies to meet these objectives are explored, and an appropriate modelling strategy identified. This strategy incorporates a strong empirical emphasis to model building. A description of the statistical methods adopted for model parametrization is provided (Chapter 5).

An essential step in modelling stand growth is the definition of land units of uniform potential for growth. Chapter 6 commences with the derivation of site index and dominant height growth curves for regrowth karri. The utility of this direct classification of site was then compared with five indirect classifications of site productivity. Site index provided the most efficient stratification of the mensurational dataset.

An individual–tree level model capable of simulating managed and unmanaged stand development was formulated and parametrized. The formulation, parametrization and testing of each module is described in Chapters 7 (stand level components) and 8 (tree level components).

Validation of the whole–model system is a critical stage of the model building process. In Chapter 9, the model is evaluated for it's biological sensibility and predictive accuracy. The limited availability of real growth series data for model validation was partially resolved by developing a separate, step–wise compatible, stand–level model. Predictions of future yield in fully–stocked stands generated from the stand–level model can be compared with those generated from the tree–level model.

During the course of research toward this thesis a number of model components, and eventually the entire model, were applied to various planning and operational problems in the regrowth karri estate. In Chapter 10 these preliminary applications of the model are outlined. They included the calculation of an optimal economic rotation age for individual stands (to assist royalty appraisal), the determination of site–specific regimes for yield regulation, and a review of thinning prescriptions for these forests.

Appropriate data collection strategies for model improvement and the monitoring of model performance are then discussed (Chapter 11), and conclusions from the research outlined (Chapter 12).

At the date of submission of this thesis some of the chapters have been published in refereed international journals (*viz.* Chapters 2, 6, a portion of Chapter 11 and Appendix 1). The published papers have been modified for presentation in this thesis to include further information and to maintain continuity between chapters.

CHAPTER 2 GROWTH AND YIELD MODELLING OF AUSTRALIAN EUCALYPT FORESTS: AN HISTORICAL PERSPECTIVE[1]

2.1 Introduction

While 'yield' is considered to be the quantity of a forest attribute that could be utilized during a period or at a particular time, 'growth' is the change in an attribute over time (Davis and Johnson 1987). As Clutter (1963) noted, the two are linked because if the yield function is continuous over time then the growth rate is (at least conceptually) the derivative in terms of time of yield at time t, and yield is the integral of the growth over a time period. Thus, although in the past growth and yield models (or tables) were often derived separately, they are currently treated together in that one is easily derived from the other. This thesis deals only with timber growth and yield, although the terms are now being applied to non-timber attributes such as water or recreation.

A 'growth and yield model' is a system of mathematical relationships that claims to provide quantitative descriptions of forest stand development over some range of time, condition, and treatment (Curtis and Hyink 1985). Although 'models' may be tabular, graphical, or expressed as suites of mathematical functions, their outputs usually comprise estimates of the growth and yield of timber within a nominated forest stand.

Yield estimates are required to facilitate forest management planning at a strategic and operational level and to augment stand management research or evaluation. For example, the preparation of short-term harvest scheduling plans in an industrial plantation often requires the projection of growth upon existing inventory of the forest estate. In contrast, long term plans involving yield regulation strategies may require simulation of tree or stand level responses to changes in stand composition, structure or treatment over many decades. Both these levels of projection are necessary inputs for forest-level optimization models such as that developed by Weir (1972) to schedule the harvesting and regeneration of native forests in Victoria, and that developed for the Otway Forest Management Plan in Victoria (Dargavel and Turner 1989).

The capacity to predict the growth and timber yield of stands under present and potential silvicultural practices is also essential for investment analyses to determine the best financial strategy from the management options available on any specific parcel of land. Such work often includes comparisons of the best forestry alternative with other competing uses of the land (Pierson 1981).

Species of the genus *Eucalyptus* are predominant in over 81% of the 34.3 million hectares of productive forest land on the Australian continent (Aust. For. Council 1989).

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[1] This chapter has been published as: Rayner, M.E., and Turner, B.J., 1990. Growth and yield modelling of Australian eucalypt forests I. Historical development. *Aust. For.*, 53: 224-237.

Management intensity of eucalypt forests typically ranges from extensive for uneven-aged stands to more intensive for regrowth and industrial plantations. However, within all the Australian hardwood forests the complexity of resource management decisions has increased dramatically within the last few decades due to the need to meet multiple planning objectives and satisfy more constraints. It is apparent that resource planning will remain a flexible and dynamic process. This increased complexity of planning has led to mounting calls (Turner 1987, Dargavel 1988a) for the use of advanced planning techniques when evaluating the numerous management and utilization alternatives for both old-growth and regrowth eucalypt forests in Australia.

The nature and quality of the information available to forest managers can markedly influence the quality of planning and subsequent decision-making. The capacity of forest managers in Australia to utilize such advanced forest management planning tools as, for example, FORPLAN (Johnson *et al.* 1986) will depend in part upon the availability of adequate stand growth models for the forest estate in question. This chapter aims to review the range of published growth and yield models developed in Australia for eucalypt forests and illustrate the historical evolution of alternative modelling approaches.

2.2 Categories of growth and yield models

A growth model may comprise a single equation or may involve a series of inter-related sub-models which together comprise a simulation system. Stand growth may be described at a number of organizational levels (Charles-Edwards 1982) and hence models to project stand growth represent a continuum of mathematical complexity, generality, and design. Moreover, most models continue to evolve as new data are acquired, design objectives are modified, or advances in mathematical and computational procedures are made.

The following classifications are useful to identify differences in modelling philosophies which have evolved over the years.

(i). Empirical, dynamic and mechanistic models

Depending upon the structure and mathematical formulation of a model system, growth models or their component sub-models may be classified as either empirical, dynamic, or mechanistic (Landsberg 1986).

Empirical models are usually derived from repeat measurements of permanent growth plots in forests, with regression techniques being used to derive equations which represent the best fit to observed data. Dynamic growth models use similar, standard mensurational variables as input but may use mathematical growth curves, tree mortality probabilities, and/or tree size distribution functions to construct simulators for extrapolation to treatments and stand conditions not necessarily represented in the database available for calibration. Within these dynamic models, equations may be selected so that their parameters purport to have significant biological meaning or they may be selected with little or no thought given to the biological interpretation of parameters (Munro 1984). There are advantages and disadvantages to both (see Munro 1984, Landsberg 1986).

The majority of growth and yield models used for operational planning of hardwood production are empirical and/or dynamic in nature, and predict growth on an annual or periodic time step. If used for growth projection operationally, such simulation models are usually one component of an overall resource information system (Turnbull 1978, Clutter 1980a). Such a system may include a geographic information system (GIS) for spatial data, inventory networks for estimation of standing resource and initialization of future growth projections, forest level optimization models, harvest monitoring systems to provide feedback on plan estimates, and possibly utilization models for product description.

In contrast, mechanistic (or process) models attempt to simulate individual tree or stand growth by describing the main physiological processes that convert carbon dioxide, nutrients, and water into biomass through photosynthesis. These models may be written at any of a number of organizational and output levels, and have often been developed to be used as experimental or analytical tools to evaluate the sensitivity of physiological processes to some parameter or sub–process. However, in the last decade considerable research has focussed on applying this category of model to simulate stand development and timber yield generated from the interaction of a broad range of environmental and treatment factors. West (1987) provides an example of a typical mechanistic model designed to simulate silvicultural response.

Mechanistic models usually consist of a series of equations which are based on established models of plant physiological and biophysical processes and soil and water dynamics (Linder *et al.* 1985). Consequently, many mechanistic formulations have used daily or monthly time steps in growth simulation and incorporate a range of environmental and climatic driving variables (see, for example, Rennolls and Blackwell (1988)).

(ii). Stand or individual tree level

Growth and yield models may be further categorized according to the state variables used to define the growth process. Munro (1974, 1984) provides a widely accepted system which discriminates between stand level models (which use stand average values) and individual tree level models (which project individual trees and sum the resulting individual tree estimates to produce stand values). In addition, individual tree models may be considered distance–dependent if inter–tree spatial locations are required in the model, or distance–independent if tree location is not required.

2.3 Historical evolution of eucalypt modelling

Australian forest organizations currently use a range of computer-based models to facilitate yield prediction for eucalypt forests (Aust. For. Council 1987). Differing model designs have evolved from differences in forest management objectives, data available for construction, the level of skills and resources within an organization, and of course the nature of the forest itself. As forest management practices and hence growth information requirements have altered significantly over the last century, so there has been an historical evolution in eucalypt modelling. The references cited in this chapter are considered representative examples of each era, as work on eucalypt yield prediction has often remained unpublished by forest organizations.

2.3.1 Even–aged monospecific and mixed–species forests

Even–aged eucalypt forests occur naturally in a number of regions, the older stands usually having regenerated following wildfires or from the burning of debris following early logging. In recent years extensive areas of regrowth eucalypt forest have been created in Australia by either planting or seeding following harvesting of the old–growth forest. Increased impetus has also developed in the establishment of industrial plantations of select species on previously cleared farmland (Clarke 1975, Aust. Cons. Foundation 1987, FAFPIC 1987, Dargavel 1988b).

2.3.1.1 Early work

Table 2.1 presents a simplified chronology of published growth and yield models developed for even–aged eucalypt stands. Although the first detailed yield table for a eucalypt species was not completed until 1939, the first measured growth rates for individual trees or on a stand basis are reported in the early Annual Reports of the State Forest Services. Such estimates were derived from a variety of sources, including the remeasurement of the first growth plots, stem analysis, or log studies. For example, Patton (1917) analyzed the growth rings from old–growth *E.regnans* logs to provide an indication of the growth rate of individual trees. Lane–Poole (1916) initiated stem analysis of regrowth karri *(E.diversicolor)* whilst Stewart (1918) reported preliminary growth rates of a range of species from remeasurements of growth plots in Queensland. In 1937 Galbraith presented data for height and diameter increment of individual trees in both virgin and regrowth stands of *E.regnans* in Victoria (Galbraith 1937).

2.3.1.2 Normal yield tables

As in other countries where virgin stands were being brought under silvicultural management, one of the earliest approaches to yield estimation and projection for the

Table 2.1 Simplified chronology of published growth and yield models for even–aged eucalypt forests.

Period	Author	Description	Model level[a]	Species
Pre–1960	Lindsay (1939)	Normal yield table	S	*E.delegatensis*
	Hall (1959)	Variable density yield table	S	*E.obliqua/sieberi*
1960–1980	Cromer and Bowling (1961)	Variable density yield table	S	*E.obliqua*
	Tas. For. Comm. (1964)	Normal yield table	S	*E.obliqua/regnans*
	Curtin (1969)	Variable density yield table	S	*E.pilularis*
	Opie (1972)	STANDSIM	T	*E.regnans/delegatensis*
	Incoll (1974)	STANDSIM	T	*E.sieberi*
Post–1980	Tas. For. Comm. (1981)	Southern Forests yield table	S	*E.obliqua/regnans*
	West (1981a)	Single tree distance independent	T	*E.regnans/obliqua/globulus*
	Swain (1985)	STEMS	T	*E.marginata*
	Qld. For. Dept. (1985)	Sawlog model	S	*E.pilularis*
	Goodwin and Candy (1986)	Single tree distance independent	T	*E.globulus*
	West (1987)	Mechanistic tree level model	T	General
	McMurtrie (1988)	Mechanistic stand level model	S	*E.globulus*

[a] Where S indicates Stand level model, T indicates Tree level model (after Munro 1974)

regrowth forests was the preparation of 'normal'[2] (Vuokila 1966) forest yield tables (Tesch 1981). Such tables were seen as providing stand yield estimates for the current forest estate whilst forming a basis for extrapolation of yields from these natural, unmanaged stands to managed stand yields.

Lindsay (1939) undertook a comprehensive study of the growth of alpine ash (*E.delegatensis*, formerly *E.gigantea*) at Bago, New South Wales. Based on measurements of 104 temporary plots aged from 3 to 134 years he prepared a yield table for 'fully-stocked' unthinned stands "as a guide to the probable yield from managed stands". The technique used in the preparation of the yield table was based on that described by Behre (1927) and Bruce and Schumacher (1950) involving the graphical fitting of growth functions as curves of stand volume or basal area yield over age or height (site index). This principle (referred to as Eichorn's Law by Assmann (1970)) is used in more recent yield tables by Bradley *et al.* (1966) in Britain and Beekhuis (1966) in New Zealand. Both total and merchantable stand volumes per acre were tabulated by Lindsay (1939).

A similar approach was adopted in 1951 when the Tasmanian Forestry Commission commenced compilation of provisional site index and yield tables for regrowth *E.obliqua* in southern Tasmania. Site index curves were derived by graphical analysis of the pattern of stand mean dominant height over stand age. Data were obtained from stem analysis of dominant trees on sites subjectively selected as high, medium, and low site quality.

Total stand volume for each age and site index was derived from measurements of temporary plots in unthinned, fully-stocked stands. The curves of stand volume against age were graphically harmonized, and 'conservative graphical extrapolation' (Tas. For. Comm. 1981) was used to provide volumes for stands older than the data available.

Although developed from fully-stocked stands, they could be used for non-fully stocked stands after applying an adjustment factor. The tables were published in 1964 (Tas. For. Comm. 1964) and later converted to metric values using multiple regression techniques. They continue to form the basis of yield projection for even-aged stands of regrowth eucalypts in Tasmania (Van Saane and Gordon 1987).

2.3.1.3 Variable density yield tables

Hall (1956, 1959) developed a series of multiple regression analyses to quantify the effects of stand density, site quality and age on the volume of pulpwood produced by *E.obliqua* and *E.sieberi* stands in Victoria. Based on the assumption that Reineke's stand density index (Reineke 1933) did not alter with age for fully-stocked stands, the equations provided the first variable density yield table for these species. Almost 100

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[2] 'Normal' is used here in the North American sense *i.e.* the average condition of natural, unmanaged stands which fully occupy their sites. In Europe, 'normal' seems to refer to forest which was conservatively and consistently thinned (West 1983a).

plots were sampled and stem analyses undertaken to derive regressions relating both total and merchantable stand volume to stand density, top height, and age.

Both the normal yield table of Lindsay (1939) and of the Tas. For. Comm. (1981) and the variable density yield table of Hall (1959) were based on an abstract series of growth data (*i.e.* temporary plots), although by the 1950's permanent growth plot networks were being established in regrowth forests. In 1950 the Forestry and Timber Bureau commenced establishment of permanent sample plots in southern Tasmania with the objective of producing a normal yield table for *E.obliqua* regrowth (Aust. For. and Timber Bureau 1951). By 1960 data were available from over 114 measurements representing a range of stand conditions, and it was evident that the fully–stocked stands represented only a small proportion of the forest estate. Consequently, Cromer and Bowling (1961) used these data to investigate the development of a variable density yield table (Vuokila 1966). The advent of computer technology and access to ordinary least squares regression routines assisted exploration of a number of multiple regression relationships. Their preliminary analysis suggested that the volume per acre of even–aged stands could be estimated adequately from a curvilinear relationship established between stand volume per unit basal area and mean height of dominants.

The relationship was believed to hold irrespective of age, site index, or stand density. However, this 'table' gave results at variance with the preliminary normal yield table developed by the Tasmanian Commission (described above) in which the principle of rising basal area with rising site index had been used (Aust. For. and Timber Bureau 1961). Further regression analysis indicated that site (*i.e.* mean height of dominants) had a considerable effect on basal area, and hence the original equation was inadequate. A stand basal area equation was therefore developed which, when used in conjunction with the above equation for volume per unit of basal area, provided a yield table. In 1962 the revised yield table equation was reported (Aust. For. and Timber Bureau 1962) in which stand basal area was estimated as a function of stand age, site index, and Reineke's stand density index.

In the latter half of the 1960's the role of the Tasmanian plots was expanded from essentially a means for estimating plot volume for stand level yield table estimation to a Continuous Forest Inventory (CFI) system in which greater detail of individual tree growth was recorded. This same plot series later formed the basis of a series of empirical model investigations by West (1979a, 1981a, 1982).

The objective of developing variable density yield tables for managed regrowth eucalypt stands based upon data from unmanaged, naturally regenerated stands continued to dominate eucalypt mensuration. Curtin (1969) prepared a preliminary variable density yield table for even–aged stands of blackbutt (*E.pilularis*) on the north coast of N.S.W. Based on growth data from more than 100 plots he prepared a series of guiding curves of periodic gross basal area increment for groups of stands having approximately the same age. These hand drawn curves represented gross basal area growth as a function of basal area and age. Stand volumes were determined by assuming that the tree of mean diameter was also the tree of mean volume: having obtained the bole height for each mean diameter a volume table was entered to give an estimate of mean tree volume. This volume was multiplied by the appropriate stocking to derive stand volume.

Curtin (1969) compared his estimates of stand basal area increment (I_{Bg}) with a growth function derived by Turner (1966) for predicting the I_{Bg} of uneven-aged blackbutt stands. Turner's regression function projected I_{Bg} based on numbers of stems, soil group, and the percentage of blackbutt in the stand. Curtin concluded that his yield table for managed even-aged stands compared sensibly with Turner's estimates for variable quality uneven-aged forest.

2.3.1.4 STANDSIM

When extrapolating temporary or permanent plot data to develop managed stand yield tables it is often hypothesized that gross yield and increment-stand density relationships are equivalent in wild and managed stands, and that gross increment is little affected over a range of conservative thinning regimes (Curtis 1972). This approximation was incorporated in the design of the first individual-tree growth model developed for even-aged eucalypts. In 1972 Opie wrote a FORTRAN computer program called STANDSIM, an empirical model for simulating the growth of individual trees on an annual or periodic cycle (Opie 1972).

Although developed initially for *E.regnans* and *E.delegatensis* in Victoria, STANDSIM has since been calibrated for *E.sieberi* in Victoria (Incoll 1974) and for *E.regnans* in Tasmania (White[3] *pers. comm.*, 1976). The model simulates stand growth from any nominated age for any nominated period. Site index and initial stand density can be varied, and thinning regimes (up to five thinnings from below) may be modelled.

Gross stand basal area increment is predicted by a nonlinear function of stand density and age, and this stand level growth is then allocated amongst individual trees according to their relative size, dominance, and degree of suppression. Tree mortality is estimated by a number of functions incorporating maximum stand density as a function of site index and basal area and a probabilistic estimator of tree size. Stand height growth is modelled as a nonlinear function of age and site index.

The original model (Opie 1972) represented the integration of considerable research (Webb 1965, 1966) on stand dynamics of the even-aged ash forests, including the first comprehensive analysis of thinning experiments (some established as early as 1947) in such forests. Despite the availability of such thinning trials and plot networks, Campbell *et al.* (1979) emphasized that limited appropriate data were available at the time of development of the original model. Consequently, estimation of the growth functions used a process of 'graphical analysis' (Campbell *et al.* 1979) involving the

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[3] cited by Opie *et al.* (1978)

specification of a suitable form of function for the process concerned, with trial and error selection of the equation of best fit.

The model has continued to be updated (Campbell 1974, Incoll 1974, Incoll 1983) and the generality of the functions extended (Incoll[4] *pers. comm.*). For example, Campbell (1974) added new algorithms to estimate product yields and subsequent economic returns for stand management regimes. Incoll (1974) calibrated STANDSIM using temporary plot data for *E.sieberi*, and later (Incoll 1981) incorporated algorithms to simulate the effect of fire on growth and mortality of this species. Based upon studies of root systems of *E.regnans*, Incoll (1983) expanded the range of thinning types which can be simulated by incorporating thinning response for the clearfelling of strips (analogous to plantation extraction rows) in naturally regenerated stands of this species. Work is currently underway to extend the generality of the model to two–tiered stands and to further amend the product out–turn computation (Incoll[4] *pers. comm.*). Campbell *et al.* (1979) describe the current component functions in some detail whilst Incoll (1983) documents later recalibrations of the model.

STANDSIM has been, and continues to be, widely applied for forest management planning in Victoria and other states. For example, it has been the basis of the stand simulator providing input to the forest optimization model devised by Weir (1972), and has been used in the formulation of working plans for subsets of the central highlands ash resource (Aust. For. and Timber Bureau 1974). STANDSIM has also been used to generate yields for a range of stand management regimes incorporated into the FORPLAN model for the Otways Planning Project (Dargavel and Turner 1989). Other applications of the model illustrate the range of potential uses of growth and yield models in forest research. For example, Rawlins and Kerruish (1988) reported the application of STANDSIM to investigate the economic benefits of an experimental program on the thinning of eucalypts. STANDSIM output was incorporated with information on nutrient balance, water yield, harvesting technology, sawmilling economics, and pulpwood valuation. Earlier Rawlins *et al.* (1984) had used STANDSIM in a computer modelling analysis of the choice of harvesting research projects in young even–aged eucalypts.

Where possible, the component functions in STANDSIM were estimated using multiple regression analysis and standard statistical procedures to select the best model. Such techniques of model parametrization were rapidly adopted following the advent of computer technology (*e.g.* Hall and Neal 1966). However, as in pine growth modelling, many workers pursued empirical models using ordinary least squares regression inappropriately (Ferguson 1983a). Consequently, West (1981a) demonstrated the methodology of generalized least squares regression (Ferguson and Leech 1978, Davis and West 1981, Ferguson and Leech 1981) to parametrize an empirical model for pure and mixed stands of *E.regnans*, *E.obliqua* and *E.globulus*.

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[4] Mr W.D. Incoll, Dept. of Conservation and Environment, Victoria

2.3.1.5 Individual tree models

West (1981a) described a single–tree, distance–independent simulation model to predict tree diameter growth of unthinned, 20 to 80 year old, even–aged regrowth in southern Tasmania. Regression equations related diameter increments of individual trees of each species to their current diameter. A second stage analysis regressed the first–stage parameters on stand age and stocking. A stochastic process generated probabilities of death of individual trees to simulate stand mortality.

In a similar two–stage regression approach, West (1982) derived functions to estimate individual tree heights and bark thicknesses at breast height from stand level variables. By combining the height and diameter prediction functions (West 1981a) a simulation model was produced which allows prediction of future diameter, height and bark thickness of individual trees of the region. Two–way tree volume tables may then be applied to predict individual tree and hence stand volume.

The accuracy and precision of estimates of total merchantable volume, sawlog volume and pulpwood volume from the model are reported in West (1983b). Over simulation periods of up to 23 years the size–class distribution of sawlogs was predicted satisfactorily whilst estimates of future total volume of a single plot lay within ± 30% of the observed plot volume. Although such precision is typical of many empirical systems, the model is currently not used for operational forest planning.

In addition to models developed for operational yield projection, many forest organizations have developed minor systems with limited application beyond specific research trials. For example, in a review of thinning experiments in blackbutt regeneration at Mapleton the Queensland Forests Department developed a mill log growth model (Qld. For. Dept. 1985). The empirical regressions compute the standing volumes of mill logs (>40 cm diameter) as a function of stand age, total stocking, and fraction of the stand of mill log size.

Emphasis on the individual tree level of modelling has continued. Swain (1985) investigated the feasibility of parametrizing the model STEMS (USDA For. Serv. 1979) for regrowth jarrah (*E.marginata*) in Western Australia. STEMS is a single–tree, distance–independent model which estimates potential growth of an individual tree in the stand and modifies the estimate according to inter–tree competition. The core of the potential growth algorithm is a Chapmans–Richards function, modified to include the independent variables stand site index and tree crown–ratio. The modifier reduces the potential growth according to a competition index evaluated from stand–level variables.

The STEMS model is possibly the most widely used single–tree distance independent model in the United States. However, Swain (1985) was unable to adequately parametrize the model due to data limitations; only one suitable dataset was available (from a thinning trial) and necessary tree–level parameters had to be approximated as they had not been previously measured.

Goodwin and Candy (1986) document a single–tree distance–independent growth model derived for a single plantation of *E.globulus* at Stoodley, Tasmania. Using stem analysis data obtained from one planting year, a series of equations for individual tree volume, total height and diameter at breast height under bark (d_u) increment were parametrized. Beta probability functions were used to describe the d_u distributions of stands by projecting the parameters of the beta function at 5–yearly intervals. Although data on individual tree mortality were unavailable, the growth of unthinned stands was simulated by estimating the stand density and volume for each d_u distribution on the basis of the Self–thinning Rule (White 1981) concept. The model is not used operationally but has assisted speculation of stand dynamics for the plantation resource (Candy[5] *pers. comm.*).

2.3.1.6 Mechanistic models

In contrast to the traditional empirical approaches described above, McMurtrie (1988) demonstrated the application of a mechanistic stand growth model (McMurtrie and Wolf 1983) relating above–ground forest productivity to canopy leaf area. The model was parametrized for stands of *E.globulus* growing in Victoria, and modelled the processes of radiation interception, dry matter production, allocation to foliage, branches and stems, and tissue mortality. It was used to estimate the maximum achievable stand productivity within a given environment by examining which biomass partitioning strategy maximizes wood production. The model was calibrated for one experimental site and illustrated the potential applications of this category of model.

West (1987) has extended the stand level mechanistic work by developing the theoretical framework of a model that will predict growth of individual trees in stands managed under any combination of thinning regime. The model is distance–dependent and comprises a system of difference equations which describe tree biomass allocation as a function of individual tree radiation interception, photosynthesis, respiration, litterfall, and root turnover. The model incorporates inter–tree competition by simulating canopy shading of subject trees by adjacent trees. The required physiological parameters are currently being obtained from experimental sites in Tasmania and Victoria (West 1991), although the generalized design is intended to make the system species, site and treatment independent.

2.3.2 Uneven–aged mixed–species eucalypts

Table 2.2 provides an indication of the range of models published for uneven–aged mixed–species eucalypt forests.

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[5] Mr. S. Candy, Forestry Commission of Tasmania

Table 2.2 Simplified chronology of published growth and yield models developed for uneven–aged / mixed–species eucalypt forests.

Period	Author	Description	Model level[a]	Principal species
Pre–1960	Fraser (1882)	Estimates (local experience)	S	*E.marginata*
	Various: *e.g.* Nunn (1959)	Continuous Forest Inventory	S	Virgin and selection
		Stand table projection		cutover stands
1960–1980	Turner (1966)	Volume/basal area regression	S	*E.pilularis*
	Phillis (1971)	Cutting cycle analysis		General
		Stand table projection		
	Grimes and Pegg (1979)	Basal area regression within *d* classes	S	*E.maculata/fibrosa*
Post–1980	Shugart and Noble (1981)	BRIND	T	*E.delegatensis*
	Kilgour (1982)	MESSIM	T	*E.obliqua*
	Sharpe *et al.* (1985)	Mechanistic model	T	*E.populnea*
	Kellas and Hateley (1987)	Estimates (local experience)	S	General
	Goodwin (1988)	STEMS	T	*E.obliqua*

[a] Where S indicates Stand level model, T indicates Tree level model (after Munro 1974)

2.3.2.1 Early work

As in even–aged forests, the earliest yield estimates for mixed–age/mixed–species hardwood forests were primarily concerned with estimating the standing volume of virgin stands (*e.g.* Fraser 1882). Because most forest services in Australia inherited forest estates in which large timber industries were established (Carron 1985), development of effective protection and regeneration measures for commercial species was a major priority. Inventory of the standing resource and the estimation of growth on cutover stands was often considered of lesser priority. In addition, for many of the forest types, projection of growth on the virgin stands was considered unnecessary as the old–growth forest was assumed to be a static resource with mortality equalling or slightly exceeding increment. This assumption is still adopted for yield regulation in some old–growth forest types (even and mixed–age) in Tasmania (White[6] *pers. comm.*) and Western Australia (Bradshaw and Lush 1981).

Subsequent forest assessment focussed on the need to provide yield estimates for the preparation of working plans to regulate the yield from particular forest types. Henry (1955) claimed that even by 1933 no detailed assessment or record of growth was available for hardwood forests in New South Wales. The techniques and progress of forest assessment up to the 1950's within three states have been documented by Lawrence and Walker (1954), Henry (1955), and Nunn (1959).

2.3.2.2 Stand table projection approaches

As cutting proceeded, most forest services and organizations established a network of CFI plots across the range of site and condition of the native forest. These plots provided standing resource and growth estimates for inventory update and yield regulation. In most states the plots have been remeasured over several decades and have formed the database for any growth modelling work undertaken for mixed–species forests. Typical tree parameters recorded include species, diameter, bark thickness, and an estimate of merchantable height or log length (Aust. For. Council 1987). Growth was estimated on a stand basis using standard or simplified stand table projection methods (see, *e.g.*, Carron 1968). Vanclay (1989a) summarized the various techniques and assumptions of stand table projection, and noted its once extensive use in Queensland.

Phillis (1971) discussed the application of stand table projection for the prediction of yield from irregular eucalypt forests in N.S.W. and Queensland. He developed a computer program (CUTAN) to perform the cutting cycle analysis method of stand table projection. The basis of the program is prediction of future forest growth by averaging the past growth of a number of plots. The program is used for short–term projection of growth in some N.S.W. forest types (Curtin *et al.* 1987).

However, the difficulty of accommodating the complex site and competitive interactions which characterize irregular eucalypt forests into a stand table projection,

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[6] Mr M. White, ANM Forest Management, Tasmania

coupled with the increased availability of computers for data manipulation (Hall and Neal 1966), prompted active investigation of alternatives.

2.3.2.3 Regression approaches

The utility of the regression alternative to stand table projection was demonstrated by Turner (1966), who developed a series of multiple linear regression equations for the prediction of stand growth of an irregular blackbutt forest in New South Wales. Growth data to develop the predictive models of basal area and volume growth were obtained from 60 CFI plots. Although a range of independent variables and their combinations were tested, only stand density, species composition, and site quality were used in the final equations. The model's predictions of mean volume growth per acre were statistically compared with the alternative method of stand-table projection. The regression model was found to be at least as accurate and more economical in its use of data as it relied upon stand variables rather than individual tree variables.

Many specific analyses have been published of stand growth rates from CFI networks. For example, Curtin (1970) attempted to summarize the available growth data for Yarratt State Forest on the north coast of New South Wales in sufficient detail for future planning in areas with similar histories and stand structures. Regression models were developed for predicting basal area increment and volume increment as functions of basal area classes and mean tree sectional areas.

Grimes and Pegg (1979) summarized growth data from a series of 24 increment plots for a spotted gum–ironbark forest in the Maryborough region of south–east Queensland. Multiple regression techniques were used to construct stand level prediction models for basal area increment, ingrowth, and stand mortality for each of three diameter classes. The approach was essentially the same as undertaken by Turner (1966), except Turner used total stand variables rather than partitioning the stand into diameter classes.

CFI plots continue to be used for growth estimation in many forest types, including the dry sclerophyll forests in Tasmania (Van Saane and Gordon 1987), the dry sclerophyll/mixed–species foothill forests of the midlands and south–west Victoria (Kellas and Hateley 1987), and areas of the jarrah forest in Western Australia (Rayner and Williamson 1984).

2.3.2.4 Individual tree models

A number of workers have attempted to develop individual tree level models for mixed–species/mixed–age stands in Australia.

Kilgour (1982) developed a model currently used to assist yield regulation of the uneven–aged messmate (*E.obliqua*) forests of southwest Victoria. Designed to project stand growth over a 30–year planning horizon, the model is initialized using typical inventory data and can output merchantable sawlog volumes by size assortments.

Individual tree diameter increment is modelled as a function of diameter, point density (a zone count of competing basal area), site index, and a dummy variable which incorporates the status of past logging history. The site index function simulates the site quality at a forest block level, whilst recruitment of regeneration was estimated using a Weibull distribution based on the stand basal area density classes. Kilgour and Rudra (1988) used this model to present some simulation studies of alternative management strategies for the messmate forests.

The most extensive attempt to parametrize a distance–independent single–tree model for mixed–aged stands has been undertaken by Goodwin (1988). Using a database of over 800 CFI plots representing mixed–age/mixed–species stands throughout Tasmania, he attempted to calibrate the STEMS model. Species identity was ignored due to the absence of site index curves for some species.

A number of difficulties were encountered, including the absence for unaged stands of an adequate way of estimating site quality. Goodwin developed a measure based on a combination of height growth, mature stand height and aerial photography interpretation. Data quality markedly influenced the final model, with poor performance of the calibrated model being attributed to such factors as the 'coarseness' of subjective crown measures, poor estimation of site index, and the necessity to combine all species for simulation purposes.

2.3.2.5 Mechanistic and gap models

Two alternative modelling philosophies have guided the development of models to simulate tree growth in mixed–age eucalypt stands, although neither were designed to provide timber yields for use in operational forest planning.

One approach was adopted by Shugart and Noble (1981) when designing BRIND, a computer model developed to investigate species succession in the alpine ash zone of the Brindabella Range in the A.C.T.. BRIND is a 'Gap' model (Shugart 1984) based on an innovative sequence of models developed for North American forests (Botkin *et al.* 1972, Shugart and West 1977). The model operates by simulating the regeneration, growth and death of individual trees in a 30 metre forest 'gap'. The model simulates annual diameter and height growth of individual trees. Light, temperature, and competition for growing space are used multiplicatively to reduce subject tree growth below that attained by a tree growing under optimum conditions – presumed to be the largest tree recorded of the species. The spatial element of gap models arises in computing the effect of shading by competitors on a subject tree, with tree mortality being dependent on tree age and current growth rate. Both recruitment and mortality are estimated stochastically using Monte Carlo methods.

Initially devised to predict the pattern of succession in a forest stand subject to a range of disturbance regimes, the model successfully reproduced the replacement patterns of vegetation along altitudinal and fire gradients in the sub–alpine forests of the

Brindabella Range. It was further tested for its ability to simulate basal area, stocking, and average diameters for different aged stands from the independent dataset for unthinned, natural stands of *E.delegatensis* collected by Lindsay (1939) at Bago, N.S.W. From year 35, both the yield table and model predict a similar range of average diameter, stocking, and basal area. Divergent estimates below age 35 were due to commencement of the simulation from different initial stocking densities. Further development of the gap model has continued, with a recent revision by M. Strasser (Strasser[7] *pers. comm.*).

Sharpe *et al.* (1985) have developed the concept of ecological fields (*cf.* magnetic fields) to examine competitive interactions among plants in *E.populnea* woodland in southern Queensland. Their aim was to include competitive interactions in a mechanistic growth model of these plant communities, where the mixtures of vegetation forms differ greatly in size and resource requirements. The model used a physiologically-based continuous time Markov approach for combining water, light and nutrients into a single growth parameter. They illustrated the methodology by simulating the diameter growth of individual woodland trees under different resource availability scenarios (Walker *et al.* 1988).

2.4 Discussion

2.4.1 Historical trends in growth model design

A number of the historical trends evident in the design of growth and yield models for eucalypts in Australia are illustrated in Table 2.3. These trends should be viewed in the wider context of international developments in forest growth and yield modelling (Moser 1980, Tesch 1981, Munro 1984).

Historically, modellers have attempted to develop systems which accurately quantify existing forest stands and their growth resulting from current or past practices, but which can also be used to extrapolate stand dynamics beyond the range of stand condition and treatments represented in the current database. This modelling objective is particularly important in those forest types for which silvicultural practices have not remained stable. The capacity to extend a model's 'generality' along the continuum from a short-term update projection to predicting responses to new silvicultural treatment has depended at any time upon the nature of the data available, the status of mathematical analysis techniques, and growth prediction theory to that date.

Early forest growth models were based on graphical and tabular descriptions of stand variables such as basal area and volume, often derived from temporary plot data. Gross working hypotheses were formulated in order to predict the consequences of management on natural stands (*e.g.* Lindsay 1939). The advent of computer technology supplemented traditional graphical analysis and encouraged the application of linear regression models (*e.g.* Cromer and Bowling 1961, Turner 1966), both at the stand- and

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[7] Mr M. Strasser, Research School of Biological Sciences, A.N.U.

Table 2.3 Examples of the range of model categories developed for Australian eucalypt forests.

	Model Category		
MODEL LEVEL	**Empirical** Regression	**Dynamic** Growth curves	**Mechanistic** Process hypothesis
STAND	Cromer and Bowling (1961)	Kilgour (1982)	McMurtrie (1988)
INDIVIDUAL TREE	West (1981a)	Goodwin (1988)	West (1987)
TREE COMPONENT			West (1987)

individual tree–level of modelling. Detailed simulation of individual tree growth was undertaken (Opie 1972, West 1981a) for aggregation to stand level detail. Investigation of sub–models to simulate growth in individual tree components (*e.g.* tree height, diameter, crown) became more common in an attempt to provide greater detail in growth predictions. This work demanded greater detail in tree growth data collection (*e.g.* Aust. For. and Timber Bureau 1974).

However, the fact that strictly empirical regression formulations cannot be sensibly extrapolated beyond the range of stand treatments represented in the available data (Jeffers 1978) encouraged attempts to incorporate more biological theory in predictive models. Clutter (1963) introduced the concept of compatibility to ensure the sum of increments must equal total yield. In a landmark publication Pienaar and Turnbull (1973), working with slash pine data proposed the use of the Chapman–Richards generalized form of the Bertalanffy growth function for prediction of growth in non–normal and thinned stands. They hypothesized biological interpretations for the coefficients of their non–linear mathematical model and revitalized attempts to incorporate 'general growth theory' into empirical mathematical models for forest stands. This 'dynamic' (Landsberg 1986) approach to model formulation has been actively pursued at both the stand and individual tree level in an attempt to define or calibrate sub–models or whole systems which could extrapolate predictions for stand treatments beyond the data available for model parameter estimation.

Improved computer efficiency and data availability encouraged detailed investigations and attempts to model inter–tree competition as a means of simulating stand density reduction (thinning) and treatment responses. During the 1970's (following Newnham 1968) numerous single–tree level models, incorporating various designs for an individual–tree competition index were developed. Depending upon the availability of tree spatial/location data, a wide range of model formulations has been devised in an attempt to describe current stands and to develop 'managed' (Curtis 1972) yield tables when only data from wild or historically treated stands were available for parameter estimation.

During the last decade considerable interest in mechanistic or process model formulations has arisen. Although many authors had studied and modelled aspects of tree physiology, it appears Jarvis (1981) was the first to propose an integrated carbon balance model for predicting stand growth and yield. Landsberg (1986) argued that such models are potentially superior to typical empirical formulations for simulating stand silvicultural responses beyond the range of site and stand treatment in growth plot databases.

2.4.2 Geographic and species coverage of current models in Australia

The majority of research and operational models available for simulating growth of eucalypts are referred to in Tables 2.1 and 2.2. Additional unpublished models developed by forest organizations for operational and strategic forest planning are listed in a brief report compiled by the Australian Forestry Council (Aust. For. Council 1987). There has been greater development and integration of models into operational planning systems for commercially important even–aged monocultures than for mixed–age, mixed–species stands. However, existing models for simulation of even–aged stand development have typically been developed from data representing naturally–regenerated regrowth stands. These models are generally inappropriate for detailed comparison of potential yields generated by intensive management regimes which may include site preparation treatments (espacement, fertilizer, weed control, ripping), repeated fertilizer applications, or multiple thinnings.

The limited number and restricted species generality of growth models developed for mixed–age, mixed–species stands has major implications for forest management planning. For example, Ferguson (1987) asserted that due to historical and data constraints, forest level planning in extensive, mixed–age forests in some regions of Victoria is often restricted to one or two broad silvicultural strategies which may neglect differences between species mixtures, age classes and stand conditions over broad areas. The true productive potential and optimal forest level strategies are potentially distorted by such generalizations. The situation summarized by Ferguson (1987) for Victoria is typical of planning for many mixed–age forest types throughout Australia. Such a paucity of simulation models can also seriously limit the range of land use management options presented for public debate. Pierson (1981), for example, examined how the limitations of stand growth predictive models can distort forest valuations and land use decision–making, particularly in plantation management analyses.

Renewed emphasis on eucalypt growth and yield research will be necessary to redress the current imbalance between the availability of models and the increasing information demands on forest planners. Considerable developmental work is required to provide basic growth models for much of the eucalypt forest estate in Australia.

2.5 Conclusion

Projections of stand growth and yield are an essential component of forest management planning. The historical evolution of modelling eucalypts in Australia has parallelled overseas experience. Within even–aged forests there has been a progression from 'normal' forest yield tables for fully–stocked stands to variable density models. Mixed–age mixed–species stand modelling has progressed in some instances from stand table approaches to detailed single–tree models. Model formulations have varied from a traditional empirical approach through to dynamic and recent mechanistic approaches in progressive attempts to introduce wider species or treatment generality into models. Increased complexity of resource management decisions further emphasizes the need for species, site, and treatment generality among future models.

Unfortunately, modelling has not been undertaken for many forest types within Australia. This poses a major constraint to the use of advanced forest–level planning systems, particularly for the more extensively managed mixed–age, mixed–species forests.

CHAPTER 3 DATA DESCRIPTION, EVALUATION AND STAND VARIABLE ESTIMATION

3.1 Introduction

A major constraint on the choice of a modelling approach is the nature, quality and quantity of data available for parametrization. The nature of the available data can markedly influence the model design selected to achieve the model objectives, whilst the quality of the data will often determine parametrization success. A brief description is given in this chapter of the available karri data, its editing, and a preliminary evaluation of the suitability of each variable for empirical modelling purposes.

3.2 Data sources

Data for model development were collated from records held by the Inventory and Research Branches of the Department of CALM. The primary dataset was a permanent sample plot network which had been established and maintained by the Inventory Branch, supplemented by plot data from a variety of stand treatment experiments.

3.2.1 Permanent Sample Plots

3.2.1.1 Sampling strategy

A network of 214 permanent sample plots (PSPs) were established during 1980–1983 throughout the age and geographic range of existing regrowth karri stands (Figure 3.1). In the absence of a forest site stratification, no formal sampling strategy had been adopted other than to ensure a representation of stands within each major river catchment. Plots were located in stands subjectively judged to be fully-stocked, of even-aged structure, and free from any suppressive influence (Rotheram 1983) of veteran overstorey. The representation of plots was unbalanced across the age classes due to the highly skewed age distribution of the existing regrowth estate.

The range in species composition and stand variables sampled by the plots is summarized in Table 3.1. The plots sample stands which vary in age from 2 to 135 years but predominantly cover the age ranges 6 to 20 and 30 to 70 years. Almost half of the plots in the 0 to 20 years age class are located in planted stands. Approximately 60% of the plots are in stands of pure karri, whilst the remaining 40% contain various combinations of species in mixture with karri. Within these plots the proportion by volume, basal area or stocking of non-karri species was generally less than 20%.

3.2.1.2 Variables measured

The location, size and measurement procedures for these plots have been described by Campbell *et al.* (1988). Both the size of each plot and the variables measured vary with stand age (Table 3.2). All plots are square, ranging in size from 0.09 hectares (≤25 yrs) to 0.36 ha (≥70 yrs). In addition, younger stands (≤25 yrs) have

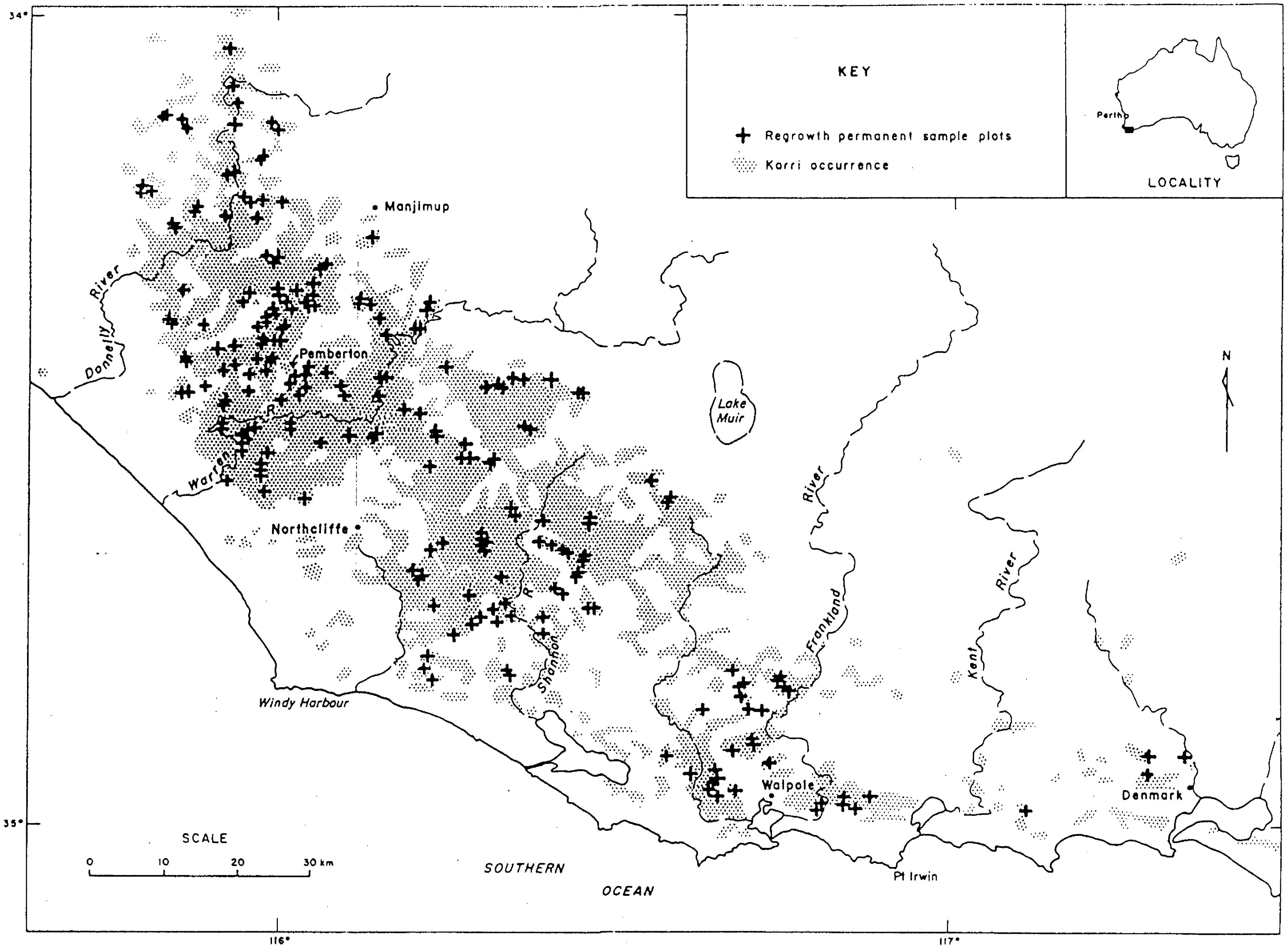

Figure 3.1 Karri forest occurrence showing location of permanent sample plots within regrowth stands.

Table 3.1 Minimum–mean–maximum values at plot establishment of stand variables by species composition in the Permanent Sample Plot (PSP) data.

Species composition	Number of plots	Age (Yrs)	Basal area[a] (m^2 ha^{-1})	Stocking[a] (stems ha^{-1})x10	Mean height of dominants (m)
E.diversicolor	129	2–29–132	5–28–56	6–58–164	2–30–61
E.diversicolor / *E.calophylla*	49	4–33–135	2–25–50	6–45–115	5–31–67
E.diversicolor / other[b]	36	2–35–102	3–23–43	5–39–93	2–30–47

[a] Live stems ≥10 cm diameter at breast height.

[b] Other species which may occur in mixture with karri include *E.marginata* Donn ex Smith, *E.jacksonii* Maiden, *E.brevistylis* Brooker, *E.guilfoylei* Maiden, *E.patens* Benth., and/or *E.megacarpa* F.Muell.

Table 3.2 Age sequence of plot size and variables measured (1980–1989) within regrowth karri Permanent Sample Plots.

Age	Plot area		Variables measured[a]	
(Yrs)	Main plot (ha x 10^{-2})	Subplots (ha x 10^{-2})	Stand level	Tree level
0– 5	9	0.14	*H*	Sp
6–15	9	0.59	*H*	Sp and *d*
16–25	9	1.00	*H*	Sp, *d, bt, h, hc, cr,* DOM, DEF, EPIC, SR, MKT, and TREE_POS
26–30	9			as for 16–25 years
31–50	16			
51–70	25			
70+	36			

[a] *H* denotes stand top height (m)
Sp denotes species
d denotes diameter at breast height (1.3 m) underbark (cm)
bt denotes bark thickness (cm)
h denotes total tree height (m)
hc denotes height to crown break (first green limb) (m)
cr denotes crown radius (m)
DOM denotes tree dominance category (dominant, codominant, subdominant or suppressed)
DEF denotes defect category (0 to 10)
EPIC denotes epicormic category (0 to 5)
SR denotes suitability for remeasurement code (1 to 4)
MKT denotes marketability code (1 to 4)
TREE_POS denotes tree position (polar co-ordinates)

circular subplots located at the centre of each North–South–East–West axis of the plot. A buffer area extends one mature tree height (70 m) from all boundaries.

3.2.1.3 Measurement procedures

Stand top height (*H*), recorded at each measurement, is defined as the mean of the tallest two trees within a 15.96 m radius from the plot centre. This is equivalent to the tallest 25 stems per hectare. Tree height was measured with a clinometer (from two independent positions) or with height sticks where practicable. The age of each stand (*A*) was determined from a combination of historical field records, planting records, or the felling of a dominant tree within the stand adjacent to the plot. When aged from a felled tree, *A* was determined from a ring count at 0.5 m height.

Measurement of the individual tree–level variables varied with the age of the stand (Table 3.2). In stands aged up to 15 years only the diameter over bark at breast height (1.3 m) (*d*) of all trees within the subplots was recorded, using a vernier or steel tape. Subsequent measurement of the subplots continued to age 25. Within stands older than 15 years, the *d* (steel tape) and bark thickness (wedge gauge) at breast height were recorded on all stems greater than 10 cm *d* within the entire square plot. A sample of trees were selected for measurement of total height (*h*), height to crown break (*hc*) (first green limb), and crown radius (*cr*) using a Suunto clinometer or telerelaskop. The measured sample comprised 15 to 40% of trees ≥10 cm *d* within the plot, subjectively selected to span the range of *d* within the stand. Unfortunately, non–karri species in the mixed–species stands were generally under–represented in these height samples. The ***h***, *hc*, and *cr* of all remaining trees in the plot were ocularly estimated using the measured trees as reference standards. Each tree greater than 10 cm *d* was allocated a rating (0 to 10) for visible defect or epicormic development along the bole and within the crown, and a dominance status was allocated using the Kraft classification system (Smith 1986). Tree position relative to the plot centre was recorded in polar coordinates for each tree greater than 10 cm *d*.

3.2.1.4 Measurement frequency

The frequency of remeasurement of the PSPs varied with stand age, from 2 years at ages 0–15, 3 years at 15–25, and 5 years thereafter. Very few measurements were available at the time of this study: over 65% of the PSPs had been remeasured only once since establishment, and the maximum number of measurements per plot was four. The PSP data therefore comprise an abstract (*cf.* real) growth series (Li 1988).

3.2.2 Stand treatment experiments

An additional source of data was the various thinning and espacement trials which had been established on an *ad hoc* basis within specific stands. Until recently (post–1985), no formal sampling strategy had been used when locating these trials: regrowth of an appropriate age and extent had typically been selected for uniformity of stand height and logistical convenience. Later site classification work (Chapter 6) revealed the siting of experiments had been biased toward stands of higher site quality.

Earlier thinning trials were often inappropriately designed for statistical analysis. Although their value is limited, they are the longest running set of plots in many stands, providing information not currently available from the PSPs. Later trials incorporated structured analysis of variance/factorial designs of thinning and fertilizing levels for one site and age class.

Measurement procedures and plot size varied between experiments. Post–1985 trials had generally been established according to the PSP procedures, whereas the earlier trials had only recorded the number and *d* of stems greater than 10 cm, with stand height measures sampled infrequently.

The plot series used in model development and validation include the Warren, Treen Brook, Big Brook, and Bamess Road thinning trials, and the Muirillup Espacement Trial (Table 3.3). The design and treatments for most of these trials have been summarized in Breidahl and Hewett (1992). All thinnings have been from below, removing all suppressed and subdominant stems and a proportion of codominants in order to evenly space the retained crop trees. Only first thinnings have been performed.

Both the Warren and Treen Brook thinning trials are factorial designs comprising 28 plots located in homogeneous regrowth stands aged 12 and 48 years (at time of thinning) respectively. Thinning treatments in each removed approximately 30%, 50%, 65% and 75% of stand basal area relative to unthinned controls. Some of the experiments have coppice control, fertilizer or soil compaction treatments (Wronski 1984) nested within the thinning treatments. Data from these plots were excluded from model building as the treatments had not been replicated on any other site or stand age.

3.3 Preliminary data editing

Programs were written to standardize all data into the PSP format, convert imperial measurements to metric, and compile one combined dataset.

The data were mostly unvalidated. As expected, when growth and yield data collected over many years by an organization are first analyzed on such a scale numerous inconsistencies were apparent within individual tree records and between remeasurements. A detailed evaluation of bias and precision within the data was prompted by both the frequency of inconsistencies between remeasurements for some variables (*e.g.* *h*), and the difficulty of reconciling data when few measurements are available in each plot.

Table 3.3 Minimum–mean–maximum values of stand variables at plot establishment, and subsequent number of remeasurements, in the stand treatment experiments. Species composition for most plots is pure karri.

Experiment[a]	Number of plots[b]	Treatment[c]	Age (Yrs)	Basal area[d] (m^2 ha^{-1})	Stocking[d] (stems ha^{-1})x10	Mean height of dominants (m)	Number of measurements
Warren RWP 3/84	14	T_1	12–12–12	8–17–29	18–48–120	21–22–23	5
Treen RWP 25/85	30	T_1	47–48–50	10–22–50	4–18–82	44–46–53	4
Big Brook IWP 1/17	2	T_1	42––74	31––36	9––28	43––53	10
Big Brook IWP 1/56	22	T_1	20–22–24	18–25–39	70–91–175	16–26–31	5
Treen IWP 1/79	12	T_1	47–47–47	15–29–53	8–22–64	42–46–50	4
Crowea IWP 2/56	1	U	41	46	52	39	5
Muirillup RWP 25/86	24	E	6–6–6	-NA-	6–18–32	6–10–13	4

[a] RWP denotes Research Working Plan number, IWP denotes Inventory Working Plan number.

[b] Number of plots refers only to those plots used in the present work. Values include control (untreated) plots.

[c] Stand treatments are T_1 first thinning, U unthinned, E espacement trial.

[d] Live stems ≥10 cm diameter at breast height.

3.4 Evaluation of the quality of PSP data

3.4.1 Introduction

Knowledge of the accuracy and precision of tree measurements, and the presence of bias is essential when validating growth data. Little is published, however, which might serve as a guide when developing validation programs to detect imprecise or biased PSP data in wet sclerophyll eucalypt forests. Five PSPs were therefore selected for a pilot study of the bias, precision and accuracy of tree and stand measurements. This investigation aimed to determine the measurement precision of select variables within the PSP data, the size of measurement errors relative to the measurement interval, and to assess the reliability of some variables for modelling.

3.4.2 Method

Most of the PSPs had been established and remeasured by one of three teams, whose standards had been regularly monitored. An estimate of precision within and between measurements was obtained by comparing the measurements obtained by each team on a sample of the PSPs. Five PSPs aged 5, 21, 45, 61, and 102 years, covering the species range from pure karri to mixed marri–karri–jarrah, were selected as representative of the PSP dataset. Each plot was measured in November 1988 according to standard plot procedures and then remeasured three days later by each team. At the second measurement all tree variables were measured, including those previously estimated. Data from plot establishment (two to five years earlier) were used to compare the magnitude of measurement error relative to the increment period for each variable.

The method of analysis of measurement bias and precision differed depending upon whether a classification variable (*i.e.* subjectively classified variable on a rank scale, such as DOM, EPIC or DEF) or quantitatively measured variable (***d***, ***bt***, ***h***, ***hc***, ***cr***) was being examined.

3.4.2.1 Categorical (Ordinal) variables

Tabular summaries and histograms of the differences between measurements for an individual team, and between teams at each measurement, were prepared for each variable (DEF, DOM, Sp, EPIC) using procedures available in the Statistical Analysis System (SAS Institute Inc. 1985). Trees were also sorted into descending order according to their ***h*** and ***d*** and the distribution of dominance categories compared between quartiles of the ***h*** and ***d*** strata.

3.4.2.2 Quantitative (Interval) variables

Scatter graphs were inspected of the estimated and measured ***d***, ***bt***, ***h***, ***hc***, and ***cr*** values recorded by each team at the first measurement against the values they and other teams recorded at the second measurement. The accuracy of measurement was inferred by overlaying on these graphs the manufacturer's error limits for the instrument, while bias and precision were readily apparent from visual inspection. If bias was evident between measurement teams within a PSP, a straight-line was fit by ordinary least squares regression to the measurements of each team and the slopes of these lines compared using analysis of covariance (ANCOVAR).

3.4.3 Results

Only results which are relevant to subsequent modelling are presented here. Although the results pertain directly to the PSPs, they are considered representative of the levels of precision and measurement error within the stand experiment plots and the few PSPs with long measurement histories. In some instances, however, the experimental data was inferior due to the use of earlier hypsometers (*e.g.* abney level versus Suunto clinometer) and the often disjoint measurement practices adopted during the life of the trial.

3.4.3.1 Accuracy, bias and precision within a measurement

3.4.3.1.1 Ocularly estimated versus measured variables

The assignment of subjective codes for each categorical variable was imprecise when, only three days later, each plot was remeasured by the same team. On average, over 30% of trees within each PSP were classified differently for defect codes, 14% were allocated different epicormic codes to those previously used, and 13% of trees changed dominance status. The reallocations were unbiased. Each team was least consistent in their assignment of dominance codes in the 5 and 21 year old stands, possibly due to reduced stem visibility resulting from the competing understorey species.

The precision of estimated variables was poor for all teams. Figures 3.2 to 3.4 illustrate the imprecision in estimates of quantitative tree variables within representative PSPs. Ocularly estimated tree heights (Figure 3.2), height to crown break (Figure 3.3) and crown radii (Figure 3.4) were highly imprecise between remeasures on each plot. Biased *cr* estimates were evident in several plots (see, *e.g.* Figure 3.4). Estimated data was clearly unacceptable for growth modelling.

Measured tree data in each plot was generally within the error limits of the instruments (Figures 3.2 and 3.3) indicating acceptable accuracy for each team. The *d* measurements were precise, unbiased and of acceptable accuracy (Figure 3.5).

3.4.3.1.2. Between-team precision

The subjective allocation of tree codes DEF and EPIC varied markedly between measurement teams, and the frequency of these differences between teams increased with increasing stand age. One team consistently down-graded tree bole quality (DEF) codes.

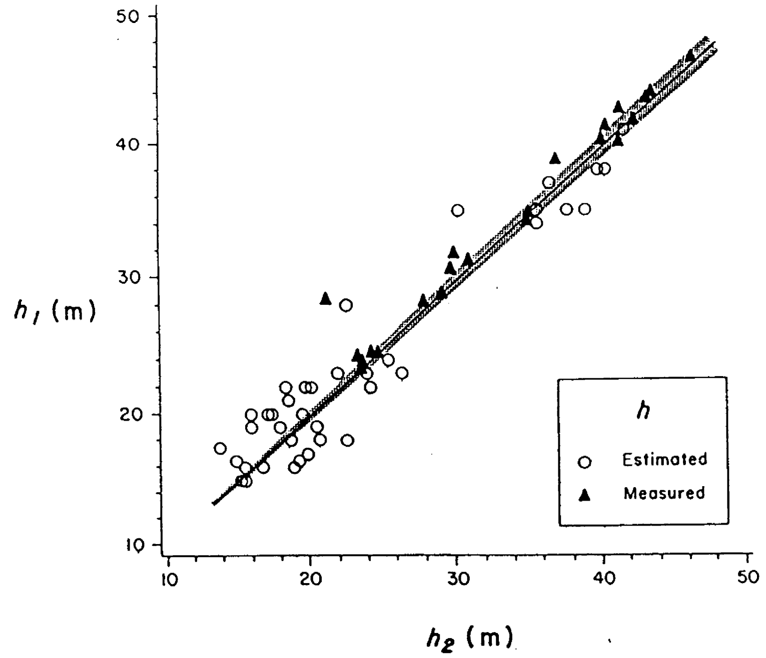

Figure 3.2 Estimated and measured tree heights (*h*) recorded in PSP 971 by the same measurement team on two occasions. The second measurement occurred three days after the first. The shaded zone represents the error limits (±2.5%) specified by the manufacturer of the Suunto clinometer used for heighting the trees.

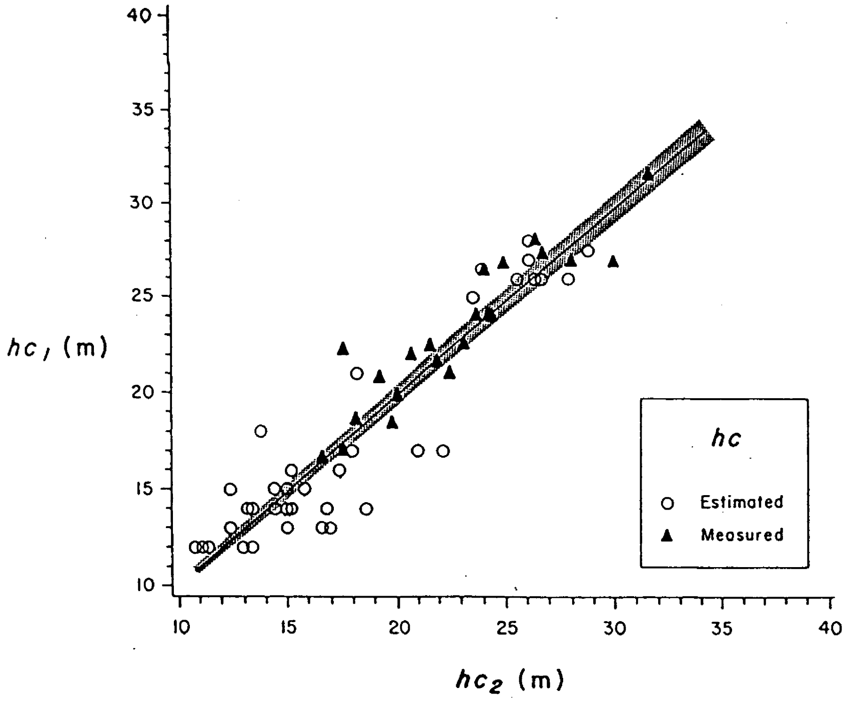

Figure 3.3 Estimated and measured tree crown break heights (*hc*) recorded in PSP 971 by the same measurement team on two occasions. The second measurement occurred three days after the first. The shaded zone represents the error limits (±2.5%) specified by the manufacturer of the Suunto clinometer used for heighting the trees.

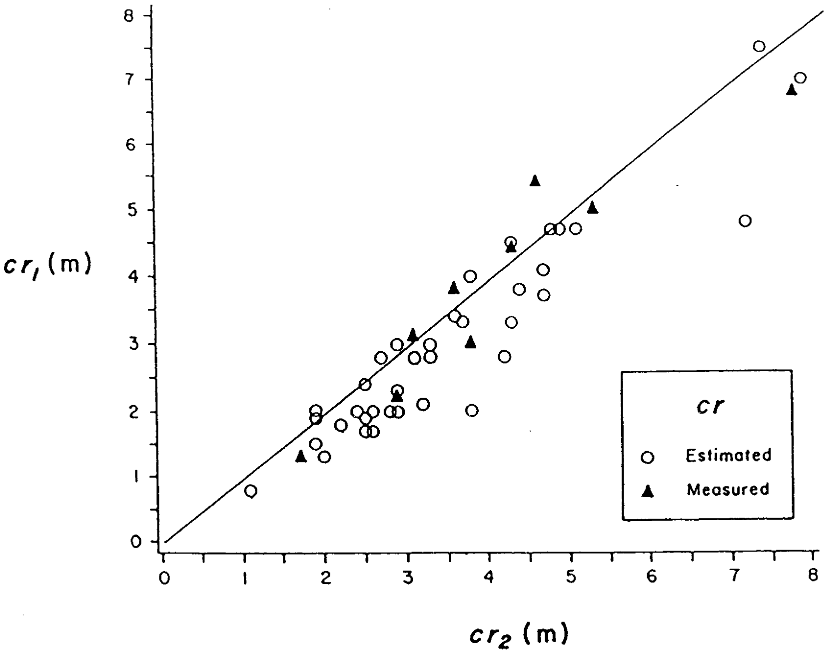

Figure 3.4 Estimated and measured tree crown radii (*cr*) recorded in PSP 985 by the same measurement team on two occasions. The second measurement occurred three days after the first.

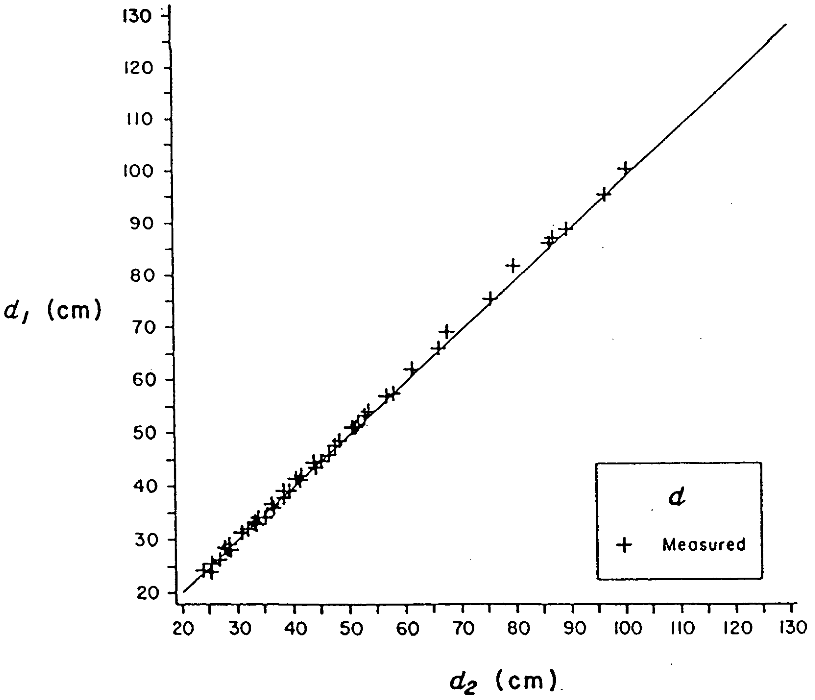

Figure 3.5 Measured tree diameter (*d*) recorded in PSP 985 by the same measurement team on two occasions. The second measurement occurred three days after the first.

The slopes of the lines fitted in each PSP to the estimated data for each team generally differed significantly ($P<0.05$ at least) between at least two of the three teams. In contrast, the slopes of measured *h*, *hc*, and *d* did not differ significantly ($P>0.05$) between the teams, confirming the reliability of these variables over time (because a plot was not necessarily remeasured by the same team that had established it). One assessment team, however, consistently overestimated ($P<0.05$) *bt* for all stand ages and species compared to the other teams (the slopes of the regression lines did not differ between teams but the intercepts did). This suggests a heavy-handed assessor. Serious bias would result from the use of uncorrected underbark *d* estimates if these results were representative of the larger dataset. Similarly, on 3 of the 5 PSPs the *cr* measurements differed significantly between teams.

3.4.3.2 Bias and precision between measurements

Examination of bias and precision between successive measurements (spanning two to five year increment periods) was confounded for some variables by the aforementioned imprecision within a measurement.

3.4.3.2.1 Length of increment period

Precise estimates of the increment of a variable over a measurement period can only be obtained if the remeasurement interval is long enough to ensure the increment substantially exceeds the measurement error associated with the measurement instrument. Remeasurement schedules often adopt a lengthening of measurement interval with increasing tree age to redress this problem (Curtis 1983). This first detailed examination of the increments for each variable in the PSP data indicated that the measurement schedule adopted was adequate for *d* at all ages, but that the measurement errors associated with precise *h*, *hc* and *cr* in closed–canopy stands older than approximately 60 years may not exceed the 5–yearly increment on some sites. For example, the recorded increase in *cr* of trees this age was seldom more than 10 cm per 5 years, yet obtaining this accuracy in dense undergrowth is difficult. The use of such data would lead to excessive variance in regression functions (Vanclay 1992).

3.4.3.2.2. Seasonal pattern of height and diameter growth

Bias in the calculation of tree *h*, *d*, and *cr* increment (and hence stand top height, basal area or volume increment) may occur if the timing of plot remeasurement ignores the seasonal variation in the growth of these variables (Campbell *et al.* 1979). Karri trees, for example, shed their bark annually in late summer–early autumn, potentially introducing a bias in *bt* and *d* measurement. Similarly, seasonal shrinkage and swelling of *d* has been observed on suppressed and subdominant stems (Rayner, unpublished data). Unfortunately, information on the seasonal pattern of growth for each variable was unavailable for karri, with the exception of some monthly dendrometer readings for a group of poles on one site (White 1974).

All PSPs had therefore been scheduled for, and usually achieved, remeasurement in the anniversary week of an exact multiple of years since plot establishment. Increment periods were therefore a multiple of calendar years, not seasonal growth periods. The plots selected for the pilot study had, however, been remeasured 'off–time' from their anniversary dates and it was not possible for any variable to separate seasonal effects from the overall measurement imprecision.

3.4.4 Conclusion

Imprecise measurements for some tree variables can severely limit the selection of a modelling approach. This issue is discussed in Chapter 4, and recommendations for improving the quality of the dataset are offered in Chapter 11.

Based on this preliminary investigation of the PSP data all estimated data were rejected for modelling purposes. For example, the ocularly estimated heights were unacceptable for either stand volume estimation or individual tree growth modelling purposes, requiring tree and hence plot volumes to be computed from tree height/ diameter regression relationships.

Much of the measurement imprecision may be attributed to the practical difficulties associated with measuring tall eucalypts within dense undergrowth. The accuracy of height measurements decreased sharply with increasing tree height, due mainly to the difficulty of sighting a growing 'tip' within large, umbrageous crowns. Similarly, the imprecision in crown radius values for both estimated and measured trees was attributed to the inappropriate assumption of a circular crown shape in other than the sapling and early pole stages, a lack of consistency in the direction of the measurement axis, and for measured trees, difficulties in plumbing the crown edge in dense understorey conditions.

3.5 Data validation

Acceptable measurement errors were defined for each variable/instrument combination based on the results of the pilot study. Computer programs were used to identify measurement inconsistencies, formatting errors or missing data within the entire dataset. Individual tree, and in a few instances whole plot data were rejected if inconsistencies could not be resolved.

The expansion of PSP size with increasing A frequently produced disjoint estimates of stand level variables (stem numbers, basal area, volume) between remeasurements on an individual plot. This was attributed to the highly contagious spatial distribution of the trees observed in the tree position maps for these naturally regenerated stands. In these instances the additional data generated from plot expansion was discarded and the original plot size retained for subsequent measurements.

The final combined dataset, comprising over 114,000 tree records, was output to structured files, from which select segments were extracted for the analyses reported hereafter. Stand-level variables were then computed.

3.6 Derivation of tree and stand-level variables

Stand volume (*V*), basal area (*B*) and stocking density (*N* – live stems per hectare) were computed for each plot at each remeasurement. *V* denotes total stem volume (to 5 cm small end diameter underbark, SEDUB) of all stems of *d* greater than 10 cm but *B* and *N* relate to all the stems within a plot.

Plot volume was estimated from those sample trees (less than 30% of the total) which had been measured for both *h* and *d*. The following logistic relationship between *h* and *d* was the most appropriate (Chapter 8) of a range of formulations tested to estimate the *h* of all other trees on the plot from their recorded *d*s:

$$h = \alpha \{[1 + \exp(\beta - \gamma d)]\}^{-1} \qquad (3.1)$$

where h denotes tree total height (m)
d denotes tree diameter (cm)
α, β, and γ are parameters estimated for each plot and measurement

A local karri tree-volume table (WAFD 1983) was then applied to compute the volume of each tree and hence plot and stand volume. The application of (3.1) reduces inter-tree variability in height compared with the true stand conditions, but this is likely to have minimal effect on the accuracy and precision of stand volume estimates (West 1982).

Separate tree-volume tables were unavailable for regrowth stems of non-karri species. As well, insufficient trees of these other species had been heighted in the mixed stands to enable species-specific regressions to be developed. The karri tree-volume table was therefore applied to all species, with the following correction factors developed for marri, jarrah and blackbutt species:

marri stem volume = karri stem volume x 0.771 ($n = 25, \sigma = 0.002, R^2 = 0.99$)
jarrah or blackbutt volume = karri stem volume x 0.945 ($n = 26, \sigma = 0.007, R^2 = 0.98$)

These regressions were derived from total stem volume (to 5 cm SEDUB) measurements on sample trees adjacent to select PSPs. The trees were carefully selected to cover the site and size (*d, h*) range of the PSP data.

Gross yield generally represents the total volume of stem wood produced on a site (including mortality), but in this instance limited cumulative mortality data were available for each stand. Gross growth information can, however, be obtained from the periodic remeasurement of permanent plots (Curtis 1967a). Gross yield was therefore defined as the total of standing live plus dead trees within the stand at a measurement. Periodic net increment (or growth) was computed as the difference in yield at two points in time, while periodic gross increment was the sum of periodic net increment plus periodic mortality (Daniel *et al.* 1979, Curtis 1983, Flewelling and Thomas 1984). Periodic Annual Increment (PAI) and Mean Annual Increment (MAI to current age) were computed for the estimates of gross and net V and B. The percentage annual mortality (AM) of stems within a stand was calculated as the number of stems dying between remeasurements, expressed as a percentage of the number alive at the commencement of each measurement period.

Because of the short remeasurement periods (1 to 5 years) for most plots, periodic increments were computed as an approximation to instantaneous growth rates for both tree and stand-level variables (Hegyi 1969). Adjustment of measurements for seasonal fluctuations was not undertaken for any variable in the dataset. Instead, the following expression was derived to compute the increment period (I_y in years) between successive measurements:

$$I_y = \{\, [31 - (ND_i)] + [(12 - (NM_i)) \times 31] + [((NY_{i+1} - NY_i)-1) \times 365] + [(NM_{i+1}-1) \times 31] + [(ND_{i+1})] \,\} / 365 \qquad (3.2)$$

where I_y denotes the total number of years between successive measurements

ND_i denotes the day number of the initial measurement

NM_i denotes the month number of the initial measurement

NY_i denotes the year number of the initial measurement

NY_{i+1} denotes the year number of the subsequent measurement

NM_{i+1} denotes the month number of the subsequent measurement

ND_{i+1} denotes the day number of the subsequent measurement

3.7 Selection of data for model validation

In studies of this nature it is common practice to reserve a random or systematic selection of up to 25% of the data from model development, to provide an independent dataset for validation (West 1981a, Shifley 1987, Meldahl *et al.* 1988). Given the limited quantity of data, however, it was considered preferable to exclude only 15% of plots from model building. To minimize the risk of randomly excluding stand treatment extremes from the parametrization process, the validation set was randomly selected from the dataset stratified by age, stand top height and stand density classes (Table 3.4).

The validation data proved useful for testing model components, but for reasons discussed later, was of restricted value for whole-model validation.

Table 3.4 Minimum–mean–maximum values of stand variables by species composition in the validation data. Plots were randomly selected from a combined PSP and stand treatment dataset.

Species composition	Number of plots	Age (Yrs)	Basal area[a] (m^2 ha^{-1})	Stocking[a] (stems ha^{-1})x10	Mean height of dominants (m)
E.diversicolor	21	4–26–102	3–24–50	6–53–130	8–37–52
E.diversicolor / *E.calophylla*	8	12–41–66	8–37–49	12–48–85	14–38–47
E.diversicolor / other[b]	3	9–31–53	7–27–42	40–54–64	13–32–42

[a] Live stems ≥10 cm diameter at breast height.

[b] Other species which may occur in mixture with karri include *E.marginata* Donn ex Smith, *E.jacksonii* Maiden, *E.brevistylis* Brooker, *E.guilfoylei* Maiden, *E.patens* Benth., and/or *E.megacarpa* F.Muell.

CHAPTER 4 EVALUATION OF ALTERNATIVE MODELLING APPROACHES

4.1 Introduction

An essential stage in systems analysis is the evaluation of alternative modelling approaches (Jeffers 1978). Modelling methodologies primarily differ in both their scale of resolution and their mathematical representation of the major growth processes. The evaluation process aims to define a modelling approach which successfully combines the biological characteristics of the species with growth modelling theory, to formulate a model which, when parametrized with the available data, can provide output acceptable for defined applications. In this chapter a suitable modelling approach for the karri, which is consistent with the information objectives for the model and the data available for its development, is defined.

4.2 Modelling objectives for a karri growth model

Model objectives and data availability are the major determinants of a modelling approach (Charles–Edwards 1988). The modelling objective was to mathematically simulate the growth and consequent yield of even–aged regrowth karri stands, subjected to varied stand treatment regimes and growing in the range of sites within the karri zone (section 1.1).

An empirical model was required to form the nucleus of a management information system for the regrowth estate. Yield estimates provided from a predictive model would be used in conjunction with an existing Geographic Information System (Pearce 1988) and future inventory systems to generate input to a forest–level Decision Support System (*e.g.* DCE 1991). Such a Decision Support System would incorporate traditional simulation and mathematical programming techniques when evaluating alternative strategies for the multiple–use regrowth forests. A karri growth model was therefore required to support three major applications:

1. Inventory update. Estimates of growth and mortality in a forest stand for the usually short period between the time a stand was last inventoried and the present were required to update stand volume and other information without remeasuring the stand. Such short–term projection for the preparation of logging plans requires precise estimates of stand volumes by product size–class distributions (Newberry and Stage 1988). Although an inventory system has not yet been defined for the regrowth resource, this application generally restricts the selection of variables in a model to those which are feasible to routinely measure in inventory assessment (Hegyi 1981).

2. Harvest scheduling. The model was required to generate stand volumes through time for a range of management regimes, so that harvest levels can be estimated using heuristic (trial and error) simulation or mathematical programming techniques. Stand level detail is often a sufficient level of resolution for this purpose, and the precision of

stand volume estimates can often be less for long-term simulations than for short-term inventory update. Much less detail is required about individual trees in the stand than for other model applications (Stage 1973).

3. Silvicultural treatment simulation. Estimation of the future yields of a given stand for current and future silvicultural practices is necessary for input to harvest scheduling applications. Considerable detail of the effects on individual trees in the stand of such treatments as stand density manipulation (type, intensity, and timing of thinning, varied initial espacement), site improvement (type and timing of fertilizer or mycorrhizae application), site deterioration (soil compaction) or the genetic improvement of planted stock, is commonly required.

Comparisons of the economics of silvicultural alternatives is an important component in a Decision Support System (Brumelle *et al.* 1991). Estimates of total tree volume should therefore be capable of being partitioned into size and quality (*i.e.* product) classes.

The level of model resolution required to provide the necessary output differs between applications. While whole stand models are sufficient for harvest scheduling, inventory update requires some detail in tree size-classes. Stand treatment simulation, however, requires the highest resolution model capable of modelling between-treatment variation in bole, branch and crown development of individual trees (Stage 1973).

4.3 Limitations of the karri data

In principle, a growth model should be based on data representing all combinations of age, site and stand treatment for which estimates may be required (Curtis 1972). This is rarely possible when developing models for managed stands based on historical bioassay data (Kimmins *et al.* 1990) collected from natural stands. Long rotation lengths, *ad-hoc* and opportunistic application of a narrow density range in stand treatments, and biased site representation due to the concentration of earlier harvesting on better quality sites are typical characteristics of such datasets.

The karri data (section 3.2) were no exception. The majority of the PSPs were located in 'fully-stocked' stands expressing density-dependent mortality. The range of site qualities available for sampling were an artifact of historical cutting practices, and the absence of a site quality stratification to guide plot establishment meant that representation of sites was unlikely to be balanced across all age classes. The absence of site stratification to organize the plots into a homological growth series presented additional difficulties when extrapolating the limited stand treatment data.

The few remeasurements available for each plot meant that parameter estimation based upon such short-term increment periods might be seriously biased by unrepresentative short-term climatic fluctuations (Curtis 1972). Were a growth model not urgently required, the present karri dataset might be considered more a validation dataset than a parametrization set. The choice of an appropriate modelling approach was further constrained by the poor quality of some tree variables (*e.g.* lack of precision in crown and height variables).

This dataset is typical of those available in many countries during the early stages of converting old–growth forests to naturally regenerated stands, and the development of managed stand yield tables from such data has traditionally been approached by the development and adjustment of 'normal' forest yield tables (Vuokila 1966). Gross yield was commonly estimated from normal yield tables plus mortality data (Lindsay 1939, Staebler 1955) or from stem analyses or increment borings on temporary plots (Dahms 1964, Curtis 1967a) and used as the basis for estimates of managed stand yields (Staebler 1960). Gross yield of future managed stands was argued to be about the same as that from well–stocked natural stands, and the extension to managed stands was achieved by presuming that 'reasonable thinning' will only redistribute a constant gross increment (Curtis 1972).

The restricted generality of this stand–level approach to 'reasonable' thinning regimes was unacceptable in this study, as conditions of low density may need to be simulated in some planted stands. The lack of stand treatment data militated against the direct empirical extension of this approach in whole–stand models. Whole–stand modelling approaches provide growth or yield estimates for the whole stand (or some merchantable portion) as a function of stand level variables such as age, density, and site index (*e.g.* Schumacher and Coile 1960, Clutter 1963, Sullivan and Clutter 1972, Smith 1986). These empirical regression approaches require a comprehensive dataset in which all current and future stand treatments are represented, as they will only predict well within the ranges of the observed data. An alternative whole–stand approach involves specifying a theoretical growth–rate model and solving the resulting differential equations for stand yield estimates (Moser and Hall 1969, Pienaar and Turnbull 1973). Leary (1970) and Moser (1972) extended this methodology to include sets of simultaneous differential equations representing different stand components. Again, the present karri dataset does not cover a sufficient range in stand treatments to enable the direct application of these techniques.

A number of modelling approaches have been developed which consider the stand in terms of the distribution of the number of trees per unit area by size class. The most common stand models in this general category are those in which the distribution of diameters in a stand has been described by a probability density function (*e.g.* Beta (Bennett and Clutter 1968, Burkhart and Strub 1974), Weibull (Smalley and Bailey 1974, Dell *et al.* 1979, Bailey *et al.* 1985), and Johnson's S_b (Hafley and Schreuder 1977). Stand–level attributes such as age, site index, and stand density are used to define the density function parameters. The major drawback with applying this methodology to karri was the lack of suitable data to calibrate post–thinning diameter distributions, and the inherent difficulties of extending this methodology to mixed–species stands.

The central issue with the karri dataset was to identify a modelling approach which could sensibly model the effect of stand density reduction (thinning) when parametrized with data from unthinned, fully-stocked stands. Both the level of resolution required in model output and the nature of the available data indicated that an empirical, individual-tree level model was a logical choice of modelling approach. Such models simulate the effect of stand density changes through a 'competition index', derived from stand or individual tree variables (Munro 1974). The incorporation of a suitable competition index in such a model was considered a possible means of simulating stand treatments not represented in the karri dataset, while providing a suitable framework for incorporating other species as further data accrue. Approaches to modelling inter-tree competition have differed between distance-dependent and distance-independent models.

4.4 Modelling the growth of individual trees in distance-dependent formulations

Distance-dependent modelling approaches have been reviewed by Larocque and Marshall (1988), West (1988a), and Vanclay (1992). Most distance-dependent models follow the basic methodologies developed by either Newnham (1964) or Mitchell (1967). The growth rate of an individual tree is modelled as a function of its size, the site quality, and a measure of the competitive status of the subject tree. Either tree diameter (Newnham 1964) or height increment (Mitchell 1967, Ek and Monserud 1974) has been used as the primary state variable.

The detailed records of stand structure and development which distance-dependent models provide is well suited to the simulation of silvicultural treatments involving spatial and competitive influences (*e.g.* thinning). Because estimates of response are assumed to follow directly from the competition relationships included in the model (Daniels and Burkhart 1988), distance-dependent models have been used to examine hypotheses about tree and stand growth under conditions for which data do not presently exist (*e.g.* Monserud 1975, Daniels and Burkhart 1975, Mitchell 1978).

These models are, however, inefficient for inventory update purposes, as individual tree positions are seldom recorded in routine inventory, and they generally incorporate a higher level of model resolution than is necessary or efficient for yield forecasting (particularly if numerous alternatives are explored in search of an optimum solution) (Munro 1974). As well, empirical studies suggest that the competition indices incorporated in many of these models seldom provide better estimates of increment than simple measures of stand basal area (see, *e.g.* Opie 1968, Johnson 1973, Daniels 1976, Alemdag 1978, Martin and Ek 1984, Barclay and Layton 1990).

An alternative approach is to formulate a growth model, or series of models, which can operate at any of several levels of resolution, thereby providing whole stand, stand-class or individual tree predictions according to the data available for initializing a simulation and the user requirements. Such a structurally compatible framework, with the highest level of resolution as a distance–dependent model, was proposed by Daniels and Burkhart (1988). Theoretically, such a system could be operated as a distance–dependent model when tree position data were available (*e.g.* simulation of silvicultural trials) or as a distance–independent model when position data were unavailable (*e.g.* inventory update).

The key to this approach is the derivation of an appropriate competition index which mimics the competitive influences on individual trees. Three broad categories of competition indices may be recognized, *viz.* tree size–distance approaches, the competitive influence zone, and area potentially available methods.

4.4.1 Tree size–distance indices

Size–distance approaches construct an index of competition based on the diameters of and distances between each subject tree and its potential competitors (*e.g.* Lemmon and Schumacher 1962, Steneker and Jarvis 1963, Hegyi 1974, Ellis 1979). West (1988b) examined the efficacy of a number of these indices for predicting diameter growth of individual trees in thinned and unthinned 73 year old *E.obliqua* forest in Victoria. He found the variation in tree growth rates were satisfactorily explained (up to 30%) by the distances of up to the 5 nearest neighbours, suggesting that it is the proximity of competitor trees, rather than their size, which was a major determinant of the diameter growth rate of the subject tree in these regrowth stands. Unfortunately, these indices cannot be readily interpreted at a stand level and cannot be 'collapsed' to a stand variable analogue, necessitating that inter–tree distances be recorded in inventory assessment. Moreover, in a later review of the effects of inter–tree competitive processes on stand structure in forest monoculture, West (1988a) proposed that light is the major competitive process operating in monocultures, suggesting that competition indices based on the competitive influence zone of tree crowns might be more appropriate when modelling monocultures.

4.4.2 Competition indices based on 'zones of influence'

This category of competition index is based on the overlap of hypothetical 'zones of influence' of competing trees (*e.g.* Opie 1968, Bella 1971, Arney 1973). These indices are commonly derived from a circular zone of crown influence from crown diameter measurements (*e.g.* Newnham 1968, Gerrard 1969), and have seldom explained more than 20% of the observed variation in tree growth rates in empirical studies with conifers and temperate hardwood species (Daniels 1976, Noone and Bell 1980, Martin and Ek 1984). The assumption of regular crown shape for all tree ages is unrealistic for eucalypts (Jacobs 1955) and there is some evidence to suggest that effective leaf area (*cf.* crown area, which expands slowly) is the major variable determining future tree increment (Webb 1966, Pook 1985, West 1987). Dramatic fluctuations in the effective leaf area of eucalypts is possible without major alteration to crown size (Pook 1985, 1986), particularly in older trees where epicormic development can occur following heavy thinning or fire events. This approach to quantifying the level of competition between trees was therefore abandoned, as detailed crown measurements were unlikely to be recorded for every tree at inventory, and most importantly, the available karri *cr* and *hc* measurements were imprecise.

4.4.3 Area potentially available

The third category of indices, those based on the derivation of an area about each tree to represent the growing space available to it, offered the most promise for developing a compatible model. The most common approach has been to derive an area potentially available (APA) to each subject tree by tessellating the stand area into Voroni polygons (*e.g.* Moore *et al.* 1973, Adlard 1974). The polygons may be variously weighted according to tree size (*e.g.* Pelz 1978, Nance *et al.* 1988). The theoretically compatible distance–dependent / distance–independent model proposed by Daniels and Burkhart (1988) used APA at the distance–dependent level which was replaced by the inverse of stocking at the distance–independent level. Daniels *et al.* (1986) had earlier concluded from a detailed empirical comparison of competition indices that APA would be an effective index for growth prediction models when other tree and stand attributes are included. Similarly, Tomé and Burkhart (1989) demonstrated the superiority of APA indices when explaining variation in tree growth in *E.globulus* espacement trials in Portugal, and concluded the index should be useful in the simulation of thinnings and the study of the impact of mortality.

These findings suggested that using APA as a competition index might provide a practical approach for the extrapolation of stand treatments not represented in the karri dataset. An empirical evaluation was undertaken (data not shown) of the utility of APA for predicting individual tree diameter growth in thinned and unthinned karri stands aged 12 and 50 years. The unconstrained and constrained APA indices derived by Nance *et al.* (1988) were calculated for each tree in each of five plots sampling the density range in both the Warren and Treen thinning trials. A constraining function based on the maximum crown radius observed for a tree of similar diameter as the subject tree was used to limit the maximum expansion of a tree's polygon in any one direction. Programs developed by Nance *et al.* (1988) were used to examine the contribution of the APA indices with other stand variables to future diameter growth over 1–6 year periods following thinning. The area of each polygon (either constrained or unconstrained) was used as an independent variable — either alone or in combination with other measured or derived variables — to predict the future diameter growth of individual trees. The squared correlation coefficients between the unconstrained APA indice and future diameter increment for the 1,312 sample trees were generally below 0.16 for all stand densities, while the correlation coefficients of the constrained APA approached 0.4 but exhibited serious multicollinearity with tree diameter and stand basal area variables due to the use of basal area in the weighting process. The poor performance of the constrained APA index may be partly due to the use of imprecise *cr* measurements when parametrizing the constraining function, and further investigation of this approach may be warranted when precise data are available. The failure of APA indices to satisfactorily model individual tree growth in these stands supports the proposition by West (1988a) that competition between trees in these monocultures occurs mainly for light rather than other environmental resources.

The APA indices were of only limited practical value for predicting future tree diameter growth in thinned and unthinned stands. The development of a compatible distance–dependent / distance–independent model system was therefore abandoned in favour of a solely distance–independent approach.

4.5 Modelling the growth of individual trees in distance–independent formulations

Single–tree, distance–independent models simulate tree growth individually, usually as a function of present size and stand–level attributes (Clutter *et al.* 1983). No account is taken of which trees in a stand are the competitors with any particular subject tree. Although methodologies followed in their construction vary markedly, two main approaches may be recognized based on whether individual tree growth is modelled directly or indirectly (West 1988a).

4.5.1 Direct modelling of individual tree growth

The first approach predicts growth of individual trees directly as a function of tree and stand variables. Individual tree growth is frequently defined as the product of potential growth times a modifier function (*e.g.* Daniels and Burkhart 1975, Leary 1979). The maximum potential diameter increment may be based on the site quality, tree age and the quantity of resources available for growth and/or growth in the absence of competition. Newnham (1964) assumed that the potential diameter increment of forest trees growing free of competition was equivalent to an open–grown tree of the same size. Concern that open–grown trees may exhibit a different distribution of increment between the bole and branches prompted Hahn and Leary (1979) to use the 95th percentile of observed growth to approximate the competition–free growth. Vanclay (1983), however, contends that this approach will bias estimates of diameter increment toward positively biased measurement errors and the influence of exceptionally favourable growing seasons. He argued that it is more appropriate to use increments from trees subjectively determined as free of competition (Vanclay 1988a). The karri tree–position maps suggested that few PSPs had gaps within which individual trees could be reasonably assumed to be growing free of competition. The use of open–grown trees as potential increment standards was impractical as few such karri trees had been recorded across the site and age range necessary for this approach.

The modifier function, which serves to adjust the potential growth to correspond to the individuals ability to use site resources, may be a function of a tree's individual size or relative size and a measure of competition from neighbours. Crown variables are commonly used as a measure of relative size (*e.g.* Monserud 1975, Hahn and Leary 1979), but recent attempts to calibrate a model of this type using eucalypt data suggest that precise data representing a range of growing conditions is necessary to develop a competition modifier of sufficient biological detail to remain applicable over a wide range of stand conditions (Swain 1985, Goodwin 1988). The lack of such data for karri militated against this approach.

Other approaches to modelling the growth of individual trees have involved regressing diameter increment directly against tree and stand variables (Stage 1973, Incoll 1974) or in a two-stage regression in which the individual tree increment/tree size relationship is determined for each PSP in the first stage, and the parameters of these equations are modelled as a function of stand variables in the second stage (West 1981a). These strictly empirical approaches were unlikely to adequately simulate the growth of individual trees after thinning given the limited thinning data available for parametrization.

4.5.2 Indirect modelling of individual tree growth

An alternative to modelling individual tree growth directly is to model stand increment (basal area) and then distribute that stand increment among the individual trees in the stand. Various approaches have been used to apportion the stand increment among individual trees, including the direct apportionment according to tree size (*e.g.* Campbell *et al.* 1979, Woollons and Hayward 1985) or by assuming an appropriate mathematical function can be used to represent the frequency distribution of the diameters of the trees of a stand. The model then predicts from stand variables the values for the parameters of the function (*e.g.* Schreuder *et al.* 1979, Amateis *et al.* 1986, Borders *et al.* 1987). West (1988a) reasoned that because the shape of the frequency distribution of tree diameters in a monoculture is very complex and changes markedly during the life of the stand (Gates *et al.* 1983, Cannell *et al.* 1984, Hara 1984) no single mathematical function is likely to adequately describe the distribution. He contends that those models which do not involve frequency distributions directly may more appropriately express the differential effects of competition which apply in different tree size classes (Ford and Diggle 1981, Cannell *et al.* 1984).

The prediction of stand increment and the allocation of that increment among trees has proved a robust approach for modelling monospecific stands (Vanclay 1988a). This empirical approach to individual tree model development was employed in the present work.

4.6 A modelling approach for karri

4.6.1 The approach

Modelling stand growth and then apportioning that growth among trees in the stand is a logical extension to the traditional technique of developing managed stand yield tables from data representing fully-stocked, unmanaged stands (section 2.3.1). Stand gross basal area increment, I_{Bg} (*i.e.* the increment on both surviving and dying trees but excluding ingrowth) could be estimated from the few periodic remeasures of the PSPs and stand treatment trials and used as the basis for estimates of managed stand yields by assuming that gross yields of future managed stands should be about the same as that from well-stocked natural stands.

The estimation of I_{Bg} was used by Opie (1972) as the basis of STANDSIM (section 2.3.1.4) for even-aged mountain ash forests in Victoria. This modelling approach was most suited to the development of a modular, individual-tree level model for regrowth karri. The approach adopted in the present work was not to calibrate STANDSIM but rather to adapt and where appropriate enhance the model design within the limitations of the available data.

The design and parametrization of component models is described in Chapters 6 to 8. The limited data available for parametrization emphasized the need for biological realism when formulating model components. As far as possible mathematical formulations which were consistent with known biological behaviour of the species were favoured over simple mathematical goodness-of-fit criteria. Thus, although the emphasis in statistical parameter estimation was to select model forms which adequately describe the functional relationship between variables, a primary consideration in growth model formulation was the biological sensibility of the equation (Leary 1970, Leech 1978).

4.6.2 Assumptions of the approach

This modelling approach assumes the following:

(i). That the PSPs provide an adequate representation of fully-stocked stand conditions across the range of karri sites. This assumption is examined in Chapter 6.

(ii). That an adequate index of site productivity can be developed which appropriately captures the differences in stand dynamics between sites (examined in Chapter 6).

(iii). That the stand dynamics of even-aged stands can be adequately modelled if the identity of non-karri species in the mixed-species stands is ignored, thereby grouping all species as 'karri'.

(iv). That gross yield – density relationships are the same in wild and managed stands. Data to test this hypothesis would take many years to collect, but experience with European species suggests it is a reasonable working hypothesis (see, *e.g.* Davis and Johnson 1987).

(v). That thinning response can be generalized for all stand age/site combinations. This assumption is examined in Chapters 7 and 8.

4.7 Constraints on component model formulations

The nature, quality and quantity of the karri data restricted the design of model components and hence the generality of an individual–tree model. The empirical nature of the model restricts generality to those species and stand conditions represented in the present karri dataset. Species differences were ignored due to the very restricted representation of measured non–karri species (section 3.2.1.1). Similarly, only thinning response was modelled due to the limited, site specific data for other stand treatments (fertilizer, coppice control, or soil compaction).

Simulation of the effect of thinning treatments on tree quality factors (knottiness, length of clear grain, kino, gum veins, occurrence of decay or decomposition) is essential for the proper evaluation of thinning regimes. Unfortunately the subjective defect codes used to describe tree categories were inappropriate for product modelling unless visible defects could be correlated with internal defect and hence sawn recovery or pulp value. Waugh and Rozsa (1991) have demonstrated some correlations for ash eucalypts. Limited data is available for regrowth karri (Brennan *et al.* 1991), and the preliminary work suggests that total tree description, similar to that described by Strelein and Boardman (1992) for jarrah, is necessary for proper utilization modelling.

CHAPTER 5 STATISTICAL METHODS

5.1 Introduction

The statistical estimation of the parameters of model equations is an essential step in the model building process. This chapter summarizes those statistical methods commonly used in this study for parametrization and model testing. Variations to the following statistical procedures are discussed when they occur in relevant chapters.

5.2 Equation systems in tree and stand modelling

Growth and yield models may be considered as a system or series of related equations (or models) describing such component processes as tree or stand basal area growth, mortality, and ingrowth (Furnival and Wilson 1971). These systems of related equations are generally either simultaneous or recursive, and parameter estimation procedures vary with these categories.

Models formulated as a simultaneous system of equations generally require such full information methods as Three–Stage Least Squares or Maximum Likelihood for simultaneous estimation of the parameters (Wonnacott and Wonnacott 1979). Alternatively, Maximum Likelihood, Generalized Least Squares and Two–Stage Least Squares procedures may be used to estimate parameters for an individual equation (one at a time) within a simultaneous system (Kmenta 1971). The advantage of fitting a systems formulation for a growth model is that a variance–covariance matrix is produced which can be used to estimate the standard errors of predicted growth and yield (Furnival and Wilson 1971). Few models, however, have been based solely on simultaneous systems of equations for components of stand or tree growth (see, *e.g.* Moser 1972).

Most growth and yield models are formulated as recursive systems of equations. These systems possess sequential relationships in which solutions of individual equations are input as independent variables into subsequent equations. Recursive systems, such as those developed by Ek (1974) to describe the ingrowth, mortality and survivor growth for uneven–aged hardwood stands in north Wisconsin, have an important advantage of facilitating the application of mathematical programming techniques (Adams and Ek 1974). As well, recursive systems are generally easier to parametrize than simultaneous systems because ordinary least squares (OLS) regression can be used to fit each equation independently, provided there is no cross–equation correlation between the error components of the various equations in the system (Borders 1989). Unfortunately, this assumption is frequently violated because the equations in the model contain dependent variables which are correlated, or parameters in different equations may be shared or functionally related. Borders (1989) recommended the application of a two–stage instrumental variable technique (not the traditional two–stage least squares) and the Generalized Least Squares procedure for such circumstances, although hypothesis testing following the application of such sophisticated techniques to typical forestry datasets may still be unreliable (West *et al.* 1984), and any gains over the use of ordinary least squares regression may be marginal (Gregoire 1987).

In this study a recursive system of related equations (models) was developed. Ordinary least squares (OLS) regression was used for parameter estimation for most of the linear and nonlinear equations. Each sequential equation was formulated and parametrized independently. Such a 'functional' (Monserud 1975) approach to model building has been widely adopted when constructing individual-tree level models (Alder 1977, Opie 1972, Stage 1973, Campbell *et al.* 1979).

5.3 Application of OLS for parameter estimation

5.3.1 The OLS model

A linear regression model (5.1) and a nonlinear regression model (5.2) may be represented as

$$Y_i = \alpha + \beta X_i + \varepsilon_i \qquad (5.1)$$

$$Y_i = \alpha X_i^{\theta} + \varepsilon_i \qquad (5.2)$$

where Y_i denotes the dependent or response variable

X_i denotes the independent or regressor variable

$i = 1, 2, 3 \ldots. n$

α, β, θ denote unknown parameters believed to be constant for a given model or data combination

ε_i denotes unobservable random error, assumed to be independent and identically distributed normal (iidN) random variables with mean zero and finite variance σ^2

The basis for estimating the unknown parameters in most models developed in this thesis (whether linear or nonlinear) was the criterion of least squares (LS). The LS estimator of $\hat{\beta}$ in (5.1) is obtained by minimizing the sum of squares of deviations of the observed Y_i from the assumed true model. Where the data and model conform to the assumptions underlying the application of OLS, the LS estimators $\hat{\alpha}$ and $\hat{\beta}$ of model (5.1) will be unbiased, efficient (*i.e.* minimum variance estimator), consistent and sufficient (Draper and Smith 1981). The OLS estimators will also provide predictors which are best (*i.e.* minimum variance) linear unbiased predictors (Theil 1971).

For nonlinear model (5.2) with iidN errors the LS estimators cannot be determined analytically and must therefore be obtained by an iterative procedure. Unbiased, efficient, consistent and sufficient estimators are only obtained asymptotically *i.e.* only for large sample sizes do the properties of $\hat{\theta}$ approach those of $\hat{\beta}$. Under these asymptotic conditions the OLS estimators of a nonlinear model are also identical to the maximum likelihood estimators (Ratkowsky 1983).

Thus, unlike a LS estimator of a parameter in a linear model, the properties of a LS estimator of a parameter in a nonlinear model are poorly defined for small (finite) sample sizes (Kendall and Stuart 1967). Consequently, the properties of predictors based on small-sample OLS estimates of nonlinear models are also poorly defined (Leech 1978).

Because the distributional properties of the parameter estimates usually have no theoretical basis for small sample sizes, and because no guidelines exist as to how large the sample size must be before asymptotic properties are approached (Ratkowsky 1983), approximations that make use of the theories and methods of linear least squares must be employed when making inferences about nonlinear parameter estimates (Gertner 1984).

The assumptions underlying the use of OLS and subsequent hypothesis testing and prediction for linear models are well documented (see, *e.g.* Draper and Smith 1981, Neter *et al.* 1985). The following sections detail the approaches used for model parametrization and testing in the present study, where the theories and methods of linear least squares were used as a basis for extension to nonlinear systems. Where theory was absent in some nonlinear applications the philosophy pursued was to endeavour to maintain statistical rigour whilst adopting a practical approach to model building.

5.3.2 Assumptions underlying the use of the least squares criterion

The use of the least squares criterion in the fitting of models assumes a number of specification conditions are met. The application of OLS estimation methods for a model that is mis-specified in terms of these assumptions may produce biased, inefficient and/or inconsistent parameter estimators depending on the form of the model mis-specification (Leech 1978). Tests of the following assumptions were performed for each model and corrective measures taken if any of the assumptions were found to be violated.

5.3.2.1 Model specification error

Application of OLS assumes the functional form of the model and the 'appropriate' independent variables are correctly specified *i.e.* the form of the model is consistent with known information concerning the relationships between the dependent variable and the independent variables (Johnston 1972). Structural mis-specification of a model can arise from the use of an inappropriate form for a dependent variable, the omission of important independent variables or the inclusion of irrelevant independent variables. Such mis-specification can result in unbiased but inefficient parameter estimators if there are irrelevant independent variables, or biased and inefficient parameter estimators if there are too few independent variables (Wonnacott and Wonnacott 1979). As well, the presence of irrelevant independent variables can result in a model which is an erratic predictor, especially when used outside the range of the original data (Leech 1978).

Detection of model mis–specification often relies upon the diagnostics for other OLS assumptions. For example, high multicollinearity between independent variables may imply the model contains irrelevant independent variables.

The following steps were performed for each model. Independent variables were selected and the parameters of the model identified using inferences drawn from biological growth theory for karri and other eucalypts, and hypotheses based on mathematical formulations which had been successful in comparable modelling efforts with other similar datasets. Graphs of the dependent variable against each candidate independent variable were inspected to assist model definition and to detect the presence of outliers before fitting the regression. Diagnostic statistics were inspected and remedial measures taken if required. The model was then refit and residuals re–examined until an acceptable model, consistent with all the OLS assumptions, was found. As far as practicable, inclusion or exclusion of independent variables and selection of final model form was based on the predictive capabilities of the resulting models, determined using tests described below in section 5.5 and graphs of the fitted model overlain by the raw data.

5.3.2.2 Homogeneous error variance

The variance of the error or residual term (ε_i) is assumed to be homogeneous and independent of the independent variables (Wonnacott and Wonnacott 1979). Application of OLS methods in the presence of variance heterogeneity can result in (1) parameter estimators that do not have minimum variance in the class of linear, unbiased estimators, and (2) biased estimators of the variances of the estimated parameters (Gregoire and Dyer 1989). Both conditions can distort the actual significance levels of hypothesis tests relating to the model parameters. Variance heterogeneity may also produce parameter estimates with signs that are counterintuitive (Box and Hill 1974).

Detection of variance heterogeneity for each model involved examination of scatterplots of the residuals (ε_i) by each of the fitted values (Neter *et al.* 1985). Suspect or 'borderline' heteroscedastic data were partitioned into at least six equal–sized intervals of the independent variable and subjected to Bartlett's (1937) test. Note, however, that Bartlett's (1937) and all similar tests are sensitive to non–normality in the underlying distribution (Leech 1978).

One of three approaches is commonly adopted to correct for heterogeneity in a linear regression model where observations are uncorrected (Gregoire and Dyer 1989). These approaches involve either (1) transforming the dependent variable to stabilize the variance (Neter *et al.* 1985) (2) estimating the heterogeneity in the fitting process by modelling the variance, or (3) using variance estimators that are robust to the error variance heterogeneity. The first option can be difficult in complex nonlinear formulations, and where logarithmic transformations are used, requires bias corrections when back-transforming the fitted regression (Flewelling and Pienaar 1981, Spriegel 1983). The third option utilizes such methods as jackknife estimation to produce a robust estimator of the variance of $\hat{\beta}$ (Gregoire and Dyer 1989).

The second option, to model the error variance heterogeneity in the fitting process, was adopted in this study. When heteroscedasticity was present, functions were used to relate the error variance to the fitted values and the other variables used in the regression. A final parametrization was then obtained using an iteratively reweighted least squares procedure in which individual weights where calculated as the inverse of the appropriate error variance function. The weighted residuals were then examined for homoscedasticity.

Selection of an appropriate error variance function depended on the nature of the model and the range in the independent variables being fitted. Where the data observations were evenly distributed across the range of the independent variables, the inverses of the empirical residual variance within each of at least 10 equal-sized intervals for the independent variable were used as weights in the weighted regression (Maddala 1977). In many instances, however, the models fitted in the present work contained unbalanced, unevenly distributed data across the range of the independent variables. Under these circumstances the comparability of partitioned variance estimates when differing numbers of observations occur in each interval is uncertain (Gregoire and Dyer 1989). In these instances an approach detailed by Gregoire and Dyer (1989), in which an estimate of a weight parameter (w) is obtained from an OLS fit of a suitable model for the heterogeneous error variance, was used. Weights were calculated as the inverse of X^w. An alternative approach was used when the model being parametrized was cast as a Generalized Linear Model (McCullagh and Nelder 1983). Following the work of Candy (1988, 1989a), a range of functions were tested to model the error variance, including analogues of the binomial, gamma, and poisson distributions. These functions are described where used in Chapter 9.

5.3.2.3 Independent observations

The error terms in a linear model are assumed to be unbiased and independent of one another *i.e.* $E(\varepsilon_i, \varepsilon_{i+1}) = 0$ for all i (Johnston 1972).

Error terms which are positively correlated over time are termed 'autocorrelated' or 'serially correlated'. Serial correlation commonly arises in time-series datasets and forestry datasets containing multiple measurements from individual sampling units (West *et al.* 1984). The karri data potentially contain several 'nested' levels of correlation. For example, measurements on the many individual trees within an individual PSP may be correlated, as may the consecutive measurements which accrue with age on each plot. Correlation may also arise between measurements of different plots within a region over the same time period due to the synchronous action of weather conditions. Multiple measurements on individual trees, such as stem taper and volume measurements, may also be correlated.

Application of OLS when autocorrelation is present can produce inefficient estimators, and although the estimators will be unbiased for linear models, hypothesis testing will be inexact because of the bias in the estimates of the residual variance of the regression equation and the covariance matrix of the parameter estimates (Neter *et al.* 1985). Autocorrelation can seriously bias nonlinear parameter estimates, (Gertner 1981), and only when the assumption that the errors are mutually independent with constant variance is valid, can the OLS estimates of the variance–covariance matrix of the parameter estimates be used to approximate the variance–covariance matrix for the nonlinear model (Gertner 1984).

Most empirical growth and yield models are developed from datasets in which both heteroscedasticity and autocorrelation are present. Unfortunately, no general theory exists to prove that a nonlinear least–squares estimator is unbiased in the presence of both heteroscedasticity and autocorrelation (Maddala 1977).

Testing for first–order serial correlation involved examining the pattern of residuals against lagged time (age or measurement interval), irrespective of whether time had been explicitly incorporated as a variable into the model. The Durbin–Watson test statistic (Durbin and Watson 1951) was computed on a plot by plot basis where relevant (*e.g.* for regressions of multiple growth observations within plots) or pooled across all plots when appropriate, although the Durbin–Watson statistic is not a definitive test for serial correlation with pooled data (Leech 1978). In a number of instances the results of the test were inconclusive due to the limited number of observations.

Estimation of an autoregressive parameter (Maddala 1977, Neter *et al.* 1985) simultaneously with the model parameters has also been used as a guide to the presence of autocorrelation and the extent of likely bias on the final parameter estimates (Monserud 1984a). The complexity of many of the models reported in this study made such an approach impractical.

Remedial measures adopted when autocorrelated error terms are present include the use of transformed variables or the addition to the model of one or more independent variables that have time–ordered effects on the dependent variable (Neter *et al.* 1985). An effective solution adopted where possible in this work was to model growth in preference to yield: periodic increments are more nearly independent than measurements at points in time (Garcia 1988).

Dielman (1983) and West *et al.* (1984) have reviewed the difficulties arising from autocorrelation in regression with multiple measurements from individual sampling units in forest yield modelling. Among the approaches developed to deal with it is a Generalized Least Squares procedure (Ferguson and Leech 1978, Davis and West 1981, Ferguson and Leech 1981). Unfortunately, West *et al.* (1984) found this and all of five other theoretical solutions apply only asymptotically, so that hypothesis testing with these approaches would still be unreliable. They recommended a two-stage regression procedure, adopted in this study, which provides a practical framework for dealing with both autocorrelation and heteroscedasticity. In this approach OLS was used to fit an appropriate first-stage model to each sampling unit (PSP or tree). Graphs of the first-stage parameter estimates with each variable were then examined to determine appropriate model forms for the second-stage regressions. Where a number of remeasurements per plot were available, the two-stage approach was used to help decide on an appropriate model form and then all but one observation from each sampling unit was randomly rejected and the model fitted using OLS to allow exact significance tests (West *et al.* 1984).

5.3.2.4 Normality of the error distribution

The application of OLS assumes that the error terms ε_i are independent and normally distributed with a mean of zero and a finite variance σ^2 (Graybill 1961). This assumption is necessary to undertake hypothesis tests and to construct interval estimates. Because estimation and testing procedures are based on the *t* distribution, which is insensitive to moderate departures from normality, departures of the distribution of ε_i from normality are not serious unless marked skewness is present (Neter *et al.* 1985). Irrespective of the functional form of the distribution of ε_i (and hence Y_i) the least squares method provides unbiased point estimators of $\hat{\beta}$ which have minimum variance among all unbiased linear estimators (Draper and Smith 1981).

A normal probability plot of the ε_i (*i.e.* ε_i plotted against their expected values when the distribution is normal) was used in conjunction with a histogram of the ε_i to detect gross departures from normality. Markedly skewed distributions with a sample size of less than 51 were subjected to a Shapiro–Wilk test (Shapiro and Wilk 1965) to test the hypothesis that the input ε_i were a random sample from a normal distribution. If the sample size was greater than 50, the Kolmogorov–Smirnov test statistic was used to test distribution normality.

Transformations are generally recommended to correct serious departures from normality (Draper and Smith 1981). However, because many other departures from the assumptions of OLS can affect the distribution of the ε_i (Maddala 1977), the normality of the error terms was investigated after the other assumptions had been corrected. The remedial measures adopted for correcting variance heterogeneity usually resolved any problems.

5.3.2.5 Independence of independent variables

Perfect correlation between a linear combination of one or more independent variables must not exist when applying OLS regression. If partial correlation exists then the regression is said to contain multicollinearity between the independent variables

(Bare and Hann 1981). Warren (1979) and Bare and Hann (1981) have reviewed the problem of collinearity between independent variables in forestry datasets.

Models with a high degree of multicollinearity provide parameter estimators that are unbiased but very imprecise (*i.e.* erratic from sample to sample) (Kmenta 1971). Such imprecision can cause parameter estimators to be of the opposite sign to that expected from theoretical considerations or prior experience, or cause estimators to change drastically when new independent variables or new data are added or deleted. Inflated variances of the estimators may lead to substantial overestimates of the F–ratio and t–tests, and thus to the acceptance of unnecessarily complex models (Neter *et al.* 1985).

Serious multicollinearity was suspected from such informal diagnostics as nonsignificant results in individual tests on the parameter estimators for important independent variables, or large changes in the estimators when a variable or observation was added or deleted (Draper and Smith 1981). Simple correlation coefficients between the independent variables were also examined: where they exceeded 0.95, the standard error of the parameter estimators for the variables concerned might be very large, reflecting either mis–specification or data problems.

In addition to these inspections, variance inflation factors (VIF) (Marquardt 1970) were computed for linear models for each combination of independent variables. A maximum VIF exceeding 10 was taken as an indication that multicollinearity may be unduly influencing the least squares estimates (Neter *et al.* 1985).

Model development sought to avoid multicollinearity by the careful specification of model form. For example, the inclusion of H with site index as independent variables in a regression would introduce multicollinearity due to the functional relationship between these variables.

In the few models where multicollinearity was detected a re–specification of the model to exclude one or more of the correlated variables was undertaken. Application of ridge regression (a biased estimation procedure) has been suggested as a remedial measure (Hocking 1976) but was not pursued in this work because ordinary inference procedures are not applicable with ridge regression and exact distributional properties are not known (Warren 1979). Moreover, model predictions will not be affected by the presence of multicollinearity if the use of the fitted model is restricted to making inferences for values of the independent variables which follow the same pattern of multicollinearity (Neter *et al.* 1985).

5.3.2.6 Measurement errors in variables

Both the dependent and independent variables are assumed to be measured without error when applying OLS regression (Johnston 1972). Random measurement errors in the dependent variable are of limited concern if these errors are unbiased and uncorrelated, as they are absorbed into the model error term ε_i.

If, however, the independent variables contain measurement errors (and hence the individual observation of the independent variable is correlated with the error term), then the parameter estimators may be biased and inconsistent (Draper and Smith 1981). Most independent variables used in this study contained measurement error (Chapter 3). However, with the exception of some *bt* measurements (section 3.4.3.1.2) the errors were unbiased. As well, data used in subsequent model prediction will be measured in the same way as that used to estimate the parameters, so OLS estimators should provide unbiased predictions, even though the estimators may be biased relative to those appropriate to the independent variables when measured without error (Draper and Smith 1981).

The detection of extreme or outlier observations which might represent measurement errors was undertaken for each model during the preliminary inspection of model form (section 5.3.2.1). Graphs of the dependent variable against each independent variable were inspected to detect possible measurement errors, while for linear models, studentized residuals and Cook's (1977) distance measure were also used to identify influential observations. Those influential observations which represented gross measurement errors were deleted from the analysis.

5.4 Parameter estimation

Unless indicated otherwise, the method of least squares was employed to estimate parameters in all models reported in this study. Standard algorithms available in the widely used Statistical Analysis System (SAS Institute Inc. 1985) were used for linear models. Procedures REG, STEPWISE and GLM were used in model construction, and provided comprehensive diagnostic statistics. The GLM procedure was used for analysis of variances, while all graphs were produced using the GRAPH procedures.

The Gauss–Newton (Taylor series Linearization) method (see Maddala 1977), as executed under the SAS procedure NLIN, was used for parametrization of nonlinear models. Initial parameter estimates and partial derivatives were derived analytically using procedures outlined by Bard (1974) and Ratkowsky (1983). Poor convergence of a model using the Gauss–Newton method was overcome by either refitting using Marquardt's (1963) algorithm or by reparametrizing the model into a 'close–to–linear' form (often a generalized linear model). Reparametrization of a nonlinear model can alter the bias and skewness of the sampling distribution of the parameter estimates without affecting the shape of the model (Ratkowsky 1983).

Where two–stage regression was undertaken, a series of FORTRAN programs developed by Ratkowsky (1983) were used for parameter estimation of nonlinear first–stage models. These programs utilize the Gauss–Newton method but in addition provide, as standard output, estimates of an asymmetry measure (Ratkowsky 1983, p37) and Box's (1971) measure of bias for the parameter estimators. These statistics were important in assessing the extent of bias in the first–stage parameter estimates. The selection of appropriate first-stage model forms aimed to provide unbiased parameter estimators because highly biased estimators might prove difficult to model in the second-stage regressions (Candy 1988).

5.5 Statistical inference: hypothesis and model testing

Tests of the assumptions underlying the use of the OLS model were detailed in section 5.3. Three further levels of testing were performed, *viz.* hypothesis testing to determine whether a model was internally consistent or to select between alternative candidate models, and tests of the predictive capacity of each model.

5.5.1 Hypothesis testing

The level of significance used in hypothesis testing was set at $\alpha = 0.05$ for all tests reported in this thesis, unless indicated otherwise.

5.5.1.1 Tests within models

Tests of hypotheses concerning the significance or otherwise of parameter estimators in linear models used the t-statistic or conventional analysis of variance based on the F-statistic. These tests are comprehensively documented elsewhere (Neter *et al.* 1985). They are not strictly appropriate in nonlinear situations. Nonetheless, parameter estimates of each candidate model were inspected for algebraic sensibility of signs and an indication of statistical significance, acknowledging the recognised shortcomings of standard t-tests and residual analyses for small sample sizes in nonlinear situations (Gallant 1975, Ratkowsky 1983).

Where regression was performed using multiple measurements from PSPs or individual trees, conventional F-tests are not strictly applicable as they assume independence of observations (West *et al.* 1984). In these cases the F-tests were based on a reduced dataset comprising only one randomly selected measurement from each independent sampling unit. This strategy would reduce the power of the F-test (Neter *et al.* 1985) but enabled exact significance tests to be undertaken (Candy 1989a).

5.5.1.2 Comparisons between models

With the variety of complex and often nonlinear models developed in this work no single statistical criterion can be used to select between candidate models. Rather, the strategy adopted when selecting final model forms was to combine the use of goodness of fit statistics, graphical analyses of residuals across the independent variables (to detect bias), and the comparison of their predictive properties using independent test data from the validation set (section 3.7).

For the simple case of linear models involving the same dependent variable and number of independent variables the adjusted, squared, multiple correlation coefficient (R^2_a) was used for model screening. Where models differed in their number of parameters and the objective of the analysis was the development of a model with good predictor properties, the most parsimonious model (fewest variables) with the smallest Error Mean Square (MSE) was evaluated further (Hocking 1976, Clutter *et al.* 1983).

Nonlinear models were evaluated on their fit to the parametrization dataset by ranking models according to a number of residual statistics (minimum, mean, maximum, standard deviation of residuals) and the residual mean square. A rank was allocated for each residual statistic and, other things being equal, the model with the lowest combined ranking and lowest MSE was preferred. Bias in the fit across the range of the independent variables was examined graphically and by partitioning residual statistics across the range of independent variables. R^2_a values for nonlinear models are reported for broad illustrative purposes only.

Comparisons between models developed with different dependent variables were avoided by minimizing the use of transformations to stabilize error variance heterogeneity (*i.e.* by modelling the variance directly) and through the use of reparametrizations. In those instances where different dependent variables were compared the evaluation was based on comparing the predictive properties of the models using independent test data.

5.5.2 Testing the predictive properties of models

Although statistical estimation and testing procedures can guide model development and selection, equally important is the capacity of the final model to provide biologically reasonable predictions across the range of stand conditions of interest. Graphs of the candidate models evaluated across the range of major independent variables were prepared for this purpose.

The capacity of a model to make precise inferences on the dependent variable from a knowledge of the independent variables depends upon the width of the confidence or prediction interval and the particular needs for precision, which vary from one application to another. Hence, no single statistical criterion (such as R^2) is an adequate indicator of the usefulness of a model (Neter *et al.* 1985). However, the concept of a critical error (e*), developed by Reynolds (1984), does provide a means of unifying each of these requirements and expressing them in a form which is meaningful to a model user.

The critical error provides a means of comparing the accuracies of various models, particularly when competing candidate models may be nonlinear, possess differing numbers of parameters, and incorporate differing weighting structures. The e* is a value for which it can be stated with a specified probability ($1-\alpha$, where α is the specified probability) that a certain proportion ($1-\alpha'$, where α' is another specified probability) of estimates made with the model will have an accuracy equal to or exceeding e*. The model with the smaller critical error is the preferred model. The derivation from e* of confidence intervals for predictions is detailed in Reynolds (1984) and Gregoire and Reynolds (1988).

Calculation of e* assumes the residuals are normally distributed with a mean of zero. The Kolmogorov–Smirnov Test statistic was used to test distribution normality, and a bias–corrected error (Gregoire and Reynolds 1988) was computed in those instances where the mean was not equal to zero. Where e* was computed for the parametrization data (*cf.* independent datasets discussed by Reynolds (1984)), n–p degrees of freedom were used in the Chi–square denominator, where n was the number of observations and p the number of model parameters.

CHAPTER 6 SITE QUALITY DEFINITION IN REGROWTH KARRI[1]

6.1 Introduction

An essential step in modelling forest growth and yield is to define land units of uniform potential for growth. Apart from the direct application of such site stratification in forest planning (Clutter *et al.* 1983), a classification for karri was required to stratify the mensurational database for growth model construction, and to provide a forest-wide framework for extrapolating the results from the limited number of research experiments covering a restricted geographic range (section 3.2.2).

Carmean (1975) distinguished between 'direct' and 'indirect' methods of site quality definition. Direct methods assess forest growth potential by quantifying a land unit in terms of a production attribute of interest (such as stand volume, basal area or the height of a select number of dominant trees) for stands actually growing on each site. Indirect methods involve estimation of direct measures of site productivity from either single or multiple environmental attributes of a site, such as the edaphic, topographic, climatic or vegetative characteristics. The correlation of classification units with direct measures of site quality is then evaluated (Kilian 1984).

A brief review of the approaches to site classification for eucalypts confirmed that despite reservations concerning its utility as the sole productivity indicator of timber yield within monocultures (Hagglünd 1981, Lavery 1986) and mixed-species forests (Monserud 1984a, b), site index remains one of the most widely used site discriminators for even-aged stands (Lindsay 1939, Hall 1959, Tas. For. Comm. 1964, Incoll 1974, Campbell *et al.* 1979, Goodwin 1988). Site index is therefore a common state variable in stand-level growth and yield models for species in which dominant height is positively correlated with stand volume. A number of authors (Monserud 1975, Wensel and Biging 1988) have also used dominant height growth curves to represent maximum potential height growth when modelling the growth of individual trees.

A preliminary set of site index curves for regrowth karri was developed by Campbell *et al.* (1988) but this is known to incorporate bias from the guide curve technique (Clutter *et al.* 1983) used in its derivation. Although the regrowth karri stands are currently stratified for timber inventory and yield regulation on the basis of age and

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[1] Sections of this chapter have been published as:

Rayner, M.E., 1991. Site index and dominant height growth curves for regrowth karri (*Eucalyptus diversicolor* F. Muell.) in south-western Australia. *For. Ecol. Manage.*, 44: 261–283. and

Rayner, M.E., 1992. Evaluation of six site classifications for modelling timber yield of regrowth karri (*Eucalyptus diversicolor* F. Muell.). *For. Ecol. Manage.*, 54: 315–336.

species composition, a number of indirect classifications are available as potential stratifications for modelling. These include classifications based on edaphic (Inions 1990), landform (McArthur and Clifton 1975), climatic (Inions 1990) and vegetative attributes (Inions *et al.* 1990). However, none of these classifications had been evaluated for their correlation with timber production potential.

Considerable management benefits might accrue if any of the existing indirect site classifications were also suitable for stratifying timber productivity. Where intensive multiple-use management of forests has been practised, indirect classifications, particularly the multifactor ecological classifications of the type described by Barnes *et al.* (1982), offer greater flexibility for broader land-use classification than direct timber measures. Such classifications may assist decision-making on land use priorities, disease management (Havel 1975), logging and regeneration requirements (Strelein 1988), the allocation of site-specific silvicultural and burning regimes for different forest ecosystems (Pojar *et al.* 1987) and managing fauna habitat (Davey 1989).

From a growth modelling perspective, indirect classifications which successfully integrate those processes determining site productivity may provide a better framework within which to extrapolate the effects of silvicultural treatments beyond the range of data available in empirical databases (Landsberg 1986, Meldahl *et al.* 1988). Their use in conjunction with such direct classifiers of site productivity as site index (the height of the dominant portion of a stand at an index age) may provide improved precision in mensurational models (*e.g.* Monserud 1984a) and partly overcome reported limitations of single indices to adequately stratify all mensurational parameters of modelling interest (Assmann 1970, Lavery 1986, Sterba 1989).

The indirect classifications available for karri differ in the scale at which they describe the land units, from the local-level site description of the edaphic and vegetative categories to the regional-level landform categories. They were potentially useful either as single classifications or in combination with direct measures of stand productivity.

The individual-tree level modelling approach adopted in the present work required the development of a dominant height growth model. The definition of a suitable site quality stratification for karri therefore involved two stages, *viz.* the development of a dominant height growth and site index model, followed by an evaluation of both the site index model and the indirect classifications for their correlation to timber productivity.

6.2 Site index and dominant height growth model for regrowth karri

6.2.1 Introduction

This section describes the development of a dominant height growth and site index model for regrowth karri using stem analysis and PSP data. A secondary objective was to evaluate the relationship between the height/age model and existing landform, edaphic, climatic, and vegetative classifications for these stands.

In this study stand dominant height is taken to be synonymous with stand top height (section 3.2.1.3), and stand site index (*SI*) is defined as the top height of a stand at age 50 years (half the nominal rotation length).

6.2.2 Data

6.2.2.1 PSPs

The few measurements available for each PSP provided an abstract growth series of *H*s across the site and age range of the existing forest. The parametrization of a site index model based on these few measurements could be seriously biased by unrepresentative short–term climatic fluctuations (Curtis 1972). The PSP data were therefore used for validation only, necessitating the collection of stem analysis data. The sample plots for stem analysis were selected following the allocation of each PSP within a stratum of each of the following indirect classifications.

6.2.2.2 Indirect site classifications

Each PSP was located within a stratum of each of the following classifications:

Landform – identifies 9 land units (strata) within the study area according to the major geological formation with which they are associated, including the nature of their topography and soils. This regional–level classification was developed by McArthur and Clifton (1975) and Churchward *et al.* (1988).

Edaphic – 3 or 5 groups (strata) were defined from hierarchical cluster analysis of 4 physical and 8 chemical properties sampled from the <10 cm and >10 cm horizons of the soil profile within each PSP (Inions 1990). Physical variables were the proportion by weight of gravel, coarse sand, and fine sand, and basic density. Chemical variables included pH, cation exchange capacity, phosphorus concentration and potassium concentration.

Climatic – 4 or 8 homoclimes (*i.e.* categories of similar climate characteristics) were identified from hierarchical cluster analysis of 17 variables derived for each PSP from the Bioclimatic Prediction System database (see Booth *et al.* 1988a). Attributes used in the analysis included annual mean temperature, radiation and rainfall, mean radiation and rainfall in the driest and wettest month, the range in evaporation values, and the number of rain–days in the wettest and driest period of the year (Inions 1990).

Vegetative – hierarchical cluster analysis of the floristic composition of sites formed 5 community–groups or 13 community–types on the basis of the presence or absence of non–herbaceous perennial species (Inions *et al.* 1990).

Overstorey Species Composition – 6 categories representing the dominant overstorey species composition were identified from interpretation of 1:15 000 scale air–photos. This is the current method of classifying site used for operational planning in regrowth karri forest.

Because the edaphic, climatic and vegetative classifications were derived using clustering techniques the number of categories in each of these classifications may be varied by hierarchically aggregating individual strata. Each of these classifications was therefore evaluated at the two levels of aggregation defined by Inions (1990) and Inions *et al.* (1990).

6.2.2.3 Stem analysis plots

Thirty–one stem analysis sites were selected to sample the range in *H* and the indirect classification categories present within the PSP network (Figure 6.1 and Tables 6.1 and 6.2). Stands older than 50 years were selected to ensure a measured estimate of plot site index and to include the longest real growth series available for that site and stand quality. In order to check for any decline of mean *SI* with respect to increasing age (Monserud 1985) a further sample of trees in stands less than 50 years of age were selected for stem analysis.

Table 6.1 Number of permanent sample plots and (stem analysis plots) within each site classifier category of the edaphic, climatic, vegetative and landform classifications.

Category[a]	Number of plots[b]			
	Edaphic	Climatic	Vegetation Type	Landform
1	27 (5)	37 (4)	12 (2)	2 (0)
2	35 (4)	25 (4)	15 (2)	7 (3)
3	64 (9)	35 (5)	4 (0)	8 (2)
4	49 (8)	20 (0)	35 (4)	38 (6)
5	18 (5)	28 (8)	3 (1)	68 (8)
6	–	10 (3)	13 (2)	9 (5)
7	–	28 (4)	9 (3)	15 (3)
8	–	4 (2)	23 (4)	9 (2)
9	–	1 (1)	11 (3)	5 (2)
10	–	–	44 (5)	–
11	–	–	6 (1)	–
12	–	–	17 (4)	–
13	–	–	13 (0)	–

[a] Numbers refer to sequential listing of categories for edaphic and climatic (Inions 1990), vegetation (Inions *et al.* 1990) and landform (McArthur and Clifton 1975) classifications.

[b] Incomplete field records meant that some PSPs could not be properly classified for all classifications. The total number of PSPs available for analysis therefore differed between classifications.

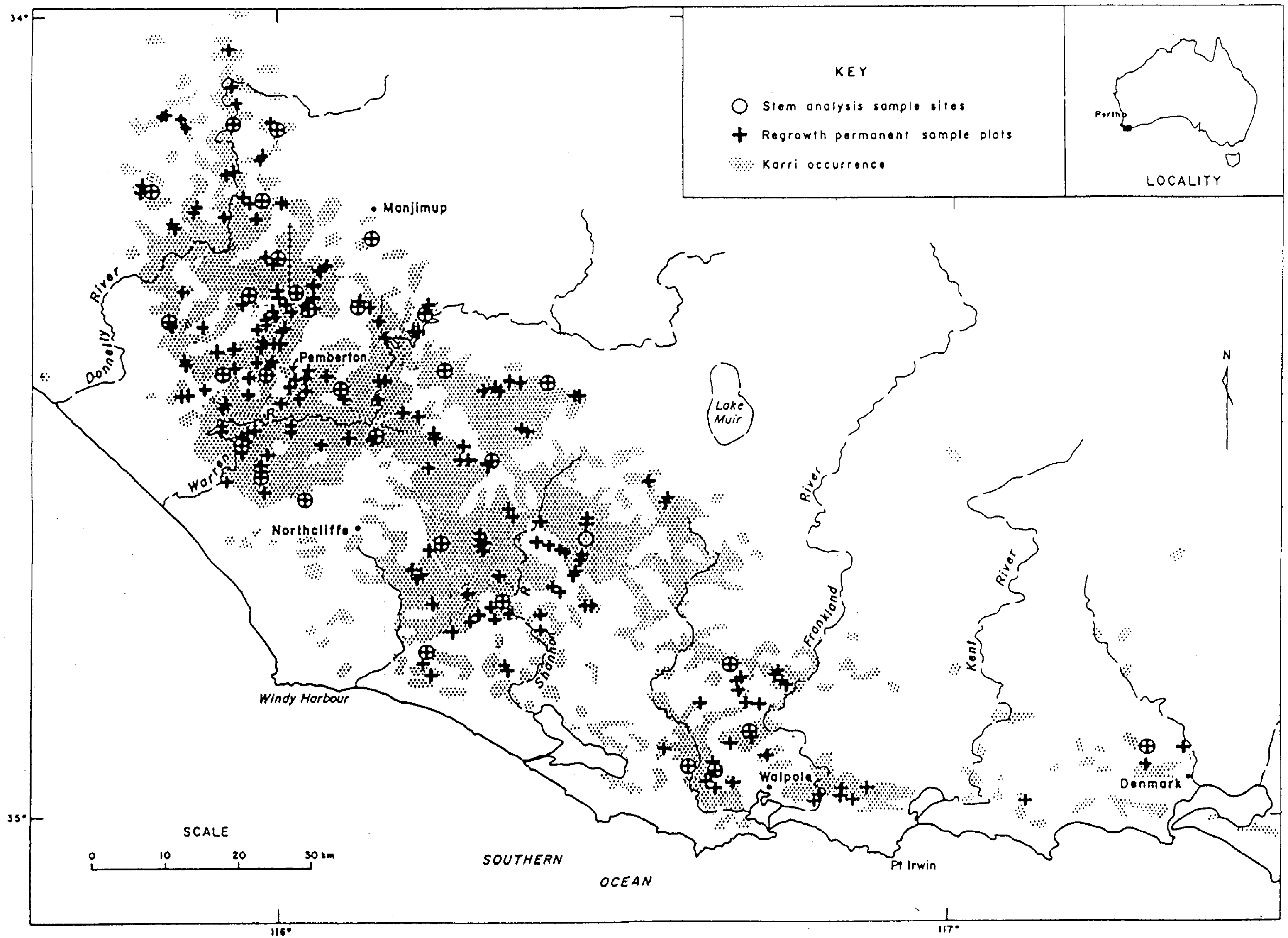

Figure 6.1 Karri forest occurrence showing location of permanent sample and stem analysis plots within regrowth stands.

Table 6.2 Minimum–mean–maximum values of stand variables by species composition in the stem analysis (parametrization) dataset.

Species composition	Number of plots	Age (Yrs)	Basal area[a] (m^2 ha^{-1})	Stocking[a] (stems ha^{-1})x10	Mean height of dominants (m)
E.diversicolor	17	27–60–132	24–38–56	9–46–109	33–46–61
E.diversicolor / *E.calophylla*	8	52–82–135	29–36–50	6–22– 46	38–48–67
E.diversicolor /other[b]	6	13–46– 71	9–25–43	10–34– 68	16–35–44

[a] Live stems ≥10 cm diameter at breast height.

[b] Other species which may occur in mixture with karri include *E.marginata* Donn ex Smith, *E.jacksonii* Maiden, *E.brevistylis* Brooker, *E.guilfoylei* Maiden, *E.patens* Benth., and/or *E.megacarpa* F.Muell.

Suitable site trees were the three tallest dominants within an approximate 16 m radius of a representative point located adjacent to the PSP for that site (thereby ensuring compatibility with both the estimate of *H* and the available classification attributes of the PSP). Site trees had no visible evidence of past crown damage (scarring, abnormal forking, or crown dieback) or bole malformation. The three tallest trees were selected because changes in the dominance status of individual trees with age had been observed within the PSP data and preliminary investigations confirmed that the tallest tree at time of sectioning may not necessarily have been the tallest throughout the life of the stand. Three dominant trees provided sufficient information to derive the tallest two at any stand age. Each tree was measured for crown depth and *h* while standing and on the ground to provide a comparison of heighting accuracy within the stem analysis and PSP datasets.

At each stem analysis plot five basal area sweeps were taken and the *d*, *h*, and *hc* recorded for each 'in' tree. These data were used to compute a variety of stand density measures.

Complete stem analysis (Carron 1968) was performed with each tree being cross–cut and a section removed at 0.5, 1.3 (breast height) and at 3–4 m lengths thereafter along the stem to the tip. For each section tree height, total ring number, and five–yearly diameter–under–bark increment were recorded. Because it was necessary to ensure conformity with previous regrowth ageing in the PSPs (Armstrong 1984), tree age was determined from the ring count at the 0.5 m section, despite the mensurational advantages of basing tree age on breast height ring count (Curtis 1983).

Growth rings on all sections were counted on three planed radii by two independent assessors using x10 magnifying lenses. An observed correlation between drought events (measured as the percentage deviation from average annual rainfall) and the occurrence of very narrow rings provided a useful pointer sequence when cross-matching tree chronologies. In an approach similar to that described recently by Yamaguchi (1991), the ring widths associated with major rainfall deficits (<75% of average in 1940, 1959, and 1969) were used as pointer years to assist across-site accuracy in ring counting (Rayner 1992). The accuracy of the ring counts were tested against sections obtained from plantation-grown trees of known age, with a random sample of 25 sections being x-rayed to further test the accuracy of the visual counts. No significant difference (P>0.05) was found between ring counts of either assessor and the test sample ages.

An additional stem analysis dataset was used in the graphical evaluation of the parametrized models. Ageing of dominant old-growth trees across a range of sites in stands of even-aged structure provided an indication of the range in asymptotic dominant height in stands older than 200 years. These data were unsuitable to include for model parametrization due to imprecision in ageing arising from rot in the centre of the stems.

6.2.2.4 Preliminary site-curve preparation

Height/age data recorded from stem-analyzed trees can be biased if the height of the cross-cut is taken as the tree height for the given age, because of the presence of a 'hidden tip' above the cross-cut (Carmean 1972). Six published algorithms (Dyer and Bailey 1987) for estimating the true height within a section were compared by locating the position of the tip in a subsample of 30 logs. Each stem analysis site contributed one log to this dataset, randomly selected from either the butt, bole, or crown zones of each sample tree. The method of Carmean (1972), which assumes the annual height growth to be constant for each year for which height growth is contained within a section and that on average, a cross-cut will occur at the midpoint of a year's height growth, provided accurate, unbiased estimates of tree height (Appendix 1). The raw stem analysis data was thus adjusted using Carmean's (1972) algorithm to calculate tree height corresponding to the age at each cross-cut.

For each site tree a graph of tree height versus age was used to delete or truncate data if suppression or damage was apparent. Two trees were deleted and three truncated due to anomalous measurements within their crown zone.

An average growth curve (dominant height versus age) was derived for each site by fitting a curve to the tallest two measurements at each age from the combined data of the three site trees for each plot. The following Richards (1959) three-parameter equation proved superior to a range of functions for summarizing the Carmean–corrected data on each plot:

$$H = \alpha \, [1 - \exp(-\beta A)]^{\gamma} \qquad (6.1)$$

The 31 within–plot standard errors for model (6.1) averaged 0.91 m, with a standard deviation of 0.42 m. Model (6.1) was evaluated for each plot at 5–yearly intervals to provide the database used in constructing the site index curves. An estimate of *SI* was obtained for each plot by evaluating model (6.1) with index age equal to 50 years.

Plot *SI* and the *H* observations of the PSP data were then analyzed for any correlation with stand density. *SI* and *H* were regressed against stand basal area and stocking measures, with no significant ($P>0.05$) regressions. However, the majority of the plots were located in fully–stocked, self–thinning stands so the range of stand density represented at any age was limited. Nonetheless, evidence from thinning studies and espacement trials in both karri and other eucalypt species support the contention that *H* is independent of stand density within their range in managed forests (Webb 1966, Bredenkamp 1984).

6.2.3 Method

6.2.3.1 Model formulation

A number of authors have reviewed the historical development of site index estimation techniques (Carmean 1975, Hagglünd 1981, Tesch 1981, Monserud 1984b). Clutter *et al.* (1983) provide a useful overview of recent developments in site index equation estimation.

The mathematical convenience and biological realism of using difference equations to model growth/functional size relationships of trees, stands, and forests has been noted by many authors (Furnival and Wilson 1971, Turelli 1977, Garcia 1983, Borders *et al.* 1984, Ramirez–Maldonado *et al.* 1988). The algebraic difference equation method (Borders *et al.* 1984) of deriving *SI* and dominant height growth curves was adopted in this study. A difference form of the height/age equation was derived in which height at remeasurement (H_{i+1}) was expressed as a function of remeasurement age (A_{i+1}), initial measurement age (A_i), and height at initial measurement (H_i). This approach ensured optimal use of the limited plot remeasurements available, as it explicitly recognized the association between two remeasurements at different ages on the same stand. Both anamorphic and polymorphic equation forms may be tested depending on the choice of site–specific parameter, and the resulting site index curves are base–age invariant (Bailey and Clutter 1974). Importantly, the method avoids the need to estimate instantaneous growth rates common to differential formulations (Borders *et al.* 1984). The compatible derivative–integral relationship between growth and yield (Clutter 1963) exists for models formulated by the algebraic difference equation method (Ramirez-Maldonado *et al.* 1988). The difference equation approach is consistent with the state-space approach of Garcia (1983), in which the top height of a stand at age A_i is predicted by assuming that the current state of the stand (H_i) incorporates all the information necessary to predict its future state (H_{i+1}).

6.2.3.2 Model formulations investigated

Suitable height/age model forms were sought by inspecting scatter-plots of the relative height growth rate versus age for the combined stem analysis data. Relative height growth rate was defined as the H increment expressed as a proportion of the H at the start of the increment period. However, a suitable model form was not clearly indicated (Bruce 1981), so a range of candidate functions were selected to represent alternative height growth rate hypotheses (Devan and Burkhart 1982, Ramirez-Maldonado *et al.* 1988). These functions had been found effective in other site index studies:

$$H = \alpha \exp(-\beta / A) \qquad \text{(Schumacher 1939)} \qquad (6.2)$$

$$H = \alpha [1 - \exp(-\beta A)]^{\gamma} \qquad \text{(Richards 1959)} \qquad (6.3)$$

$$H = \alpha [1 - \exp(-\beta A^{\gamma})]^{\delta} \qquad \text{(Bailey 1980b)} \qquad (6.4)$$

$$H = \alpha \exp(\beta / A^2 + \gamma / A) \qquad \text{(Chang 1984)} \qquad (6.5)$$

Both anamorphic and polymorphic forms of each of the above equations were derived using an algebraic difference approach. For each equation this involved selection of an appropriate parameter in the model as a site-specific parameter and solving for that parameter as a function of height, age, and the other parameters. This solution was then substituted into the model to derive the future height (H_{i+1}) at a future age (A_{i+1}) as a function of initial age (A_i), future age (A_{i+1}), initial height (H_i), and the remaining parameters. The following equations were fitted to the stem analysis data:

Schumacher (1939) Anamorphic

$$H_{i+1} = H_i \exp[\beta (1/A_i - 1/A_{i+1})] \qquad (6.2A)$$

Schumacher (1939) Polymorphic

$$H_{i+1} = \alpha (H_i/\alpha)^{(A_i/A_{i+1})} \qquad (6.2P)$$

Richards (1959) Anamorphic

$$H_{i+1} = H_i \left\{ \frac{[1-\exp(-\beta A_{i+1})]}{[1-\exp(-\beta A_i)]} \right\}^{\gamma} \qquad (6.3A)$$

Richards (1959) Polymorphic

$$H_{i+1} = \alpha (H_i/\alpha)^{\log_e [1-\exp(-\beta A_{i+1})] / \log_e [1-\exp(-\beta A_i)]} \qquad (6.3P)$$

Weibull Anamorphic (Bailey 1980b)

$$H_{i+1} = H_i \left\{ \frac{[1-\exp(-\beta A_{i+1}^{\gamma})]}{[1-\exp(-\beta A_i^{\gamma})]} \right\}^{\delta} \qquad (6.4A)$$

Weibull Polymorphic (Bailey 1980b)

$$H_{i+1} = \alpha (H_i/\alpha)^{\log_e [1-\exp(-\beta A_{i+1}^{\gamma})] / \log_e [1-\exp(-\beta A_i^{\gamma})]} \qquad (6.4P)$$

Chang (1984) Anamorphic

$$H_{i+1} = H_i \left[\frac{\exp(\beta/A_{i+1}^2 + \gamma/A_{i+1})}{\exp(\beta/A_i^2 + \gamma/A_i)} \right] \qquad (6.5A)$$

Chang (1984) Polymorphic

$$H_{i+1} = H_i^{(A_i^2/A_{i+1}^2)}\, \alpha^{(1-A_i^2/A_{i+1}^2)} \exp\{\gamma\, [(A_{i+1}-A_i)/A_{i+1}^2]\} \qquad (6.5P)$$

In addition, the following difference form of the Clutter and Jones (1980) model was fitted to provide an alternative polymorphic–disjoint model.

$$\begin{aligned} H_{i+1} = \{ & H_i \exp[\alpha(1/A_i - 1/A_{i+1})]\} [\exp(\beta\{(1/A_{i+1}) - (1/A_i) \\ & \exp[\alpha(1/A_i - 1/A_{i+1})]\} + \gamma\{\exp[\alpha(1/A_i - 1/A_{i+1})] - 1\})] \end{aligned} \qquad (6.6P)$$

where H_i denotes observed height at age A_i

H_{i+1} denotes predicted height at age A_{i+1}

and α .... δ denote parameters to be estimated

Thus, nine candidate models (four anamorphic and five polymorphic) were investigated.

6.2.3.3 Parameter estimation

Parameters in each equation were estimated using the Gauss–Newton algorithm (section 5.4). An additive error structure (Ratkowsky 1983) was assumed for each model.

Significant heteroscedasticity, as indicated by Bartlett's (1937) test, was present in both the anamorphic and polymorphic forms of the Schumacher model. Functions were sought to model the variance structure of the residuals with respect to the fitted values (section 5.3.2.2). The final solution used the inverse of the residual variance for each decade as weights in an iteratively reweighted least-squares procedure (Maddala 1977).

Monserud (1984a) and Sullivan and Clutter (1972) have shown that autocorrelation does not pose serious problems with stem analysis and remeasurement data respectively. Thus, the potential problem associated with autocorrelation in the present data was not investigated further.

6.2.3.4 Model comparisons

Models were compared on their fit to the parametrization data, their ability to predict H_{i+1} at A_{i+1} given A_i and H_i, and their ability to predict *SI* from an initial height/age observation. Residuals were examined to indicate the amount of variation in the stem analysis data explained by each parametrization.

Each parametrized model was then used to compute the *H* at remeasurement of each plot in the PSP dataset (excluding those plots adjacent to the stem analysis sample sites), using the A_i and H_i at first measurement. The deviation or residuals of the observed *H* from the predicted *H* for each stand were used to compute the critical error (e*) (Reynolds 1984) associated with projections from each model.

The competing model forms were then examined for their ability to predict *SI* given an initial H_i and A_i. These comparisons were restricted because *SI* had been observed in only the parametrization data and in 23 independent PSPs for which the measurement interval spanned age 50 and hence could be linearly interpolated.

The asymptotic behaviour of each model at older ages was inspected by generating the top height curves for the minimum, mean and maximum site indices represented in the PSP data and overlaying the old-growth *H* data.

6.2.3.5 Stratum comparisons

Because the same factors that identify a soil, climate or vegetation group might also affect the shape of the height growth curves (Cajander 1926, Spurr and Barnes 1980), tests were undertaken to determine whether a separate height/age model was required for each stratum within the various classifications.

Residuals from each model parametrization and from the predictions of PSP top height were plotted against A_i, H_i and prediction period and examined for trends within classification strata. Strata in each of the vegetative, climatic, and edaphic classifications were examined for pattern at increasing levels of aggregation. For example, residuals from each model parametrization were plotted against age at both the 5-level community group and 13-level community type levels of the vegetative classification.

Additional levels of aggregation were defined by truncating the original dendrograms of Inions *et al.* (1990) at increasing levels of fusion in the cluster analysis.

If no age or stratum–by–age effects were evident in the residuals for a model, a mixed–model analysis of variance was used to test the effect of strata on mean residuals. Because strata contained unequal sample sizes (Table 6.1) an unbalanced ANOVA was necessary, with treatment mean squares computed according to procedures outlined in Neter *et al.* (1985). In general, only the higher aggregation levels could be tested because of the unbalanced sample size.

6.2.4 Results

6.2.4.1 Selection of height/age model

The parameter estimates for the various stand top height/age models are given in Table 6.3. All parameters in each model were significant, suggesting the additional flexibility introduced in the 3– and 4–parameter models had not resulted in over–parametrization.

The residual statistics for each model (Table 6.4) indicate a poorer fit to the data by models (6.2A), (6.2P), and (6.5P), but only marginal differences in the goodness of fit of candidate models (6.3A) to (6.6P). There was a consistent trend for the anamorphic formulations of each model to explain greater variation in the data than their polymorphic counterpart. The ranking on all criteria in Table 6.4 shows model (6.4A) to be the best fit to the data.

The residual statistics for estimates of H_{i+1} using H_i for each PSP (data not shown) were consistent with the trends in Table 6.4, supporting the poorer fit of models (6.2A), (6.2P), and (6.5P). However, the magnitude of the residuals was higher than in Table 6.4. This was partly attributed to eight plots in which a negative height increment had been recorded between successive measurements. Another possible reason was the potential difference between measurement accuracy of stem analysis trees (measured on the ground) and height measurements of standing trees by clinometer.

Preliminary examination of the critical errors for estimates of H_{i+1} using the H_i for each PSP suggested that the accuracy of each model varied with the age from which the prediction of H_{i+1} was made (Table 6.5). In general, e^* declined as age increased, reaching a minimum in the 60–80 year age class and then increasing for older ages. Models (6.2A), (6.2P), and (6.5P) were least accurate, with minor practical differences in accuracy between the remaining model forms. Projections of H from each model were least accurate when initial age was less than 20 years. As only this age class contained both naturally regenerated and planted stands, data were segregated by stand origin and e^* recalculated. There was no significant difference ($P>0.05$) in the magnitude or variance (Bartlett's 1937 test) of e^* between the stand types.

Thus, models (6.3), (6.4), (6.5) and (6.6) differed only marginally in their capacity to predict top height at a future age.

Table 6.3 Parameter estimates for top height/age models. Standard errors of estimates are shown in parentheses.

Model	Parameter estimates			
	α	β	γ	δ
6.2A[a]		9.316 (0.2566)		
6.2P	55.64 (0.00003)			
6.3A		0.0419 (0.0005)	1.086 (0.0393)	
6.3P	60.81 (3.3488)	0.0212 (0.0018)		
6.4A		0.0625 (0.01505)	0.8956 (0.1460)	1.233 (0.1643)
6.4P	60.58 (9.1750)	0.0717 (0.0166)	0.7650 (0.0028)	
6.5A		30.20 (1.4269)	−15.53 (0.3776)	
6.5P	59.20 (0.9374)		−17.58 (0.5044)	
6.6P	−0.713 (0.0304)	2.855 (0.1399)	−10.81 (0.7619)	

[a] A indicates anamorphic formulation, P indicates polymorphic formulation

Table 6.4 Residual (observed minus fitted height) statistics for the parametrization of each top height/age model. Figures within parentheses show the rank among models (1= most desirable) for each statistic.

Model	Statistic						
	Min. residual	Mean residual	Max. residual	|Mean residual|	Std. deviation	Error Mean Sq.	Rank Sum
	………………	………………	……metres……	………………	………………	………………	
6.2A[a,b]	−9.81 (9)	0.35 (6)	3.27 (3)	1.21 (7)	1.83 (8)	2.19 (8)	(41)
6.2P[b]	−7.87 (8)	−0.53 (7)	1.91 (1)	1.22 (8)	1.84 (9)	1.86 (7)	(40)
6.3A	−3.36 (3)	0.03 (2)	4.02 (8)	0.74 (2)	1.04 (3)	1.08 (3)	(21)
6.3P	−3.45 (4)	−0.03 (2)	4.20 (9)	0.90 (5)	1.15 (6)	1.32 (6)	(32)
6.4A	−3.24 (2)	0.08 (4)	3.96 (6)	0.73 (1)	1.02 (2)	1.05 (1)	(16)
6.4P	−3.57 (5)	−0.04 (3)	3.71 (4)	0.84 (3)	1.06 (4)	1.13 (4)	(23)
6.5A	−3.71 (6)	0.20 (5)	3.79 (5)	0.74 (2)	1.01 (1)	1.06 (2)	(21)
6.5P	−5.29 (7)	−0.02 (1)	3.98 (7)	1.20 (6)	1.52 (7)	2.32 (9)	(37)
6.6P	−2.92 (1)	−0.03 (2)	2.93 (2)	0.88 (4)	1.09 (5)	1.19 (5)	(19)

[a] A indicates anamorphic formulation, P indicates polymorphic formulation

[b] Iteratively reweighted least squares solution

Table 6.5 Critical errors (e*) for estimates of stand top height with various top height/age models (using the PSP validation data). Data were segregated by the age class of the initial top height/age pair used to estimate subsequent top height. A minimum of 14 observations were used to calculate the value in each age class. Rankings are indicated in parentheses.

Model	Critical error					Rank Sum
	Age class (yrs)					
	<20	20–40	40–60	60–80	>80	
	metres					
6.2A[a]	11.7 (7)	3.0 (6)	2.5 (6)	1.8 (3)	2.3 (3)	(25)
6.2P	5.6 (5)	6.1 (7)	2.2 (4)	1.6 (1)	2.5 (4)	(21)
6.3A	3.4 (3)	2.5 (3)	2.1 (3)	1.7 (2)	2.3 (3)	(14)
6.3P	3.3 (2)	2.3 (1)	1.8 (1)	1.9 (4)	2.2 (2)	(10)
6.4A	3.4 (3)	2.3 (1)	2.0 (2)	1.6 (1)	2.2 (2)	(9)
6.4P	3.2 (1)	2.3 (1)	1.8 (1)	1.8 (3)	2.3 (3)	(9)
6.5A	3.8 (4)	2.6 (4)	2.1 (3)	1.7 (2)	2.2 (2)	(15)
6.5P	3.2 (1)	2.7 (5)	2.3 (5)	1.7 (2)	2.6 (5)	(18)
6.6P	7.9 (6)	2.4 (2)	2.0 (2)	1.8 (3)	1.8 (1)	(14)

[a] A indicates anamorphic formulation, P indicates polymorphic formulation

The residual statistics for estimates of *SI* with each top height/age model using the 23 PSPs (data not shown) failed to discriminate between models due partly to the limited projection periods of 2–5 years and the small sample size. The mean of absolute values of residuals ranged from 0.63 to 1.0 m across all models. The critical errors for estimates of *SI* with each model using the stem analysis data (Table 6.6) proved more discriminating. Initial height/age pairs were selected randomly within the age classes listed, and site index projected from that observation. For each model, the e* was at a minimum for ages of initial measurement closest to the index age, and increased with increasing length of projection either side of this age. This pattern was reproduced whatever index age was adopted. With the exception of model (6.6P) the polymorphic forms of each model produced markedly smaller critical errors than the anamorphic formulations for younger stands (<20 yrs), but thereafter the anamorphic forms were more accurate. The ranking indicates model (6.4A) was consistently the most accurate across the age range.

Inspection of graphs of the expected height development pattern for stands of various site indices overlain by the PSP and old–growth stem analysis data confirmed the choice of model (6.4A) as a suitable height/age function for regrowth karri. The polymorphic models produced height growth rates which were unrealistically high compared to the PSP data, particularly for stands of high site index. As well, all the polymorphic models restricted *H* to an asymptote of approximately 60 m (Table 6.3), whereas the dominant height of some old–growth stands exceeded 65 m.

6.2.4.2 Correlation of classification strata with *H* and *SI*

No trends of residuals from any of the nine models with age or initial top height were detected either within strata or pooled across strata. The absence of any trends was consistent for both the parametrization and validation data. In addition to the landform, edaphic, climatic, and vegetative classifications, segregation of the residuals based upon dominant overstorey species also failed to detect pattern in the residuals.

Table 6.7 shows the analysis of variance for the mean residuals within edaphic strata of the fit of model (6.4A) to the stem analysis data. The non–significance of strata effects implies that a separate parametrization of the model was not required for different strata. Similar results were obtained for all anamorphic and polymorphic model/strata combinations tested, concurring with the above visual inspection of the residuals. Similar results were obtained when ANOVAs were computed to test *SI* effects.

Table 6.6 Critical errors (e*) for estimates of site index with various top height/age models (using the parametrization dataset). Data were segregated by the age class of the initial top height/age pair used to estimate site index. Figures in each class were derived from 20 randomly selected initial height/age pairs. Rankings are indicated in parentheses.

Model	Critical error					Rank Sum
	Age class (yrs)					
	<20	20–40	40–60	60–80	>80	
	metres					
6.2A[a]	20.6 (8)	7.9 (8)	1.5 (3)	5.4 (2)	7.9 (5)	(26)
6.2P	7.6 (2)	4.7 (1)	1.3 (2)	6.4 (5)	12.1 (7)	(17)
6.3A	13.8 (6)	5.1 (2)	1.1 (1)	4.2 (1)	7.4 (4)	(14)
6.3P	7.5 (1)	5.3 (4)	1.6 (4)	5.9 (3)	6.9 (3)	(15)
6.4A	12.2 (5)	5.2 (3)	1.1 (1)	4.2 (1)	6.5 (2)	(12)
6.4P	7.9 (3)	5.5 (5)	1.7 (5)	6.1 (4)	10.0 (6)	(23)
6.5A	14.4 (7)	5.6 (6)	1.1 (1)	4.2 (1)	6.1 (1)	(16)
6.5P	8.7 (4)	5.8 (7)	1.8 (6)	10.6 (6)	22.8 (9)	(32)
6.6P	33.9 (9)	9.8 (9)	1.3 (2)	10.7 (7)	19.3 (8)	(35)

[a] A indicates anamorphic formulation, P indicates polymorphic formulation

Table 6.7 Mixed model analysis of variance of residuals from the anamorphic Weibull model (6.4A) fitted to the stem analysis data within edaphic strata.

Source of variation	df	SS	MS	MSE	*F*
Edaphic strata	4	3.651	0.913	15.62	1.19
Strata/plots	26	22.12	0.851	13.16	
Observations/plots/strata	613	76.54	0.125		

An alternative test was undertaken for each height/age model in which separate curves were fit to each stratum of each classification. Theil's (1971) *F*–test was then used to test for significant differences between the parameter estimates for each stratum within a classification. Parameter estimates were invariant across each classification for each height/age model, although such hypothesis tests are not strictly reliable with data of this nature (Ratkowsky 1983, West *et al.* 1984).

No attempt was made to determine whether or not average *SI* differed between classification strata. The unbalanced representation of the stem analysis sample across the various classifications (Table 6.1) militates against comparison of stratum–specific estimates of mean *SI*. Any comparison based on projected *SI* for each PSP would be confounded by the varying accuracy (Table 6.5) of the *SI* estimate due to the broad range of initial ages from which *SI* would require projection. In addition, stratum–specific estimates of mean *SI* are likely to be biased due to the differing proportions of each stand age in each classification stratum.

6.2.5 Discussion

6.2.5.1 Application of height/age model

Estimates of dominant height growth of karri regrowth stands within the study area (Figure 6.1) should be made using the following anamorphic Weibull–based formulation:

$$H_{i+1} = H_i \left\{ \frac{[1 - \exp(-0.0625 A_{i+1}^{0.8956})]}{[1 - \exp(-0.0625 A_i^{0.8956})]} \right\}^{1.233} \qquad (6.7)$$

where H_i denotes observed height at age A_i, and
H_{i+1} denotes predicted height at age A_{i+1}

H_i should be determined as the mean of the tallest two dominants in a 15.96 m radius of the sample point location. The *SI* of a stand may be estimated by setting A_{i+1} equal to 50 years. Figure 6.2 shows the final curves for four site index values.

Where more than one top height/age pair is available for the stand, the accuracy of the H_{i+1} (or *SI*) estimate will be improved by using the top height/age pair closest in age to that at which the estimate is required (Table 6.6).

Because model (6.7) has the property of compatibility described by Clutter (1963) it need not be applied recursively. That is, predictions of future *H* will be identical irrespective of the length of the increment period or the number of steps used for prediction. The advantages of this important property are discussed further in Chapter 9.

6.2.5.2 Application of anamorphic and polymorphic models

The superior fit to the stem analysis data of the anamorphic formulations compared to the polymorphic formulations was unexpected. Anamorphic models imply the relative rate of height growth is constant for all sites, in contrast to polymorphic height/age curves which reflect varying relative rates of height growth on different sites (Bailey and Clutter 1974). Polymorphic patterns of tree height growth have been recorded for many temperate hardwood (Carmean 1975), coniferous (Beck 1971) and eucalypt species (Incoll 1974, Gasana and Loewenstein 1984, Tomé 1988).

This lack of discrimination between anamorphic and polymorphic forms may be partly fortuitous, due to the limited representation of stands older than 100 years across the range of site quality. However, anamorphic curves are used for a number of eucalypt species in other forest regions of Australia, although polymorphic forms were not investigated in those instances (Lindsay 1939, Tas. For. Comm. 1981).

The anamorphic Weibull formulation adequately represented karri dominant height/age patterns at a regional level (Daniel *et al.* 1979, Spurr and Barnes 1980) of forest sampling. Procedures exist (*e.g.* Walters and Burkhart 1988) for localizing the site index equation as additional information concerning a particular stand's height growth becomes available.

6.2.5.3 Correlation of indirect classification strata with *H* and *SI*

The edaphic, landform, climatic, and vegetative classifications investigated in this study represented a wide range of site attributes with potential to explain variation in *H* growth and *SI* between stands. However, none of the classifications in their present form improved height prediction at a regional level. Such uniformity in shape of each candidate top height/age model (both anamorphic and polymorphic forms) between forest strata suggests that the site attributes upon which the groups were classified were insensitive to height growth of karri at this regional level of sampling.

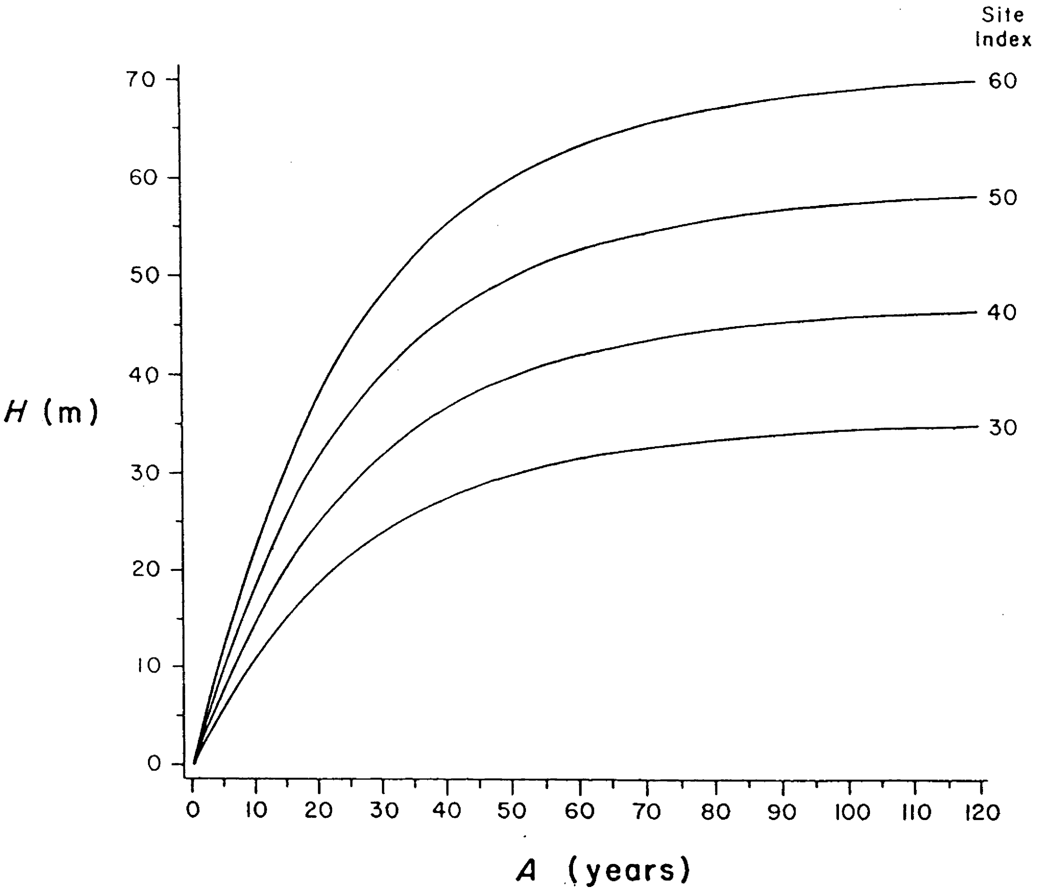

Figure 6.2 Anamorphic Weibull-based site index model (6.7) plotted as stand top height versus age for each of four site index values.

The correlation of individual topographic, soil chemical and soil physical attributes of each site with H was not pursued as the field assessment of classifications which involve detailed soil assessments and laboratory analyses was considered too expensive for routine implementation in the field. Moreover, regional or local-level site classifications based solely on soil, topographic, or climatic attributes have seldom explained more than 50–60% variation in SI and H curves (Hall 1959, Wright and Van Dyne 1971, Tesch 1981, Schmoldt *et al.* 1985, Monserud 1988).

Schönau (1987) considered one of the contributing factors to the recent decline in the use of soil classification for site quality determination is the inability of agricultural soil classification systems to distinguish parameters important for tree growth. Denton and Barnes (1988) assert that available climatic data is either relatively low in quality (*sensu* the information reported is not directly related to tree physiology), or lacking in spatial resolution. Relatively little work has been done, for example, on the prediction of microclimate from the type of macroclimatic data used in this study (Holmes and Dingle 1964, Waggoner *et al.* 1969).

Vegetation of undisturbed sites has often been claimed (Spurr and Barnes 1980) to be an efficient integrator of climatic and edaphic site attributes, and for some species, the shape of the dominant height/age curve has been demonstrated to vary significantly between vegetation groupings (Cajander 1926, Lindsay 1939, Daubenmire 1961, Corns and Pluth 1984, Monserud 1984a). In addition to the invariance of curve shape for each height/age model across the vegetation strata, the present work provided no indication of a relationship between karri H and overstorey species composition (*e.g.* pure versus mixed stands). Consequently, H strata may not be readily inferred from the existing age class and species composition classification of the regrowth estate.

The resolution of the site strata may have been improved by integrating the separate classifications into one. Such an approach is exemplified by the biogeoclimatic ecosystem classification (BEC) system used by the British Columbia Forest Service (Pojar *et al.* 1987). This classification integrates stable plant communities with their climate, soil moisture, and soil nutrient regimes. Green *et al.* (1989) reported significant differences in Douglas–fir site index (estimated using polymorphic site index curves) among site classification units of the BEC system. The need for such detailed integration of site processes has been stressed by many mechanistic growth modellers (Kimmins 1985). Landsberg (1986), for example, suggested site classification for timber growth and yield should involve modelling the potential growth of a site in terms of dry matter production and its nutrient dynamics.

The similarity across classification strata of H growth pattern at the regional level does not preclude the possibility of pattern at lower levels of sampling resolution. For example, at a genotypic level Knowe and Foster (1989) have reported polymorphism in dominant height growth between families of *P.taeda*. Similarly, Monserud (1988) reported that the genetic constitution of Douglas–fir was about a third more important than environment in determining phenotypic variation in H amongst natural stands. Schuster (1979), however, found no evidence from karri provenance trials to suggest any difference in height growth rate or pattern of young trees raised from seed collected from different river catchments within the main forest zone. Recent work by Coates and Sokolowski (1989) on the geographic patterns of genetic diversity in karri also found limited differentiation between the major river catchment populations.

6.3 Evaluation of six site classifications for modelling growth of karri

6.3.1 Introduction

Model (6.7) provided a direct classification of site which might be expected to correlate highly with timber productivity in these vigorous regrowth stands. However, the potential benefits in these multiple-use forests of using an indirect classification either singly or in combination with the site index model warranted an evaluation of the indirect classifications.

The objective of this second stage of the site quality work was to evaluate the utility of each of the existing site classifications (including site index) as a basis for yield projection in regrowth karri stands. Any comparison between alternative classifications must be based upon their ability to predict stand productivity attributes, generate hypotheses, and assist the interpretation of ecosystem dynamics (Goodall 1973, Havel 1980a). Consequently, a secondary objective was to quantify the growth patterns of stands of maximum density within site strata.

6.3.2 Data

Evaluating the utility of each classification involved comparing the measured productivity of the PSPs between the strata or levels of each separate site classification.

6.3.2.1 Stand productivity attributes

The total biomass produced in relation to age has been advocated as the ultimate quantitative measure of even-aged stands approximating full site occupation (Spurr and Barnes 1980). However, total stand biomass was rejected as a productivity measure in these stands because the PSPs had been subjected to prescribed burning regimes at varying frequencies and intensities which are known to interact in a complex way with stand age and site in determining the rates of biomass accumulation of the understorey component (Grove and Malajczuk 1985).

Stand totals for net and gross V, B, their periodic and mean annual increment (*PAI* and *MAI*), N, and annual mortality rate were selected as productivity attributes. Each variable was tabulated by species and tree dominance status (dominant and codominant categories, suppressed and subdominant categories) in order to assist in interpreting changes in stand structure and composition with age. Similarly, moment statistics (skewness, kurtosis and mean *d*) of the diameter frequency distribution were computed for each remeasurement of the pure and mixed karri stands. In the pure stands these statistics assisted in defining those of maximum density and the age-dependent pattern of skewness.

6.3.2.2 Site classifications

The five indirect site classifications available for evaluation were described in section 6.2.2.2..

For evaluation of the site index classification each PSP was allocated to one of six *SI* classes: the centre points of the minimum and maximum classes were respectively 30 m and 55 m and the class interval was 5 m. Site Index was measured for a third of the PSPs on stem analyzed trees located outside the plot boundaries. For the remainder, it was estimated using the anamorphic Weibull formulation (model 6.7).

6.3.3 Method

The analysis, which involved four sequential stages, was largely determined by the limited remeasurements available for each PSP. Firstly, the influence of variable stocking on productivity was eliminated by selecting for analysis only those stands which were at maximum density *i.e.* those undergoing substantial, continuous, density-dependent mortality (Curtin 1964, West 1983a). Graphs of each productivity attribute by age were then inspected for pattern within the strata of each classification. Visual inspection of the scatterplots provided only an indication of the within-stratum variance versus the total variance for the attribute/classification combination. 'Guide curves' were fitted to the scatter of attribute/age data, and for each attribute the residuals from the guide curve were subjected to an analysis of variance (ANOVA) to detect significant differences between strata.

6.3.3.1 Selection of stands of maximum density

The influence of variable *N* on productivity was eliminated by analyzing only those stands which had attained maximum density. Nomination of such stands has always incorporated some subjectivity (Weller 1987), but sequential application of the following criteria was designed to provide an objective, quantitative procedure for selecting them.

Because density-dependent mortality only was of interest, plots were discarded if irregular mortality arising from a prescribed burn, wildfire, or insect attack had occurred in the vicinity of the plot during the measurement interval (see Lee 1971).

'Substantial' mortality was defined as a reduction in live stem numbers of greater than 0.7% per annum between remeasurements. This figure is consistent with values of

0.5% used by Newton (1988) for black spruce (*Picea mariana*) in Canada and 1.0% by West (1985) for mountain ash (*E.regnans*) in Tasmania.

'Continuing' mortality is usually ascertained from a sequence of remeasurements. However, because only one remeasurement was available for most plots, three indirect approaches were used:

(i). Continuing density–dependent mortality implies the death of subdominant and suppressed trees within the stand (Zeide 1987). Inspection of graphs of d versus d increment for the initial growth period indicated whether or not suppressed and subdominant trees with negative increment were present, indicating incipient death (Hopkins 1968, Ashton 1976, West 1981a). Because the d frequency distribution within a density–stressed population is usually positively skewed and density stress results in the death of the smallest sized individuals (Ford 1975, Harper 1977, Mohler *et al.* 1978, Westoby 1984), stands with a marked departure from positive skewness were screened for evidence of abnormal stand history.

(ii). Full site occupation and the presence of substantial, continuing mortality infers crown or canopy closure, with the stand in an asymptotic volume/density condition and 'positioned along' the self–thinning line (Zeide 1987). A tree location plan was prepared for each PSP and crown positions (assuming circular crowns derived from measurements of crown diameter) were superimposed to detect the presence of large gaps in the canopy. Because the relative size of gaps varies with the size of the trees (age of stand), gap size was related to tree size (stage of stand development) by rejecting plots as under–stocked if they contained more than two gaps of combined area exceeding the crown area of the tree of quadratic mean diameter.

(iii). Application of the above criteria reduced the number of plots available for analysis from 214 to 144, despite the plot establishment strategy (Campbell *et al.* 1988) having aimed to select only 'fully–stocked' stands. The proximity of each of the 144 stands to an asymptotic volume–density condition was then assessed by examining studentized deleted residuals (Neter *et al.* 1985 p. 407) from the following fit of the stands to the self–thinning line relationship:

$$V_n = 8717\,N^{-0.497}$$

where V_n and N represent the mid–point values for the selected growth periods of net V and live N respectively. The adjusted coefficient of multiple determination of this equation was 0.91 with a mean absolute residual of 7.8 m^3. The 95% confidence interval for the allometric parameter of −0.47 to −0.52 included the 'theoretical' value of −0.5 (Yoda *et al.* 1963). Fitting this relationship using only pure karri stands (*i.e.* excluding mixed–species stands) did not alter these parameter values ($P<0.05$).

No plots were rejected as outliers from the above relationship when the studentized residuals were compared with the relevant t–statistics, indicating that each stand had reached an asymptotic condition. These stands comprised the final dataset used for evaluating the various site classification methods. They represented the following (minimum–mean–maximum) stand values: age (3–40–132 years), live stocking density (70–2080–17 477 stems ha^{-1}), net basal area (8–24–56 m^2 ha^{-1}), net volume (105–425–1104 m^3 ha^{-1}), and site index (34–43–57 m).

6.3.3.2 Graphical inspection of productivity attributes by age within site strata

For each of the 144 PSPs, the stand attributes were graphed against age within strata for each site classification. Yield relationships were examined using the mid–point values of each growth period, while growth rates were derived from annual increments over the period. Individual graphs were prepared for each attribute for the combined dominance classes and for the stand totals.

The trend of observations across age within the levels of each classification was interpreted according to documented stand dynamics for fully–stocked stands of other eucalypt (Webb 1966, Incoll 1974, Opie *et al.* 1978, Bredenkamp 1984) and temperate tree species (Bakuzis 1969, Assmann 1970). Gross stand volume, for example, was hypothesized to increase across the age classes with increasing site index. Because the clusters or 'stratum levels' of the edaphic, climatic, and vegetative classifications represent differing levels of fusion from the original dendrograms (Inions 1990, Inions *et al.* 1990), adjacent strata in each classification were the most similar edaphically, climatically, or floristically. Knowledge of these relationships (or degree of similarity) assisted the interpretation of the pattern within each graph as it could be examined at increasing levels of strata aggregation.

6.3.3.3 Formulation and parametrization of 'guide curves'

Suitable functions were sought to describe the age–dependent pattern of the stand attributes *N*, gross and net *B*, and gross and net *V*. Using the mid–point values of age as independent variable and the mid–point values of each attribute as the dependent variable, a range of candidate guide curves (functions) was parametrized.

The integral form of the functions of Gompertz (1825), Chapman–Richards (Richards 1959), Weibull (Bailey 1980b), and logistic (Grosenbaugh 1965) was parametrized for *V* and *B*. The derivatives of the curves of best fit were parametrized to model increment (*PAI*) assuming that annual increment approximates the instantaneous rate implied by the differential form. The compatible form was expected to be the most appropriate fit for the rate equation. However, poor convergence was obtained in all cases due to the highly variable increment data for each attribute. For example, the integral form of the base Richards (1959) function gave the best fit for net *V*, but the derivative behaved poorly for volume *PAI*, even when growth was constrained to biologically sensible values using the method developed by Shifley and Brand (1984). Several alternative equation forms were therefore examined.

Exponential decay and inverse logistic (Sadiq 1983) formulations were used to model the *N* with age. Only stands older than 15 years were used due to the difficulties encountered in parametrizing a continuous model for younger stands which could incorporate their highly variable initial stocking density.

Each equation was fitted to the scatter of attribute/age mid-points using ordinary least squares regression. First-order autocorrelation was absent from all regressions, indicating the limited plot remeasurements represent relatively independent observations (*cf.* West *et al.* 1984). Heteroscedasticity was present for both net and gross *B* and *V* and *d* with increasing stand age. In these cases, a final parametrization of the guide curve was obtained using iteratively reweighted least squares regression with individual weights calculated as described in section 5.3.2.2.

6.3.3.4 ANOVA of residuals

Provided no age or strata-by-age effects were evident in the residuals from a guide curve model, the residuals for each attribute were subjected to a mixed-model analysis of variance to test whether mean residuals differed between strata for each classification. Each forest stratum was considered fixed whilst the productivity attribute was viewed as random. The unequal sample sizes between strata necessitated an unbalanced ANOVA with treatment mean squares computed according to procedures outlined in Graybill (1961) and Neter *et al.* (1985).

A significant stratum effect would indicate that separate attribute prediction models would be required for each such stratum within a classification. Mean residuals for each stratum were ordered and compared pairwise using the Tukey (1949) multiple comparison procedure. A family confidence coefficient of 95% was adopted with separate recalculation of the Tukey multiple for each pairwise comparison due to the unequal sample sizes.

6.3.4 Results

6.3.4.1 Stand dynamics within the indirect classifications

The growth patterns represented by the guide curves in Figures 6.3, 6.4, and 6.5 for the maximum density karri stands are typical of the stand dynamics reported for regrowth stands of similar eucalypt species (Ashton 1976, West 1981a, Florence 1988). The 'preferred fit' relationships between stand age and *N*, *B* and *V* are summarized for select attributes in Table 6.8.

None of the indirect site classifications were useful in stratifying the stands into groups of differing productivity and no consistent age-related trends were found for the surviving *N*, *B* and *V* between strata. Figures 6.3, 6.4 and 6.5 illustrate the lack of correlation between stand variables and the edaphic, climatic, and vegetative classifications respectively. The almost random scatter of observations around each

Table 6.8 Final guide curve equations relating each stand productivity attribute to age for the 144 maximum density stands.

			Fit statistics[b]	
Stand attribute	Equation[a]	R^2_a	MSE	Eqn number
Stocking density (Stands >15 yrs)	$N = 2961 \exp(-0.0349A)$	0.67	1.675	(6.8)
Basal area net	$B = 45.82\,[1-\exp(-0.0293A)]^{0.6311}$	0.64	41.22	(6.9)
	$\mathrm{PAI} = 31.91\,(A)^{-1.247}$	0.73	0.2481	(6.10)
gross	$B = 47.43\,[1-\exp(-0.0271A)]^{0.6290}$	0.63	41.99	(6.11)
	$\mathrm{PAI} = 26.86\,(A)^{-1.158}$	0.71	0.2336	(6.12)
Mean DBHOB	$d = 4.321 + 0.5413\,(A)$	0.93	2.476	(6.13)
Volume net	$V = 1605\,[1-\exp(-0.0073A)]^{1.082}$	0.76	419.1	(6.14)
	$\mathrm{PAI} = 14.47\,[\exp(-0.0112A)]$	0.36	22.75	(6.15)
gross	$V = 1760\,[1-\exp(-0.0062A)]^{1.045}$	0.77	415.8	(6.16)
	$\mathrm{PAI} = 13.54\,[\exp(-0.0057A)]$	0.37	20.94	(6.17)

[a] All regression coefficients are significant ($P<0.05$). A denotes stand age.

[b] The adjusted coefficient of multiple determination (R^2_a) is provided only for broad illustrative purposes. Most equations represent iteratively reweighted solutions.

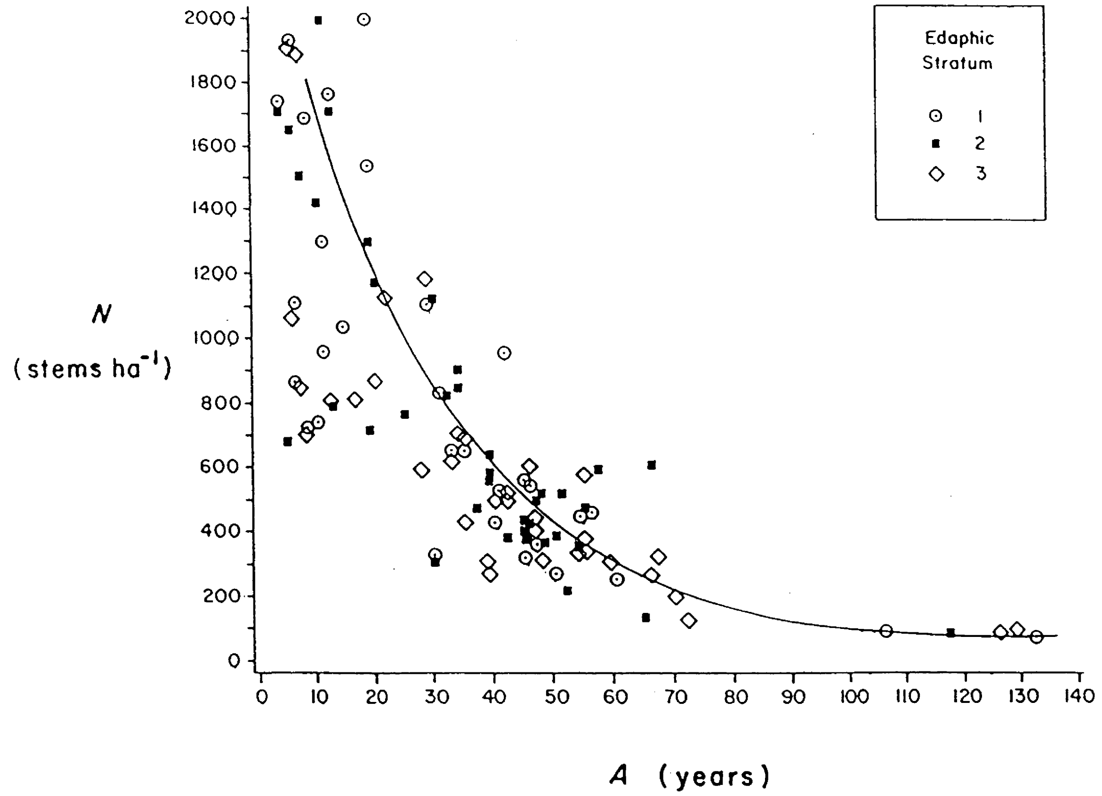

Figure 6.3 Total stocking densities (live stems per hectare) by stand age within edaphic strata for maximum density regrowth karri stands. The solid line shows the fit to the data of the guide curve Model (6.8). Note that only stands of less than 2000 stems per hectare are illustrated to increase the clarity in this figure.

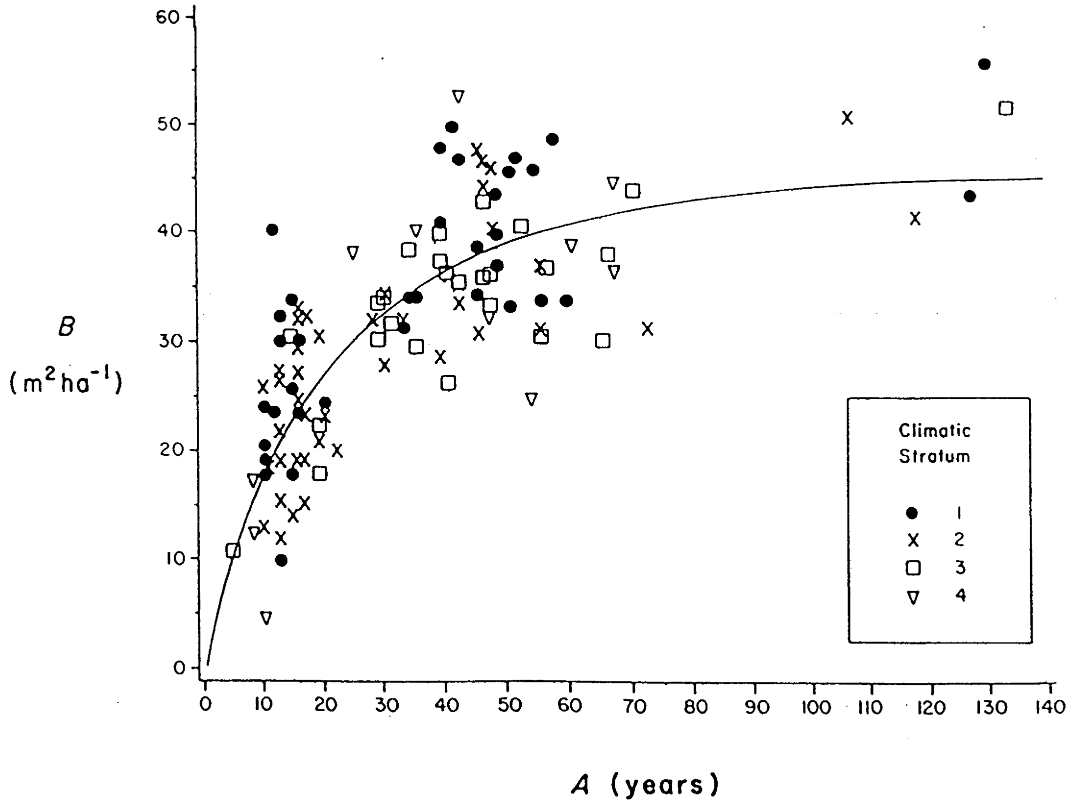

Figure 6.4 Total net (live) stand basal area over bark per hectare by stand age within climatic strata for maximum density regrowth karri stands. The solid line shows the fit to the data of the guide curve Model (6.9).

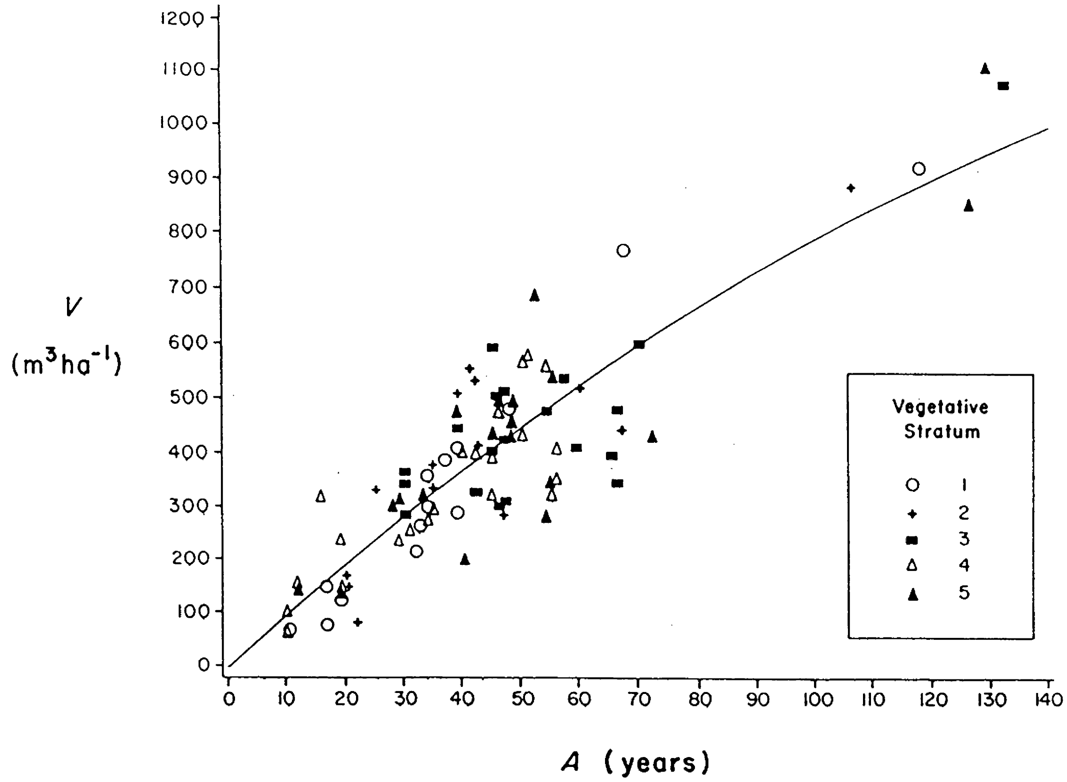

Figure 6.5 Total net (live) stand volume (to 5 cm top diameter) per hectare by stand age within vegetation strata for maximum density regrowth karri stands. The solid line shows the fit to the data of the guide curve Model (6.14).

guide curve for each classification stratum was repeated when the productivity measures were segregated by crown categories.

Each classification was also inconsistent between stand attributes. For example, the lower levels of aggregation for the edaphic and vegetative classifications (5 and 13 levels respectively) provided weak and inconsistent separation of one or two site categories possessing higher or lower net B than other strata within the classification. However, these trends were not repeated with N and net or gross V. For the 8-level climatic and 13-level vegetative classifications a weak, consistent trend of volume separation was observed for only 3 strata. The direction of the trend was inconsistent with the fusion hierarchy used to aggregate the stands when the classifications were originally defined. Similarly, in the 5-level edaphic classification groups 2 and 5 possessed the highest and lowest d for each stand age, but these trends were not consistent with the skewness and kurtosis patterns of the d-distributions.

The inconsistent behaviour between productivity attributes within the one classification was reflected in the ANOVA of residuals from the guide curves. In most instances an individual stratum within a classification possessed a higher or lower N, B or V across all stand ages than all other strata. This produced significant differences ($P<0.05$) in the ANOVA between mean stratum residuals from the guide curve for many attributes (Table 6.9). However, when strata were ordered and compared pairwise, generally only one stratum in the classification was significantly different from the others, indicating the poor resolution of each classification. This was particularly evident for the Overstorey Composition classification, where the statistically significant differences between strata reported in Table 6.9 for the N and V attributes resulted from inconsistent differences between only two strata in the classification.

Although there was a tendency for mixed karri–jarrah stands to have the lowest volume PAI across all stand ages, the vegetation classifications in general did not discriminate between pure and mixed-species stands for any of the productivity attributes. This consistency was probably due in part to the restricted range in species composition represented in the PSPs (*i.e.* in stands containing less than 20% minor species).

Annual increment in B and V (net and gross) varied consistently among strata of the climatic classification. In the 8-level classification, homoclime 2 had the highest increment ($P<0.05$) through to homoclime 5 the lowest. This pattern was absent from the B and V attributes, suggesting that it might have represented short-term climatic fluctuations. However, the trend was not apparent with mortality rate and volume MAI (net and gross) which were both highly variable. As well, the BIOCLIM data from which the climatic classification were derived represent long-term (smoothed) trends for each attribute, and therefore would not necessarily represent the short-term drought conditions which prevailed over much of the study region during the measurement period 1981–1985.

Table 6.9 Probability values of the 'between stratum' tests from mixed-model analysis of variance (ANOVA) for residuals from guide curves for each stand productivity attribute. Values in bold type indicate that mean residuals for at least one stratum in the classification differed significantly ($P<0.05$) from the group mean. Data refer to the stand totals for each attribute.

Stand attribute		Probability value								
				Site classification						
		Site index	Landform	Edaphic		Climatic		Vegetative		Overstorey composition
				3-level	5-level	4-level	8-level	5-level	13-level	
Stocking density (*N*)	Net	**0.0001**	**0.0210**	0.4381	0.6217	0.0733	0.0886	**0.0291**	0.0621	**0.0307**
	Gross	**0.0012**	0.0563	0.4645	0.6866	0.0906	**0.0335**	**0.0175**	0.1841	**0.0299**
	AM %[a]	**0.0022**	0.3117	0.3555	0.3961	**0.0431**	**0.0220**	0.1989	0.2526	**0.0154**
Basal area (*B*)	Net	0.1031	0.5543	0.3965	**0.0464**	0.1916	0.2200	0.5235	**0.0368**	0.6750
	Gross	0.1182	0.5882	0.3248	0.2929	0.1653	0.2868	0.4920	**0.0071**	0.5916
	MAI(net)[b]	0.1662	0.7131	0.5612	0.0926	0.2771	**0.0001**	0.4133	0.6363	0.2494
	PAI(net)[b]	**0.0268**	**0.0336**	0.1783	0.1336	0.3189	**0.0241**	**0.0428**	**0.0084**	**0.0013**
Volume (*V*)	Net	**0.0001**	0.0531	0.4838	0.2137	0.1145	0.1791	0.5324	0.1295	**0.0296**
	Gross	**0.0001**	**0.0477**	0.4179	0.2440	0.1432	0.2352	0.4651	0.1471	**0.0054**
	MAI(net)[b]	**0.0001**	0.1782	0.2600	0.5475	0.4120	0.2046	0.3300	**0.0464**	0.1337
	PAI(net)[b]	**0.0031**	0.2731	0.3365	0.0892	0.2117	**0.0006**	0.2778	**0.0031**	**0.0061**
Mean diameter (*d*)		**0.0001**	0.1313	0.1758	**0.0043**	0.1896	0.3935	0.0966	0.1875	0.2234

[a] Percentage annual mortality
[b] Similar results were obtained for the gross data

6.3.4.2 Stand dynamics within *SI* classes

Inspection of stand dynamics within site index classes confirmed that *SI* provided a consistent segregation of stands for most productivity attributes. Within stands of comparable age, higher site indices were associated with a lower live *N*, increasing net *V* (Figure 6.6), and higher *d* (Figure 6.7) across the range of age and species composition represented in the data. The strong positive correlation of *d* with *SI* class was associated with a lesser skewness of the *d*–distribution on the higher site indices.

These consistent trends across the *SI* classes can be partially attributed to the mathematical correlation among the direct measures. For example, stand volume is positively correlated with stand top height in many even–aged eucalypt stands (Webb 1965), so the positive correlation of both gross and net volume *MAI* and *PAI* with site index could be expected from the correlation of *V* with site index. Similarly, for many species, the *B* of closed stands has been shown to be highly correlated with *V* for a given site class and age (Daniel *et al.* 1979).

Karri is characterized by fast growth rates and a capacity to rapidly occupy a site in the early years of stand development. This leads to intense density–dependent competition and hence self–thinning among individual trees in the stand. Segregation into crown (or tree vigour) classes rapidly occurs in these vigorous stands and a suppressed and subdominant stratum develops. Slower rates of density–dependent mortality and segregation into crown dominance classes occurred in stands of lower site index (<40 m). In contrast, stands of higher index (>45 m) had fewer dominants and codominants but their *d* was larger. This trend was not as apparent in the subdominant and suppressed crown classes, where weaker trends of higher site index having fewer stem numbers were observed.

Variation in net basal area and basal area increment with site index was inconsistent. The stands of highest site index represented median values, the stands of lower site index having *B*s randomly scattered around this 'guide curve'. This was unexpected and does not conform to the relationships of either directly or inversely proportional to site index observed for other eucalypts (Opie 1972, Incoll 1974).

Karri stands, both pure and mixed species, of higher site index (>45 m) generally carried a higher proportion of *V* in dominants and codominants than did stands on poorer sites.

6.3.5 Discussion

6.3.5.1 Utility of indirect site classifications

The most striking, and disappointing, feature of these results was the failure of each of the climatic, edaphic, landform and vegetative classifications of site to facilitate interpretation and prediction of stand dynamics. This was unexpected given the broad correlations observed in the field between the occurrence of old–growth karri and many

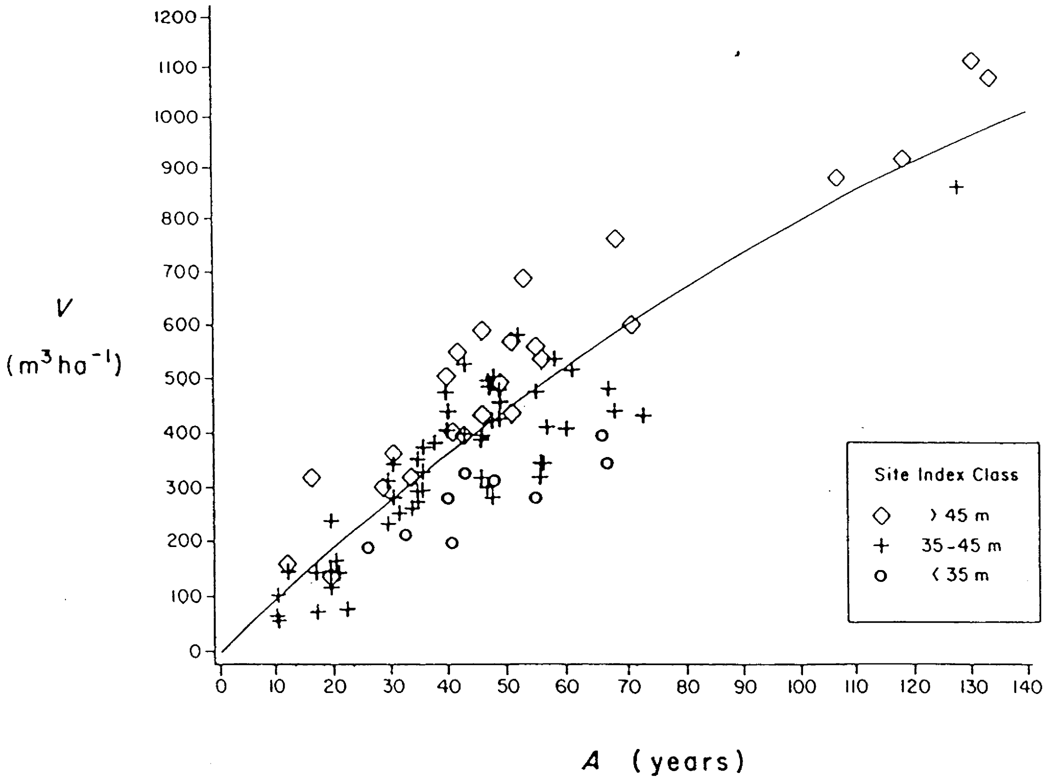

Figure 6.6 Total net (live) stand volume (to 5 cm top diameter) per hectare by stand age within three site index (stand top height at 50 years) classes for maximum density regrowth karri stands. The solid line shows the fit to the data of the guide curve Model (6.14).

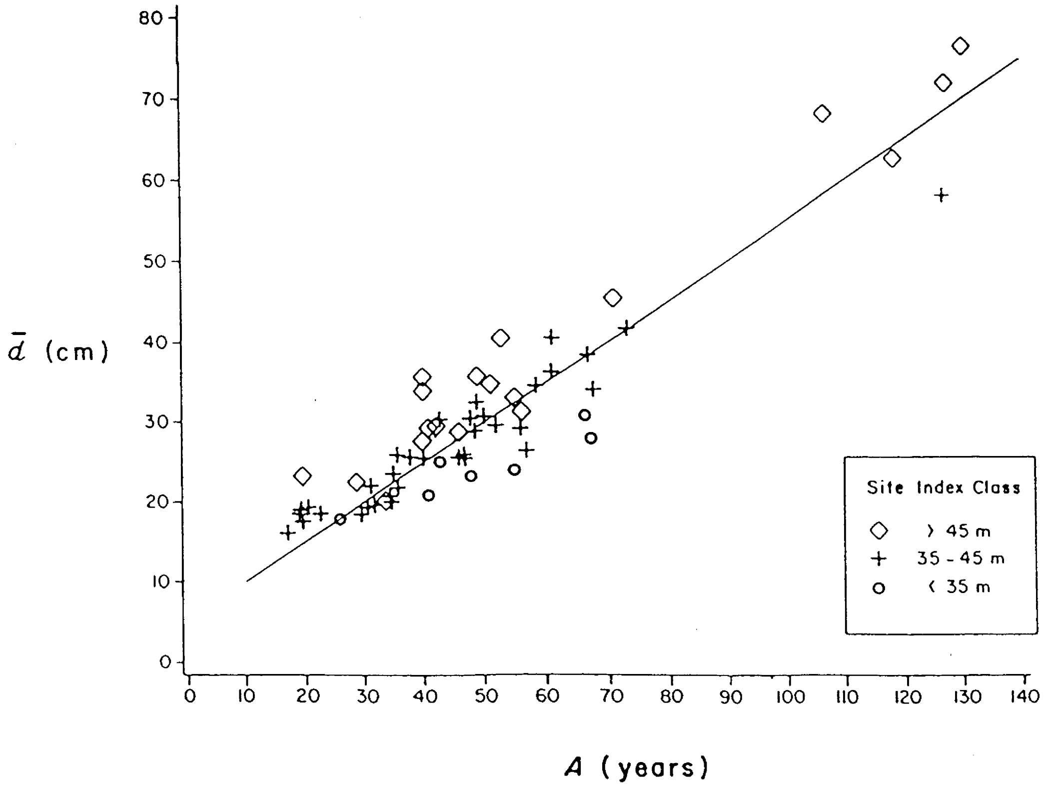

Figure 6.7 Stand Mean *d* (cm) by stand age within three site index classes for maximum density regrowth karri stands. The solid line shows the fit to the data of the guide curve Model (6.13).

of the regional–level attributes used in deriving the site classifications. Bradshaw and Lush (1981), for example, interpreted the broad soil surveys of McArthur and Clifton (1975) to describe the strong association between the existing mozaic pattern of karri distribution and the soils and landforms of the lower South–West region. Both Loneragan (1961) and Churchill (1968) had previously emphasized the dominating influence of annual and seasonal rainfall on the distribution of karri. Beard (1981) reviewed these studies and concluded that the distribution of karri was limited firstly to sites with fewer than four dry months per year, and within this climatic range, to sites with favourable soil types. These broad factors were inferred by each author to correlate with the productivity of regrowth stands on these sites. This study suggests that whilst these indirect classifications may be useful in delimiting species occurrence they are inadequate for precise, quantitative comparisons of timber productivity.

The consistent lack of discrimination by these classifications for each stand productivity attribute suggests that karri tree and stand growth are insensitive to the site variables used in the classification process. That is, the climatic, edaphic and landform variables apparently failed to measure the true determinants of site productivity, whilst the vegetative classifications failed to effectively represent their combined influence on stand growth. This insensitivity may have arisen from the omission of important discriminating variables from the classifications. For example, the possibility that important discriminatory soil variables were not sampled in preparing the edaphic classification was noted by Inions (1990). In particular, wide variation in the concentration of trace elements such as zinc, copper and cobalt have been recorded in karri soils (McArthur and Clifton 1975), but were omitted as classificatory variables when the PSPs were sampled. Similarly, Inions (1990) excluded all soil nitrogen variables from the dataset used to derive the classification because of the high within-plot variance of these attributes. However, the capacity of nitrogen to limit stand productivity has been demonstrated for karri by Loneragan and Loneragan (1964) and Grove (1988).

Alternatively, a discriminating variable may have been rendered ineffective by the adoption of a 'coarse' measurement scale or technique when sampling to derive the classifications. For example, the importance of soil phosphorus in the eucalypt ecosystem has been emphasized by Richards and Charley (1983) and for karri in particular by Grove (1988). However, the concentrations of phosphorus reported by Inions (1990) are particularly low and have a small range compared to other soil studies both within and outside the karri zone (*cf.* McArthur and Clifton 1975, Bowman and Kirkpatrick 1986, Attiwill and Leeper 1987). Although direct comparisons of soil chemical data, particularly phosphorus, are confounded by differences in soil sampling technique, location of sample within the horizon, and the chemical extraction method, revised estimates of soil phosphorus for the karri stands may have improved the capacity of the edaphic classification to stratify site productivity.

Similarly, the values for the meteorological variables selected when developing the climatic classification were obtained from the BIOCLIM database by interpolating data collected at the closest meteorological stations and using smoothing techniques (see Hutchinson and Bischof 1983). Site–specific micro–climatic data (*cf.* the macro–climatic variables used in this work) may be more highly correlated with tree physiological processes and hence more appropriate to distinguish between stands on their potential for growth (Denton and Barnes 1988, Holdaway 1988). Site micro–climate is markedly influenced by local topography and physiography, and field observations suggest that both of these variables correlate well with the occurrence of overstorey species in karri.

There is a clear precedent for the lack of correlation between the vegetation strata and timber productivity (Tesch 1981, Schönau 1987, Green *et al.* 1989). Jahn (1972), in particular, challenged the utility of solely floristic classifications to characterize optimum (*cf.* extreme) sites, while Havel (1980b) and Barnes *et al.* (1982) stressed the need to adopt an ecological approach which explicitly combines vegetation with environmental factors. Although Inions *et al.* (1990) concluded that there was a significant relationship between the floristic composition of the regrowth karri stands and certain edaphic and climatic variables, this relationship did not translate into a meaningful stratification of timber productivity.

The lack of discrimination by the indirect methods used in this study to classify site emphasizes that the choice of site attributes, how they are measured, and the intensity of sampling required to develop a satisfactory classification is complex (Spurr and Barnes 1980, Schönau 1987). The importance to tree growth of soil nutrient levels, temperature regimes and water availability is well documented (Kozlowski 1982, Landsberg 1986, Sands and Mulligan 1990) but the relative importance of each is likely to vary with species and site (Kimmins *et al.* 1990). Grey (1987), for example, demonstrated the complexity of the relationships between mensurational parameters and climatic and edaphic factors for *Pinus radiata* stands in the Southern Cape region of South Africa, and stressed the difficulty of incorporating such relationships into traditional stand–level yield prediction models. Thus, an alternative explanation for the poor predictive capacities of the indirect classification methods used in this study could be that the number of complex, interacting site factors across the endemic range of the karri estate far exceeded the limited number of sample plots (144) used in the analysis. Monserud (1990) speculated that a possible reason for the lack of soil–site correlations in his study of site productivity for inland Douglas–fir was the limited sample size of 133 plots. Hall (1956) attributed the poor correlation between a number of soil variables and *E.obliqua* productivity to the narrow ecological range represented by his sample of fully–stocked stands. Outlier populations of karri located at Boranup, Porongorup and Albany were excluded from this study, but as these stands occupy limestone–derived soils their inclusion may have accentuated the contrasting effects of soils on tree growth. Similarly, the apparent similarity between the productivity of pure karri and mixed karri–marri stands should be treated with caution due to the limited sample size and species representation within the PSPs. The comparative productivity of pure versus mixed–species stands is an issue of considerable management importance in the regrowth estate (White 1971), but the analyses of management strategies that favour alternative species composition are best performed using balanced experimental designs in which site factors are controlled in order for valid hypothesis testing (Kelty 1989). A series of studies would be required in which species composition is controlled in a designed experiment on experimental units established on similar sites.

6.4 Conclusion: defining site in regrowth karri

Results presented here confirm that site index is an appropriate basis for stratifying the regrowth karri estate. Stratification based on *SI* enables the few remeasurements presently available for each PSP to be arranged into a homological growth series (Zeide 1987) for yield modelling. The consistency between the stand dynamics of karri stratified by *SI* and that of other eucalypt species provides a useful starting point in modelling the growth and yield of karri. Such comparisons are important when, as in the case of karri, limited stand treatment data are available and stand response to silvicultural treatments must be inferred from the response of similar species.

The indirect classifications are obviously inadequate by themselves in defining productivity strata for growth and yield modelling. However, one option is to combine an indirect classification with a direct classification which uses some type of height/age relationship or other direct measure (Spurr and Barnes 1980, Hagglünd 1981, Monserud 1984b). Unfortunately, the lack of pattern at each level of each of the karri classifications suggests that such a procedure would be ineffective. This view is reinforced by the earlier findings of the invariance of the parameters of the stand dominant height/age curves across each of the indirect classifications (section 6.2.4.2). Other alternatives, such as the construction of a detailed integrated classification of similar detail to the Biogeoclimatic Ecosystem Classification described by Pojar *et al.* (1987) or the direct modelling of site process variables (Landsberg 1986, West 1987, McLeod and Running 1988) would involve extensive data collection and development costs which could not presently be justified solely for the purpose of predicting timber yield.

Thus, the site index model (6.7) provides a regional site stratification which can be used to assist inventory, the scheduling and assignment of silvicultural treatments, and the development of the growth model.

CHAPTER 7 GROWTH MODEL DEVELOPMENT — STAND LEVEL COMPONENTS

7.1 Introduction

In this chapter the development, parametrization and validation of stand–level components of the growth and yield simulator for regrowth karri stands is described. An overview of the complete model design is presented, followed by a description of each of the dominant height growth, stand initialization, gross basal area increment estimation, and stand ingrowth modules.

7.2 KARSIM - an overview

7.2.1 Model design

KARSIM (**k**arri **r**egrowth **sim**ulator) is an individual–tree level model for simulating the growth and yield of even–aged karri stands. As discussed in Chapter 4, the design and structure of KARSIM is an adaptation of the STANDSIM model developed by Opie (1972) for regrowth ash forests in Victoria. The STANDSIM model has been comprehensively described elsewhere (Incoll 1974, Campbell *et al.* 1979).

Figure 7.1 shows the main model components, their interactions, and the flow of program control for the simulation process. KARSIM comprises a series of integrated modules which predict the development of stand and tree attributes on an annual time step. The core of the model is the representation of individual trees in the stand by their diameters within an array. All growth, mortality, and stand treatment processes update and adjust this array. Model components are deterministic, with the exception of the mortality component.

The initial stand condition is described by the stand level variables A, H (or SI), B and N. The d distribution may be input as the number of stems within d classes or, for unthinned stands, generated via a Weibull cumulative probability density function, the parameters of which are determined from the stand statistics. Following stand initialization, tree and stand volumes are computed for later output in a yield table.

The main growth cycle commences with projection of H increment. Depending upon stand H and thinning history an estimate of ingrowth into the smallest (10 cm) d class is computed, followed by computation of I_{Bg}. The I_{Bg} is then allocated among the number of trees in the stand. An estimate of mortality over the increment period reduces the live stocking density within the diameter array at the end of the increment period. Thinning is simulated by removing trees from the diameter array according to general rules derived from present thinning operations in the regrowth forest. Up to five successive thinnings can be simulated, with an option on each occasion of either uniform thinning from below or strip thinning.

Summaries of live and dead V in size assortments are generated by aggregation of individual tree (or class) volumes. Tree volumes are computed using a three–stage

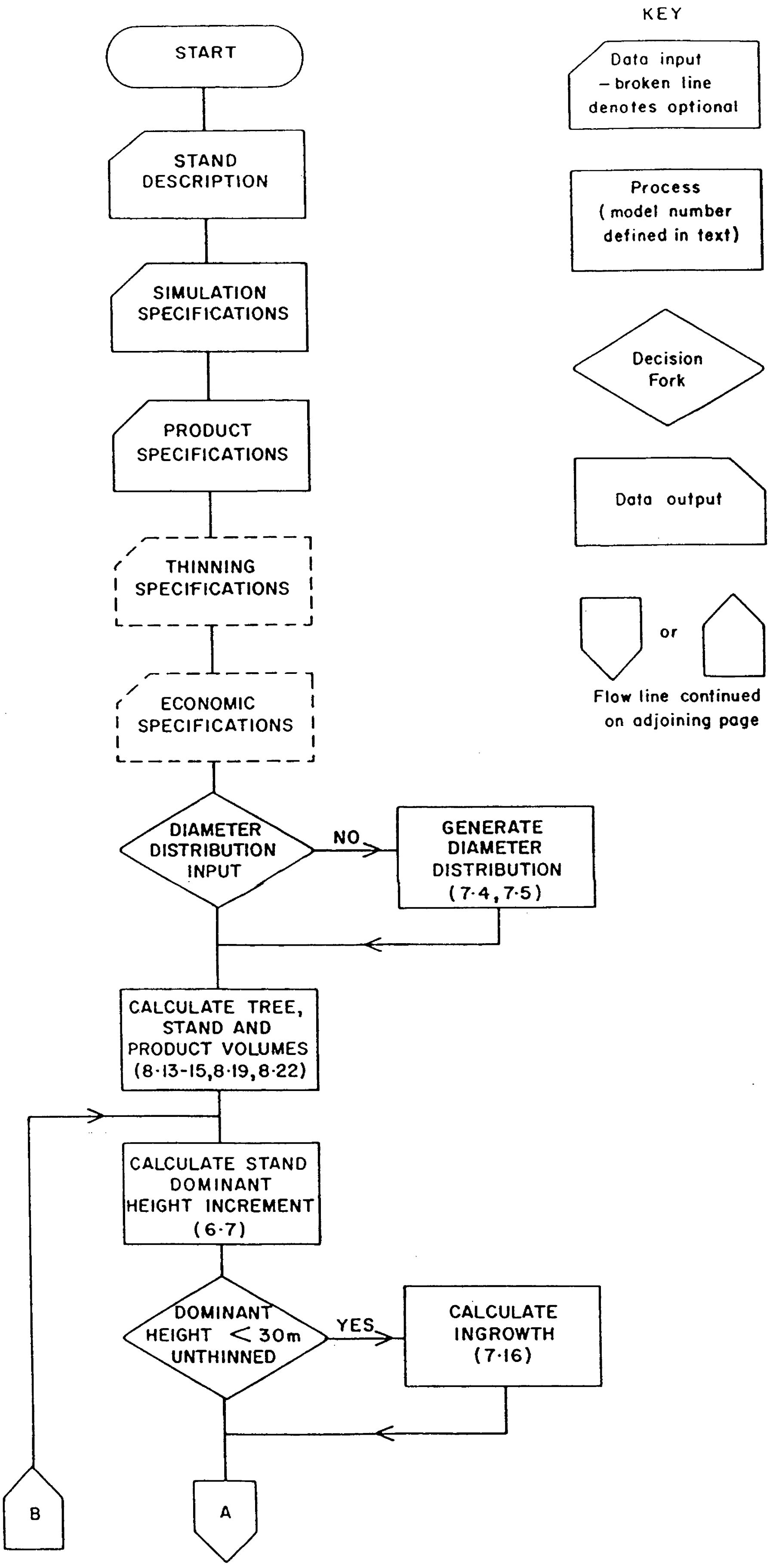

Figure 7.1 Flow chart representation of the main program of KARSIM.

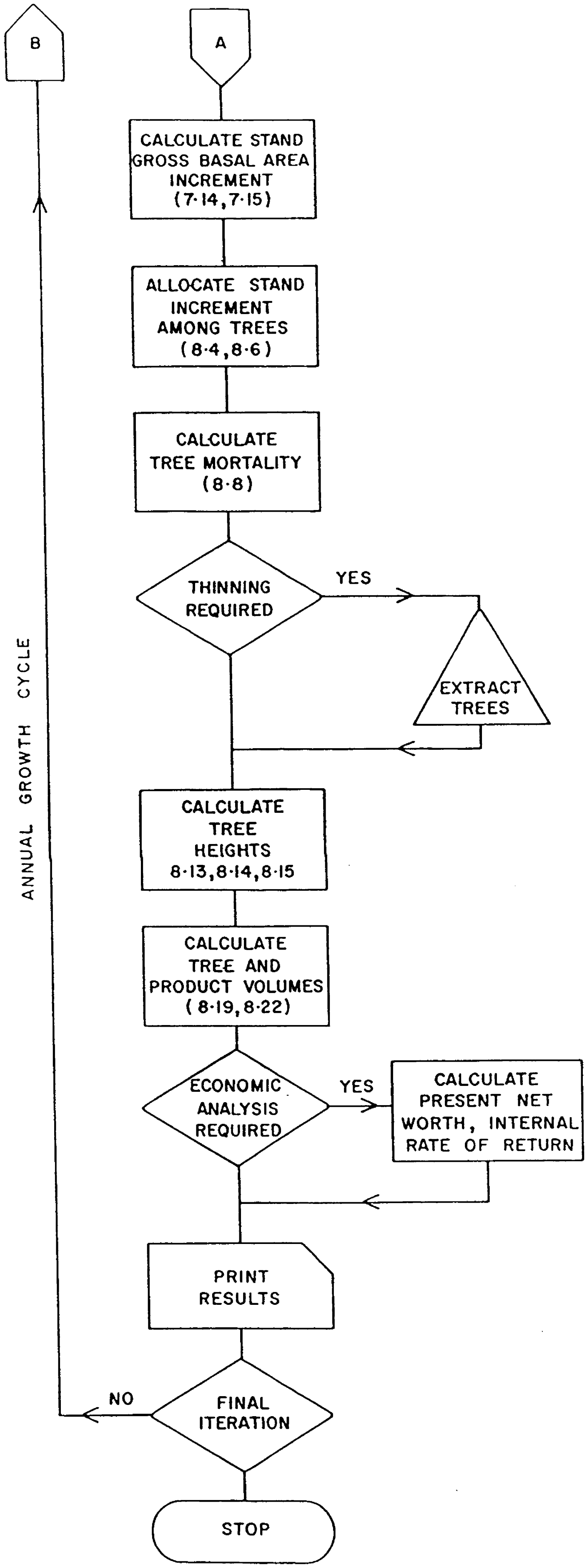

Figure 7.1 (continued)

process. Firstly, tree *h* is estimated from a logistic function of *d*, the parameters of which are estimated from stand–level variables. Total tree volume (*v*) is then computed using a Schumacher–type function before taper functions are applied to estimate volumes to user–specified product dimensions. Standard tabular output of gross and net *V*, *B*, and *N* are produced, within *d* classes if specified.

An economics module enables the Present Net Worth and Internal Rate of Return to be output for each simulation. Real interest rates, overhead levels and establishment and tending costs can be varied by the user.

7.2.2 Model implementation

KARSIM is written in ANSI–Standard FORTRAN–77 operating on a VAX 8650 computer. The VAX DEBUG utility was used extensively in program verification. Model construction was expedited by the direct incorporation of those sections of STANDSIM source code dealing with array handling and storage. These subroutines were adapted with minor modification from STANDSIM Version 11/83 (Incoll 1983).

7.2.3 Design restrictions

Model generality was restricted by the nature and quality of the available data. Stand simulation commences at age 10 or older, and the model simulates only stems larger than 10 cm *d*. The absence of distance–dependent or crown zone parameters restricts the application of the model to stands of relatively uniform spacing.

7.3 Stand dominant height

The integrated effect of all environmental factors determining site potential is assumed to be adequately quantified by site index. Stand dominant height is therefore a primary driving variable in the model. Estimates of *H* growth are derived for any stand using model (6.7). Height is predicted from *A* and *SI* only if a direct measurement of *H* is not available.

7.4 Stand initialization

Within KARSIM a stand is characterized by its *A*, *H*, *B*, and *N*. Values for each of these variables must be specified to initialize a stand for simulation. In addition, the distribution of tree *d*s within the stand must be defined, as individual trees are represented by their *d*s in an array. For inventory update applications this is likely to be supplied directly from inventory plot measurements. For stand simulation, however, a more general approach is to generate a hypothetical distribution by estimating the parameters of a probability density function (*pdf*) from stand–level variables (Hyink and Moser 1983).

7.4.1 Selection and fitting of an appropriate probability density function

Bailey and Dell (1973) define criteria for selecting a suitable *pdf* for modelling stand diameter frequency distributions and review a range of available functions. The Weibull function (Weibull 1951) was selected to model the *d* distribution of unthinned regrowth stands on the basis of its flexibility, ease of integration to determine the proportion of the total trees per hectare within *d* classes, and most importantly, because preliminary investigations confirmed that it provided an adequate basis for describing the full range of observed unimodal distributions within the regrowth stands.

The three–parameter Weibull *pdf* with location parameter a, scale parameter b, and shape parameter c is

$$f(d, a, b, c) = c/b\,[(d - a)/b]^{c-1} \exp\{-[(d-a)/b]^{c}\} \qquad (7.1)$$

for $d \geq a$, $a \geq 0$, $b > 0$, $c > 0$
where *d* denotes tree diameter over bark

Integration of the *pdf* gives a corresponding sigmoid–shaped cumulative density function (*cdf*) given by

$$F(d, a, b, c) = 1 - \exp\{-[(d-a)/b]^{c}\} \qquad (7.2)$$

The location parameter a may be interpreted as the lower limit of the first *d* class to have a non–zero frequency. In the case of inventories of densely stocked regrowth stands of karri, only those stems larger than 10 cm *d* are measured on temporary plots, thereby fixing the value of a to 10.0 for a large range of stand ages. PSPs in unthinned stands younger than approximately 70 years contained stems of this minimum size.

Consequently, the following left–truncated, two–parameter form of the Weibull *cdf* was fit to each PSP for each measurement:

$$F(d, b, c) = 1 - \exp\{(10.0/b)^{c} - (d/b)^{c}\} \qquad (7.3)$$

where $d \geq 10.0$, b and $c > 0$, and 10.0 is the left truncation point.

Joint maximum likelihood estimation (Cohen and Whitten 1983) was selected to solve for the values of the Weibull parameters, as it is generally regarded by statisticians to be best at estimating known parameters in terms of mean square error (Shiver 1988). Maximum likelihood estimation requires iteration in a system of three equations to obtain parameter estimates. The computer program WEIBUL (Zutter *et al.* 1982), which incorporates a constrained modified quasilinearization process described by Wingo (1973), was used for this purpose. Parameter values were obtained for all unthinned stands expressing unimodal continuous distributions, providing a total of 566 measurements from stands aged less than 70 years. Only stands sampled by plots larger than 0.006 hectares had sufficient stem numbers (>30) to adequately quantify the distribution (Shiver 1988).

The chi–square and Kolmogorov–Smirnov statistics, and the sum of the absolute deviations of the observed from the predicted distribution, were used to determine the goodness of fit for each PSP. All three fit statistics were computed using observed and predicted frequencies within 2 cm size class intervals. There was no significant difference ($P>0.05$ at least) between the observed and predicted *d* distributions for 548 of the 566 measurements.

7.4.2 Prediction of Weibull *cdf* parameters from stand variables

The next stage in developing a model to generate initial diameter distributions was to identify a model to predict the *cdf* parameters from measured stand variables. This model was restricted to unthinned stands only because of the limited range of thinned stands across the site and stand density range.

Two and three–dimensional graphs of each *cdf* parameter by combinations of the stand variables were examined to indicate likely functional forms. Candidate stand variables included *A*, *B*, *N*, *SI*, *H*, measures of relative stand density (described in section 7.5), and stand quadratic mean diameter (D_q, calculated as $[B/\mathrm{k}N]^{1/2}$, where k is the constant $\pi/40000$ required to convert d^2 to B). A strong linear relationship between the scale parameter (b) and D_q was evident from this graphical inspection. The relationship between the shape parameter (c) and the stand variables was not clearly indicated, and many alternative equation forms involving the independent variables and their interactions were parametrized for the shape parameter. The following models were selected as the best predictors:

$$\mathrm{b} = \alpha + \beta D_q \qquad (7.4)$$

$$\mathrm{c} = \exp(\alpha + \beta H + \gamma N + \delta D_q) \qquad (7.5)$$

Parameter estimates for equation (7.4) and (7.5) were obtained using ordinary least squares regression on a dataset in which all but one observation from each PSP had been randomly rejected. This enabled exact significance tests to be performed (West *et al.* 1984). An iteratively reweighted least squares procedure was necessary to overcome variance heterogeneity associated with equation (7.5). Parameter estimates for these models are given in Table 7.1, while the relative observed and predicted frequencies within 4 cm *d* classes are shown for three unthinned stands in Figures 7.2–7.4.

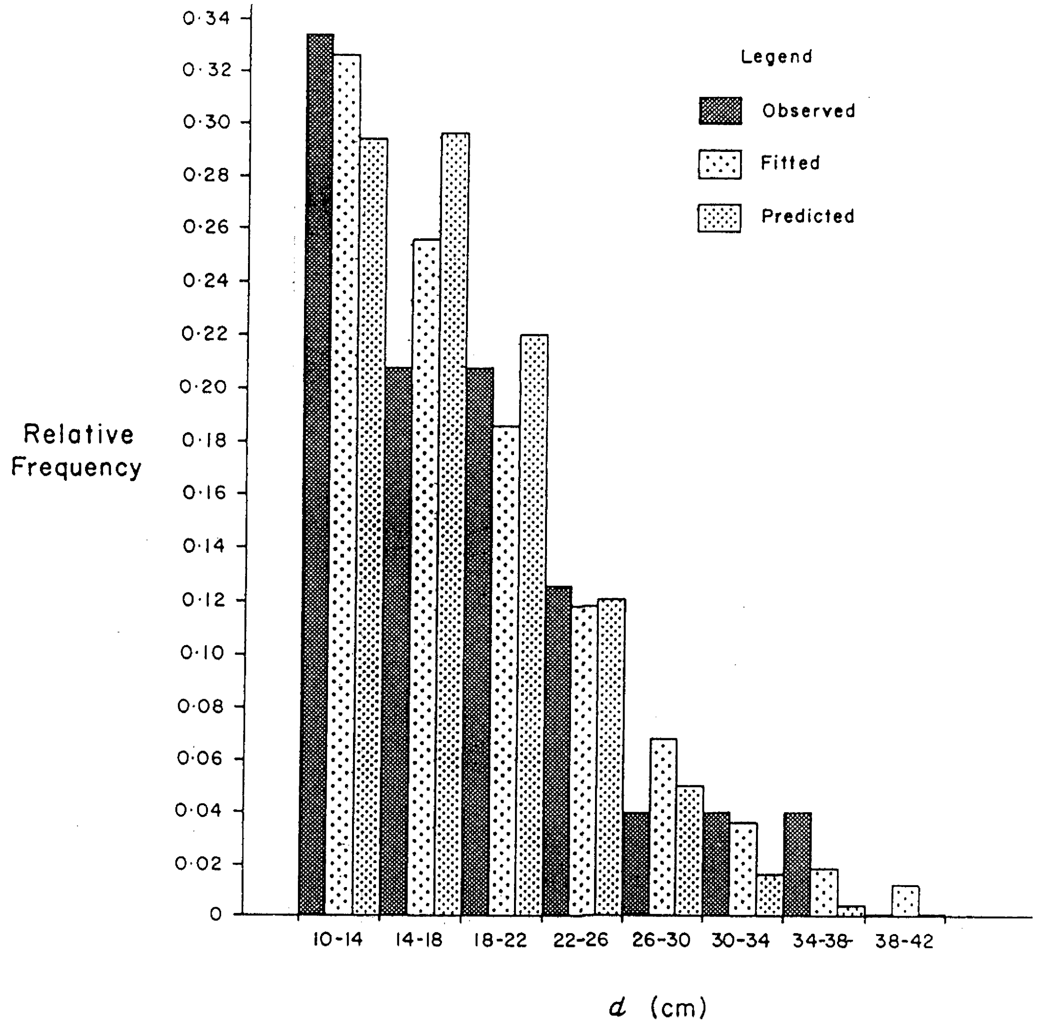

Figure 7.2 Observed, fitted and predicted *d* frequency distributions for an unthinned stand aged 19 years (PSP 837).

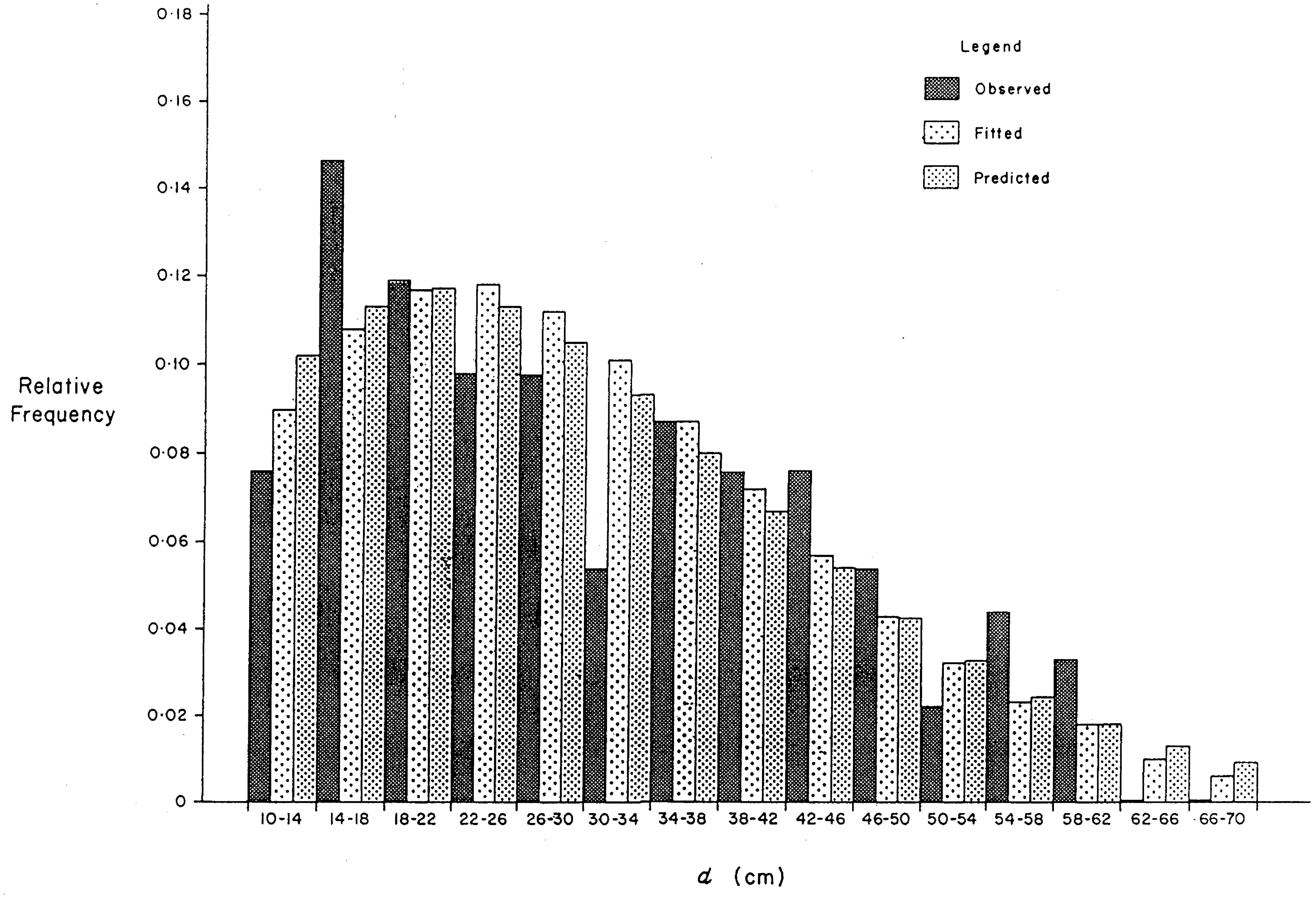

Figure 7.3 Observed, fitted and predicted *d* frequency distributions for an unthinned stand aged 42 years (PSP 935).

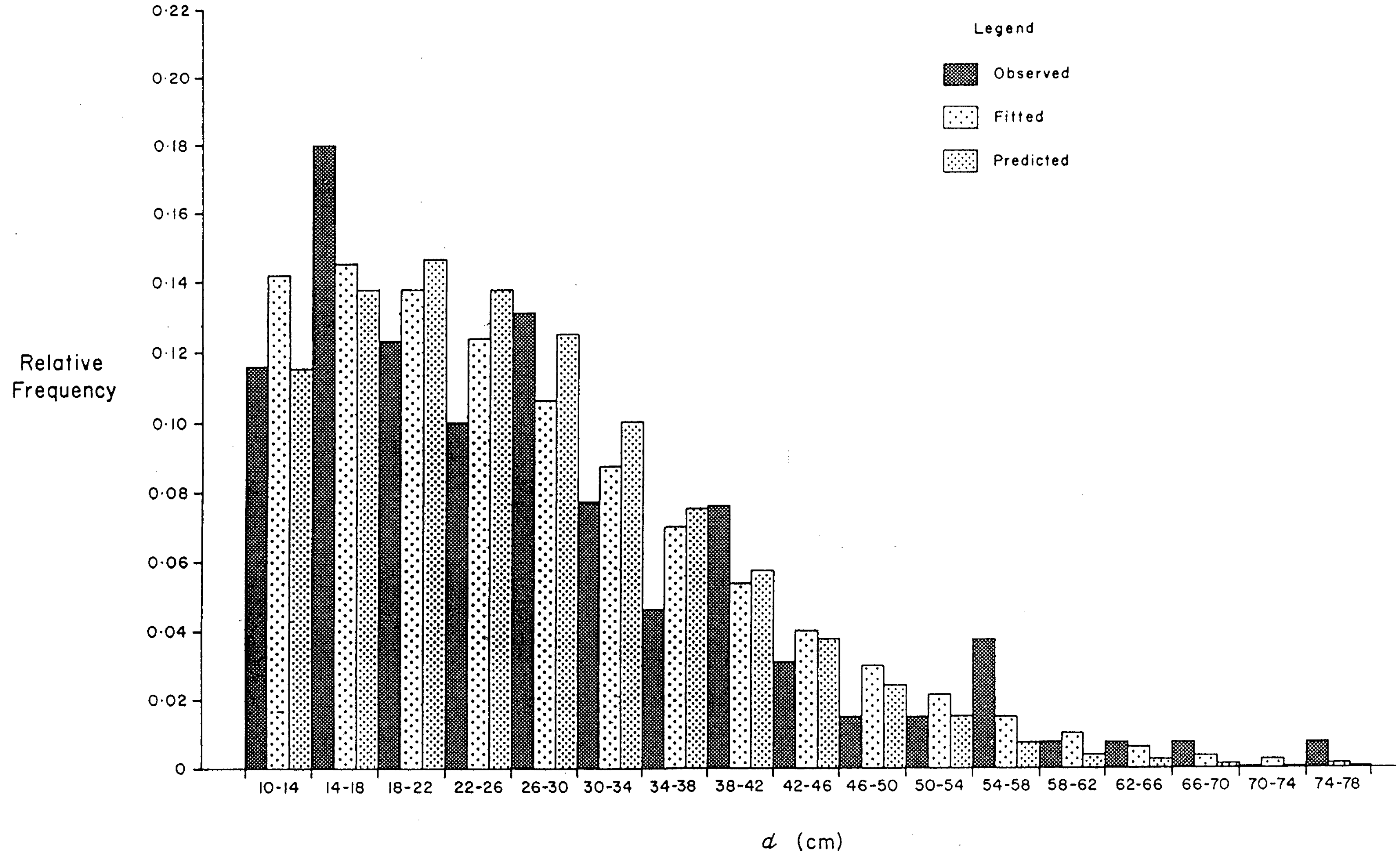

Figure 7.4 Observed, fitted and predicted *d* frequency distributions for an unthinned stand aged 64 years (PSP 840).

Table 7.1 Parameter estimates for prediction of Weibull *cdf* scale (b) and shape (c) parameters from measured stand variables. Standard errors are given in parentheses.

Equation	Parameters				Fit statistics		
	α	β	γ	δ	n	MSE	R^2_a
(7.4)	-2.0570	0.9770			283	10.45	0.94
	(0.4183)	(0.0147)					
(7.5)	1.5692	-0.0286	-0.00026	0.01438	281	0.611	0.44
	(0.0898)	(0.00272)	(0.000072)	(0.00265)			

7.4.3 Testing the functions

The capacity of the models to predict the *d* frequency distribution of unthinned regrowth stands was tested by comparing the distribution predicted by equations (7.4) and (7.5) with observed distributions for 20 PSPs selected from the validation plot series (Table 3.4) to sample the range in *H* and *N*. Estimates of the location and shape parameters obtained using equations (7.4) and (7.5) were used to generate a frequency distribution for each PSP and these were compared to the observed *d* distribution using the Kolmogorov–Smirnov test of goodness of fit (Table 7.2). The Kolmogorov–Smirnov test places equal emphasis on lack of fit throughout the distribution and is therefore more sensitive than alternative tests to deviations in the tails of the distribution (Siegel 1956).

The probabilities from all plots were combined by computing the value $-2 \Sigma \log_e P_i$ (summed across n plots), which is distributed as chi–square with 2n degrees of freedom (Snedecor and Cochran 1967).

From Table 7.2 this statistic has a value of 57.4, compared with a tabular value for χ^2 of 55.8 for 40 degrees of freedom and P=0.05. This comparison indicated that, averaged over all test plots, the observed distributions differed significantly from the predicted distributions. Table 7.2 suggests the equations were unbiased but imprecise across *A*, *H* and *N*. The poor prediction of the shape parameter was the most likely cause of the imprecise projections.

The reason for the poor correlation between the stand variables and the shape parameter is unclear. The three parameter form of the Weibull function (7.2) was parametrized for each PSP and the shape parameter predicted as a function of the a and b parameters (see Clutter *et al.* 1983), but no improvement was obtained. Neither was improvement found by reparametrizing equation (7.5) using only the pure karri plots, or by partitioning the data into stands of greater or less than 40 m *H*. Marginal

Table 7.2 The probabilities (P_i), computed using the Kolmogorov–Smirnov test, of accepting the null hypothesis that the observed and predicted *d* frequency distributions of a plot did not differ significantly.

PSP	A (years)	H (m)	N (stems ha^{-1})	Probability (P_i)
109	50	47.2	304	0.39
128	47	48.6	744	0.01
309	12	22.5	1056	1.00
712	46	42.2	534	1.00
713	58	54.7	296	0.12
729	18	24.1	850	0.61
736	11	16.0	340	0.07
827/2	28	37.1	820	0.09
828/1	20	26.5	1010	0.58
837	15	19.8	627	0.13
840	64	39.0	520	0.91
845	36	43.0	638	0.04
857	9	15.0	595	0.36
858	12	19.1	1190	0.10
862	12	17.8	680	0.43
864	18	22.7	234	0.08
896	9	15.6	892	0.21
935	42	46.9	552	0.40
979	15	23.1	1020	1.00
991	53	41.5	404	0.65

improvement ($R^2 = 0.49$) in the prediction of the shape parameter was obtained by restricting the dataset to only the 144 maximum density stands used in the site evaluation study (Chapter 6), but this was considered too restrictive for general application.

Apart from environmental attributes no other stand variables were available as potential independent variables which might explain variation in the shape parameter across stands. The earlier site evaluation work, however, found no relationship between the moment statistics of the *d* distributions and the site classifications. Moreover, Grey (1987) reported the shape parameter of the Weibull *cdf* for *P.radiata* stands in South Africa were poorly predicted from micro–climatic and soil characteristics. It was decided not to pursue the incorporation of environmental factors as predictors of distribution shape.

Alder (1977) reported similar difficulties when estimating the shape parameter of *P.radiata* stands in Tanzania, and suggested it was due to the heterogenous spatial pattern of mortality within the stands. The spatial distribution of the trees is known to influence the shape of diameter distributions at later ages (DeVries 1986). Regrowth eucalypt stands regenerated from seed possess marked spatial variability in stem frequencies (West 1984, Hamilton 1988), and in karri the spatial pattern of stems is largely influenced by an ash–bed effect originating from the position of logging slash (Loneragan 1961). It is possible that this unexplained variation is due in part to such effects, although neither Opie (1972) nor Incoll (1974) reported similar difficulties when estimating parameters of the beta and gamma *cdf*s for *E.regnans* and *E.sieberi* stands respectively.

7.4.4 Implications for simulation

The poor predictive capacity of equation (7.5) will only influence stand volume estimation when the growth model is initialized with a generated *d* distribution. Where inventory data are provided, a measured distribution will be input for initialization. As equations (7.4) and (7.5) are parametrized only for unthinned stands, a measured distribution would be required for projections within thinned or previously logged stands.

Table (7.2) suggests the equations are unbiased but imprecise. Whether or not the statistically significant difference between observed and predicted *d* distributions is of consequence in stand volume estimation will depend upon how sensitive the whole model system is to the initial distribution shape. Overestimation of stem numbers in the lower *d* classes of young stands, for example, is likely to be of limited practical consequence as these trees quickly die from competition. Nonetheless, because *N* is fixed a corresponding under– (or over–) estimation of stem numbers will necessarily occur elsewhere in the *d* distribution. The effect of *d*–class size and distribution shape on stand volume estimates is discussed further in Chapter 9.

7.5 Stand gross basal area increment

7.5.1 Introduction

The development of a model to predict stand gross basal area increment (I_{Bg}) involved a number of sequential stages. The selection of a suitable measure of stand density involved evaluation of the stand density – stand increment relationship for karri. This relationship was generalized across sites by adopting a 'stand density management diagram' framework. Finally, empirical adjustment of the I_{Bg} model was required to compensate for bias in the estimation of increment in low density stands.

7.5.2 Selection of independent variables

In an even–aged monoculture the rate of change of gross basal area with respect to time (dB_g/dt) varies according to stand age, site quality and density (Vuokila 1966, Curtis 1967a, Leary 1991). This instantaneous rate of change dB_g/dt may, for practical purposes, be approximated by an annual increment expressed as $\Delta B_g / \Delta t = \Delta B_g = I_{Bg}$.

While stand age is readily defined and site index has been shown to be an acceptable quantitative expression of site quality (Chapter 6), numerous measures of stand density are possible. Most stand density measures can be considered as approximations of the degree of approach to a reference or 'limiting' density condition for a given age and site (Curtis 1970, West 1983a). Such measures of 'relative' density attempt to quantify, relative to the maximum density condition, the occupancy of a unit area and may be interpreted as an index of the degree of relative competition for resources acting on either an individual stem (Alder 1977) or the whole stand (Candy 1989a).

Relative density indices are useful predictors of both stand and tree basal area increment (see, *e.g.* Ferguson and Leech 1976, Alder 1977, Bailey and Ware 1983, Pienaar and Shiver 1986, Li 1988, Candy 1989a). In most of these studies the availability of large numbers of growth observations covering the range of stand densities have enabled highly empirical approaches to be adopted, with relative density often defined as the ratio of net *B* to the maximum *B* observed for stands of similar age and site quality. The restricted density/site range sampled in the karri dataset, however, necessitated a relative density measure to provide a biologically sound framework for extrapolating the stand growth–stand density relationship across sites and ages. Evaluation of the form of the relationship between stand density and growth rate was therefore essential to the selection of an appropriate relative density measure.

7.5.2.1 Relationship between stand density and stand growth rate on a uniform site

Comprehensive reviews of the European literature on thinning by Møller (1954), Braathe (1957) and Sjolte–Jørgensen (1967) have identified three major variations to a general hypothesis that, over a wide range of stand density, stand growth is relatively independent of density.

The relationship between stand increment and stand density within a uniform site and common age was generalized by Langsaeter in 1941 (see Braathe 1957). He presented a hypothetical diagram depicting five zones in the stand volume growth/stand volume relationship. The first zone, containing the origin, represents low stocking densities where no inter–tree competition occurs and hence a positive linear relationship exists between growth and stand density. A second transition zone shows a flattening of the rising curve as stands approach full utilization of their site. The third zone represents full site utilization, at which stand increment is a maximum and is independent of stand density. At still higher stand densities (zone 4) a gradual decrease in increment occurs due to the commencement of competition–induced mortality. Zone 5 depicts a pronounced decrease in increment at very high stand densities, representing high mortality rates and possible stagnation or 'locking' of the stand.

Mϕller (1954) advanced an alternative hypothesis, expressed diagrammatically by a curve showing the relationship between V increment as a percentage of the maximum possible for that site and age, and B, also expressed as a percentage of the maximum possible. Mϕller proposed that the curve rises sharply from the origin and then increment is maximized and constant from approximately 50% to 100% of the maximum basal area for that site and age. This hypothesis differs from Langsaeter's in the rate of attainment of maximum increment and by the absence of a decrease in growth at maximum stand density.

In contrast to Mϕller and Langsaetter, Assmann (1961) argued that an optimum basal area exists for each site and species which results in the greatest volume increment. He identified three threshold basal area densities for a species on a given site: the maximum possible for the species, an optimum at which maximum volume growth occurs, and a 'critical' basal area (CBA) at which volume increment is 95% of the maximum. The CBA may also be defined as that basal area at which gross basal area increment is 95% of maximum. Assmann (1961) therefore differs with Mϕller and Langsaetter in not only the absence of a plateau but also a much narrower range of stand densities at which volume growth is relatively independent of stand density.

Despite the importance to stand management practices of defining the absolute values of the density thresholds or plateaus (Daniel *et al.* 1979), the many studies over the decades have generally proved contradictory or inconclusive when attempting to define a general growth theory which caters for each hypothesis. Much of the confusion may be attributed to inadequacies in experimental design, variations in the intensity and frequency of thinning, differences in thinning intervals, the arbitrary inclusion or exclusion of suppressed and subdominant trees in analyses, and the use of disparate relative density standards for data interpretation.

7.5.2.2 Evidence for eucalypts

Similar limitations have applied to experiments designed to elucidate the relationship between stand density and growth rate in regrowth eucalypt stands (Florence 1988). Nevertheless, the Mϕller–type relationship is the most common reported in the literature for I_{Bg}. Data supporting this hypothesis has been reported for stands of *E.regnans* (Webb 1966, Opie 1968, Goodwin 1990), *E.obliqua* (Curtin 1968, Goodwin 1990), *E.obliqua – E.viminalis* mixtures (Opie 1968) and *E.pilularis* (Curtin 1969). The Langsaeter–type relationship is commonly reported for net stand increment (*e.g.* Dale 1968, Dahms 1973) due to the high mortality rates in maximum density stands. Abbott and Loneragan (1983), however, reported data for regrowth jarrah (*E.marginata*) which was consistent with Langsaeter's hypothesis. Most of these studies have examined stand response to first thinning only.

Definition of the critical basal area (CBA) enables thinning regimes to be devised which maintain maximum stand increment, as net *B* production will always be maximized in the vicinity of the CBA. Alternatively, the increment forgone when pursuing regimes which maintain a stand at densities lower than CBA (and hence invoke a marked reduction in *B* increment) in order to maximize individual tree size may be readily quantified.

There has been broad agreement between studies concerning the location of the CBA in regrowth eucalypts. Webb (1966) concluded that net annual *V* growth in *E.regnans* was constant for a range of 50 to 100% of unthinned stand density. The same experiments, in 7 to 42 year old regrowth near Toolangi (Victoria) were later examined by Webb and Incoll (1969), who reported that I_{Bg} in stands older than 30 years was not markedly reduced until the *B* removed by thinning exceeded 50%. The minimum retained *B* that caused no loss of gross production increased with stand age. Goodwin (1990) reported similar results from thinning experiments in Tasmanian stands of *E.obliqua* aged 16 and 50 years.

In contrast, Curtin (1968) presented data for even–aged *E.obliqua* stands in Victoria which showed the CBA was considerably higher than 50% of the maximum. This result, however, may be an artifact of using bulked data from PSPs across a wide range of sites, in contrast to the site–specific experimental results of Webb (1966) and Goodwin (1990).

7.5.2.3 Evidence for regrowth karri

Measurements from the Warren and Treen thinning trials (Table 3.3) provided some short–term response data for evaluating the relationship between stand increment and density in regrowth karri. Fortuitously, select plots within each trial were of similar site index (49–51 m), providing the opportunity to compare the response to density reduction on a 'uniform' site in stands aged 12 (Warren) and 50 (Treen) years at first thinning to a range of residual basal areas (see Table 3.3).

These data were consistent with the existence of a Mϕller–type response for I_{Bg}, with maximum increment occurring beyond 50% basal area of the unthinned stands for these first thinnings. The minimum retained basal area that caused no loss of gross production increased with stand age (Figure 7.5), consistent with the findings of Webb (1966) and Goodwin (1990).

7.5.3 Generalizing the stand increment – stand density relationship to stands of varying site and treatment history: selection of an appropriate measure of relative density

The difficulties of partitioning site, genotype and density effects in forest experiments means that a definitive test of the validity of Mϕller's hypothesis across varying sites and stand histories is logistically prohibitive to perform. Nonetheless, it appears sufficiently general in regrowth monocultures to justify its use in model construction.

If the hypothesis that a Mϕller–type relationship consistently defines the stand density–I_{Bg} relationship for all combinations of site, age and stand history in karri is accepted, then selection of an appropriate relative density measure becomes a question of which measure might provide a consistent location of CBA across sites, ages and history. Such a relative density measure might then be used as a modifier term to scale the I_{Bg} in any stand relative to that expected in a maximum density stand, hence allowing extrapolation of stand increment for low density and multiple thinnings which are not represented in the parametrization dataset.

The most popular approach in recent years has been to use the –3/2 power law of self–thinning to define a reference or limiting density condition and thereby develop a 'stand density management diagram'. The law states that during the development of a monospecific, even–aged stand with complete crown closure, the mean plant mass, m, and the number of plants per unit area, N, are related as:

$$m = k N^{-3/2}$$

where k is a constant.

Alternatively, the total plant mass per unit area, M, which is equal to the product of m and N, may be determined as:

$$M = k N^{-1/2}$$

This relationship depicts a straight line, known as the self–thinning line (with a slope of –3/2 or –1/2 respectively) when plotted on a log–log scale. Drew and Flewelling (1977) were the first to combine the concepts of the self–thinning rule and the relationship between stand biomass and stocking density, and the approach has subsequently been applied for many species (Drew and Flewelling 1979, Long 1985, Smith 1989).

The use of the self–thinning line to define limiting stand density rests on the presumed independence of the slope of the line to age, species, and site, and the proposition that lines positioned parallel to the maximum density line represent a fixed relative density (which relate to the Langsaeter–type relationship for net stand

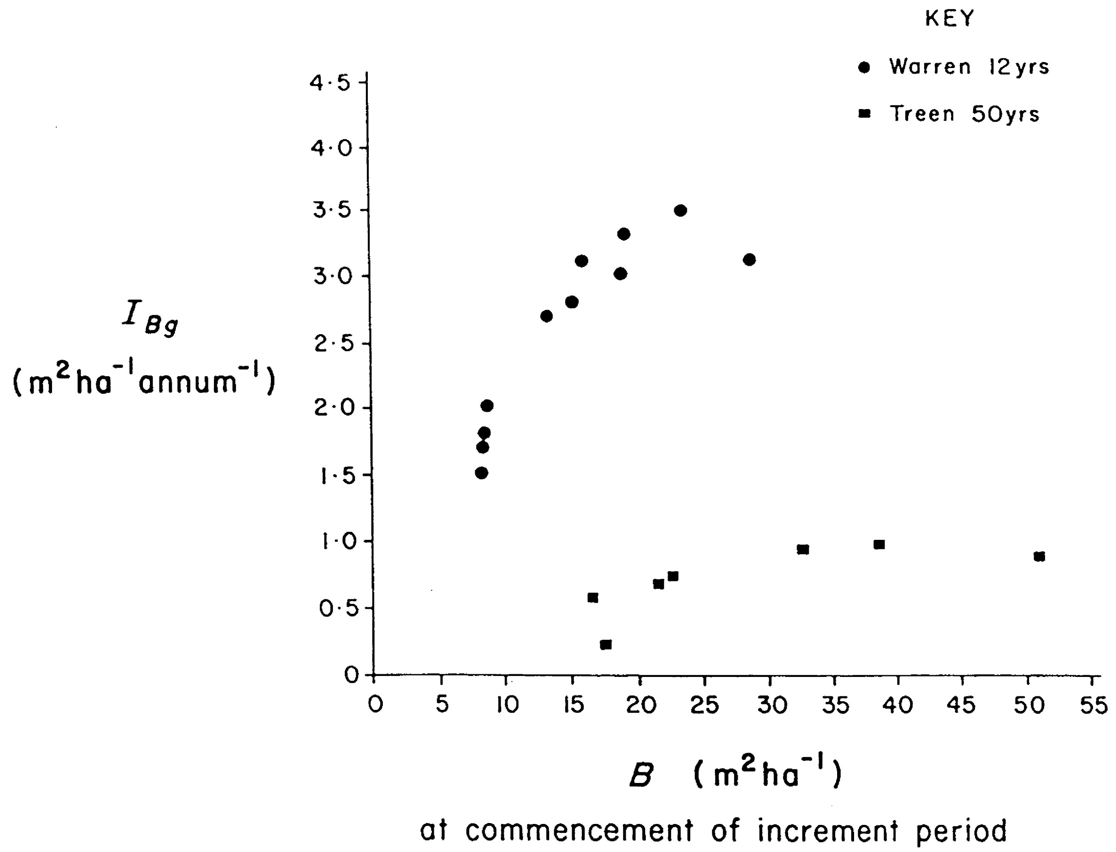

Figure 7.5 Gross stand basal area increment (I_{Bg}) against net basal area at the commencement of the increment period for regrowth karri stands of site index 49–51 m (Warren and Treen Thinning Trials).

variables). The assumed linearity of the maximum density reference line means that the approximate position of the CBA can be fitted with data from as few as one thinning experiment, enabling tentative stand density management diagrams to be prepared for *E.regnans* (West 1985) and *E.obliqua* (Goodwin 1990).

Possible curvilinearity of the self–thinning line, and dependence of its slope on age, site and species has generated considerable debate over the generality of this 'rule' and, by inference, the basis of stand density management diagrams (Weller 1987, Zeide 1987, Osawa and Sugita 1989, Weller 1990). Bredenkamp and Burkhart (1990), using South African data from a correlated curve trend experiment for *E.grandis* (a species of very similar growth rate and habits to karri) recently demonstrated the slope of the self–thinning line varies with stand age on a uniform site. The practical consequence of the variation was, however, minor, and the relationship appears to be sufficiently robust that its use as a first approximation for modelling and management can be justified (West 1985).

The choice of reference variable is the most important difference between relative density measures (Stout and Larson 1988). The self–thinning rule defines limiting density in terms of the mean–tree or stand total volume (or biomass) in relation to stem numbers. This form was parametrized for karri in Chapter 6 and good agreement was found between the observed and 'theoretical' values of the slope parameter. The preferred reference variable in this work, however, was maximum net basal area relative to stem numbers. This variable was analytically consistent with model architecture in which I_{Bg} was a primary driving variable. Most importantly, definition of relative density as the ratio of observed B to maximum B for a given N provided a direct consistency with field implementation of thinning prescriptions, as thinning control in karri is by B and N within H classes (see Bradshaw 1992). Such consistency is important in facilitating the field application of computer–simulated regimes (Wilson 1979, Bailey and Ware 1983). This consistency within a stand density diagram framework is particularly important because as West (1985) points out, the application of density management theory is difficult on the ground because stands are often not thinned 'on time' to the regime which has been modelled, and once the stand is off the scheduled regime it can be difficult to prescribe further treatment.

The measure of density relative to the maximum basal area for a stand of comparable stem number on a similar site may be expressed as

$$\mathrm{RDBN} = B \,/\, [\, B_{max} \,|\, N \,] \qquad (7.6)$$

where B denotes the observed net basal area of the stand

B_{max} denotes the expected maximum net basal area of a stand of similar stocking density N

RDBN is the Relative Density Basal area based on stem Numbers.

An estimate of $B_{max} \mid N$ may be derived directly from Reineke's (1933) stand density index, which defines the following limiting relationship between the number of stems per hectare (N) and the stand quadratic mean diameter (D_q) in fully-stocked stands:

$$N = \alpha D_q{}^{\beta}$$

$$i.e.\ D_q = \alpha' N^{1/\beta}$$

but as the tree of mean basal area, $B_{mean\ tree} = \mathrm{k}\, D_q{}^2$

$$B_{mean\ tree} = \gamma N^{(2/\beta)}$$

for a stand, multiply both sides by N

$$B_{max} = \delta N^{(2/\beta)+1}$$

Similar transformations have been independently reported by Goodwin (1990) and Somers and Farrar (1991), who substituted the 'theoretical' value for β of −1.605 in their work. Bredenkamp and Burkhart (1990) have also demonstrated the mathematical interdependence of Reineke's (1933) density index, the self-thinning rule and relative spacing measures of limiting density. As considerable variation in the value of β for many species has been reported (Clutter *et al.* 1983), these relationships were parametrized using the 144 maximum density stands selected in Chapter 6. Principal component analysis was used to parametrize the relationship to avoid potentially biased parameter estimates from OLS regression (see Ferguson and Leech 1976, Weller 1987). The final equations, for stems ≥ 10 cm d, were

$$D_q = 1445\, N^{-0.6348} \tag{7.7}$$

$$B_{max} = 164\, N^{-0.27} \tag{7.8}$$

The limiting boundary of the maximum basal area zone (7.8) is usually determined subjectively by positioning a line of appropriate slope near the upper limit of the data (see, *e.g.* Drew and Flewelling (1979)). This subjectivity was avoided in the present work by defining the limiting stand density as the upper tail of the 95% confidence limit for equation (7.8):

$$i.e. \quad B_{max} = 279.2\, N^{-0.27} \tag{7.9}$$

$$\text{thus} \quad \mathrm{RDBN} = B \,/\, [\, 279.2\, N^{-0.27}\,] \tag{7.10}$$

Figure 7.6 shows a stand density management diagram for regrowth karri, developed using (7.9) as the limiting density. The line joining those combinations of B and N for which full site occupancy occurs with the minimum basal area (*i.e.* CBA) was positioned at a relative density of 0.4, consistent with the I_{Bg} data from the karri thinning trials (Figure 7.7). Data from the Muirillup espacement trial (Table 3.4) was used to determine the location of the line delimiting free-growth, approximated by crown closure at the relative density of 0.15. The line delimiting the mortality zone

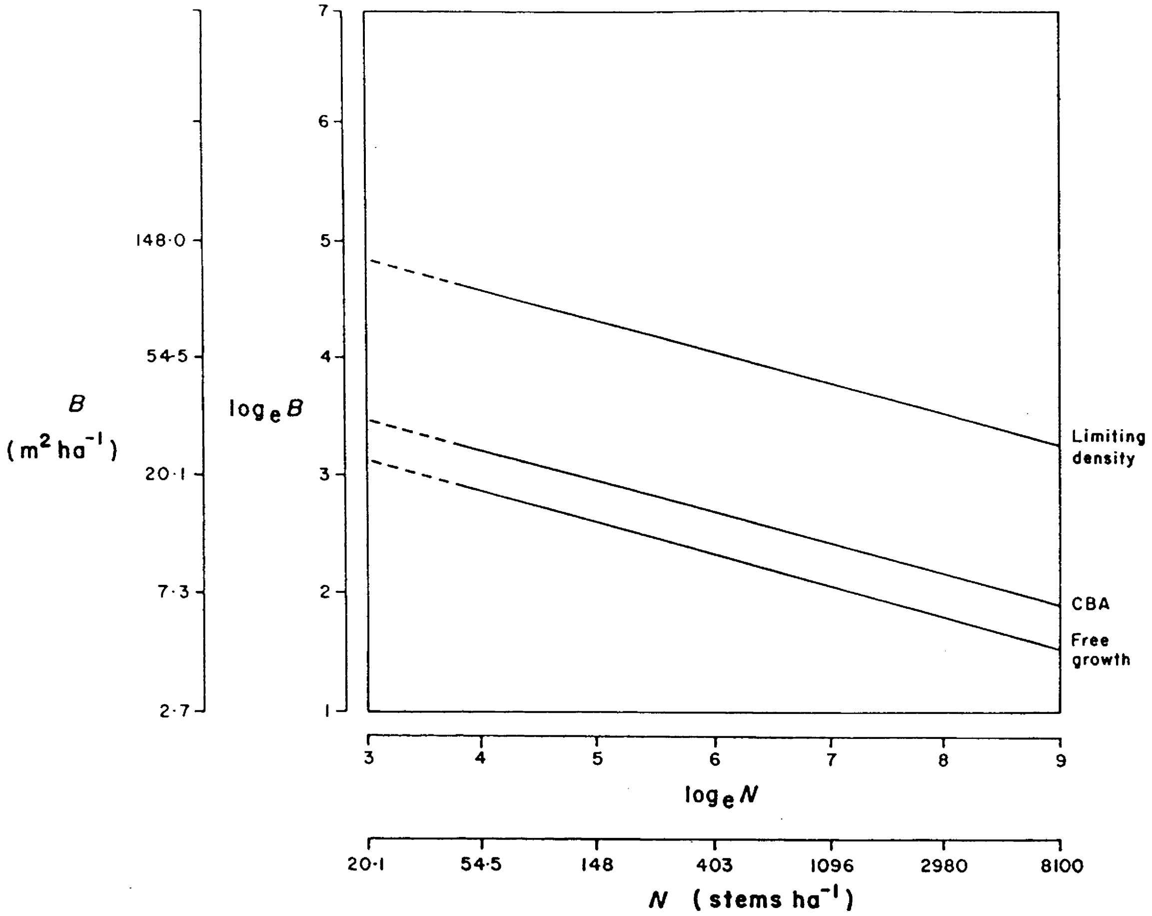

Figure 7.6 Stand density management diagram for regrowth karri.

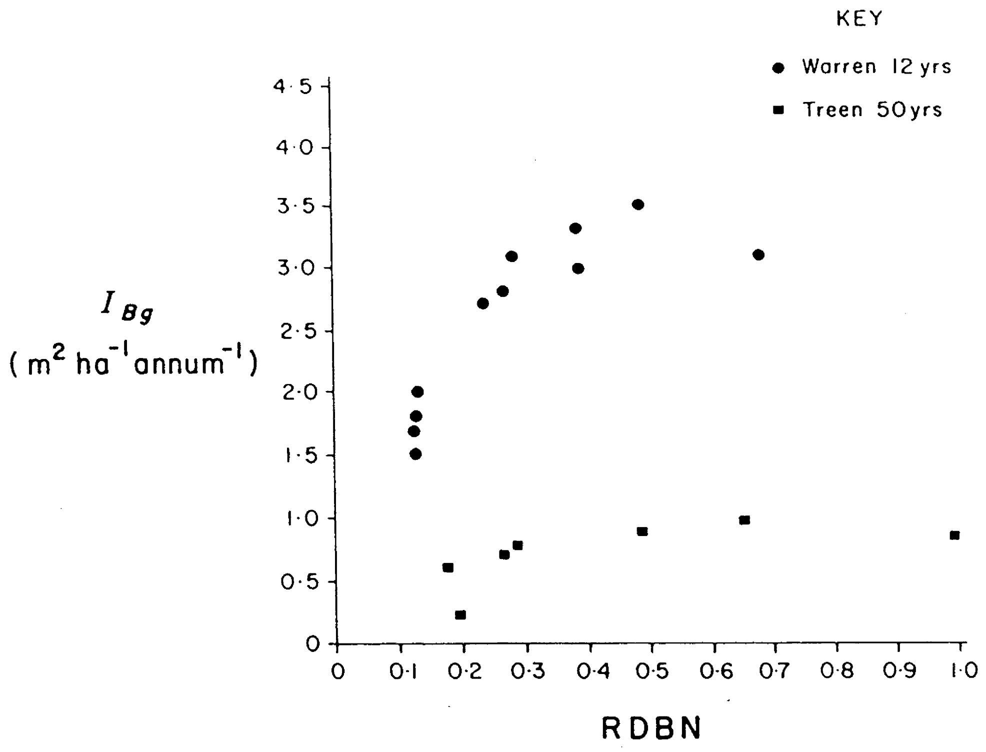

Figure 7.7 Data from Figure 7.5 replotted on a RDBN relative density scale.

corresponded to a relative density of approximately 0.55, positioned from those combinations of B and N for the stands in the PSP dataset at which substantial mortality had commenced. Gross basal area growth at relative densities exceeding 0.55 will be similar to that in the 0.4 to 0.55 region, but net growth may be considerably less than this if substantial mortality has occurred.

The advantages of using RDBN as a relative density measure are readily apparent if one compares the consistency of the position of the CBA for age or height-based measures. Figures 7.8 and 7.9 show the karri data in Figure 7.5 replotted on relative density scales based on the ratio of net B to the maximum net B of a fully-stocked stand of identical age and dominant height respectively. That is,

$$\mathrm{RDBA} = B \,/\, [\, \mathrm{E}(B_{max} \mid A) \,] \tag{7.11}$$

where B denotes the observed net basal area of the stand

B_{max} denotes the expected maximum net basal area of a stand of similar age A

RDBA is the Relative Density Basal area based on stand Age.

$$\mathrm{RDBH} = B \,/\, [\, \mathrm{E}(B_{max} \mid H) \,] \tag{7.12}$$

where B denotes the observed net basal area of the stand

B_{max} denotes the expected maximum net basal area of a stand of similar dominant height H

RDBH is the Relative Density Basal area based on dominant Height.

The RDBA relative density measure has been used by many workers (see Sjolte-Jϕrgensen 1967) when examining how the hypotheses of Mϕller, Langsaetter and Assmann relate to the maximum basal area expected on a given experimental site. The RDBH measure subsumes the effect of both age and site into a dominant height term and has been used in several stand-level models (see, *e.g.* Alder 1977, Candy 1989a).

The maximum or limiting B was derived for each measure using measurements from the 144 maximum density PSPs selected in Chapter 6 for the site evaluation study. The following models were fitted to the three highest B values in each of 5 year A classes or 5 m H classes:

$$B_{max} \mid A = 53.15 \, \{[1-\exp(-0.2337A)]^{10.39}\} \qquad R^2=0.94$$

$$B_{max} \mid H = 59.82 \, \{[1-\exp(-0.0986H)]^{4.949}\} \qquad R^2=0.96$$

In Figure 7.8 the RDBA corresponding to the CBA (for this constant site quality) increases with increasing age: CBA shifts from a relative density of approximately 0.35

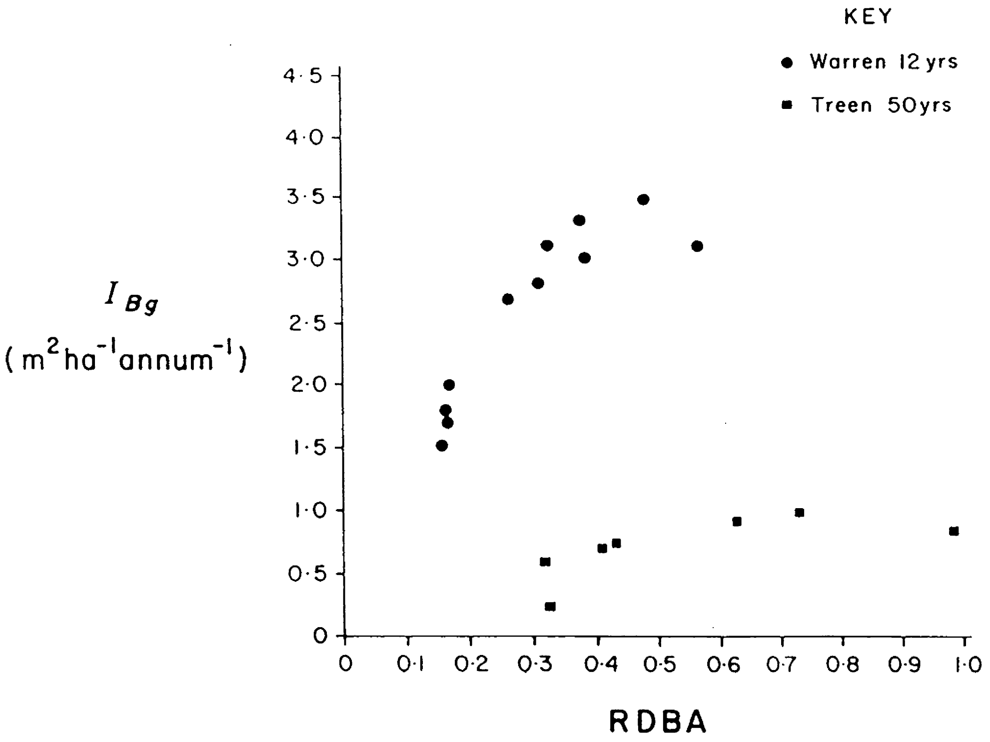

Figure 7.8 Data from Figure 7.5 replotted on a RDBA relative density scale.

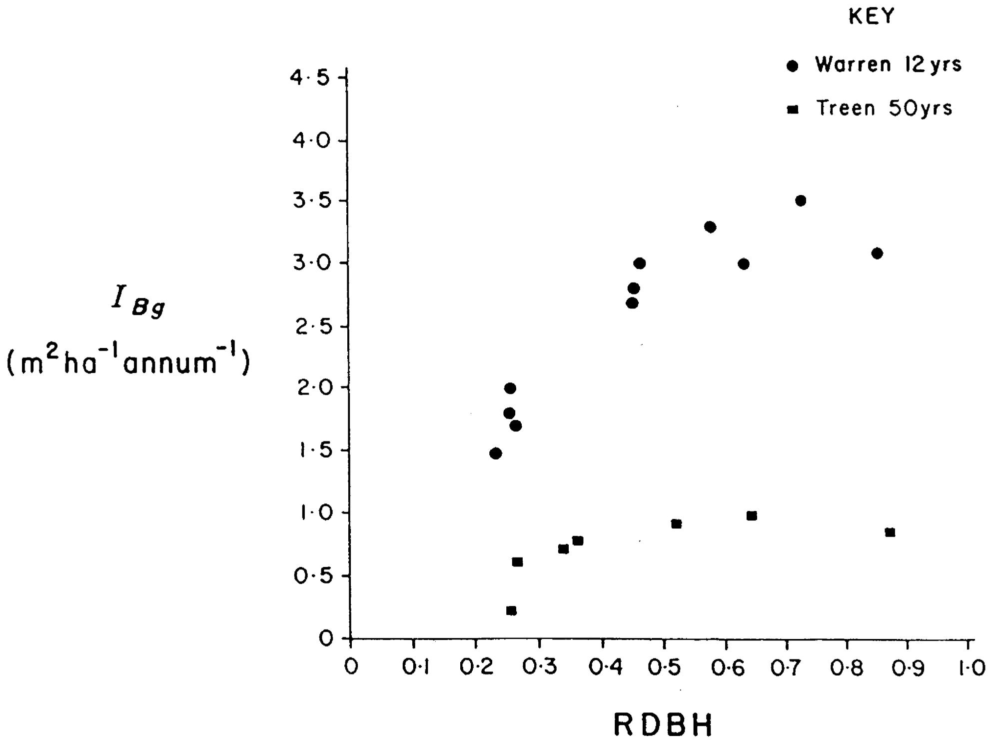

Figure 7.9 Data from Figure 7.5 replotted on a RDBH relative density scale.

at age 12 to 0.45 by age 51. The shape of this relationship may alter with multiple thinnings (Bradley *et al.* 1966). Consequently, the use of this relative density measure in a IBg model would necessitate a large dataset containing a balanced representation of site and density ranges for each age. The lack of such data makes RDBA an unsuitable relative density measure for karri.

Similarly, changes in the location of the CBA threshold using RDBH (Figure 7.9) militate against its use in restricted datasets of the type available in the present work. As with RDBA, a disadvantage of this relative density measure is the dependence of the estimate of $B_{max} \mid H$ upon the range of stocking densities present in the parametrization dataset. The lack of karri data does not permit estimation of the change in position of CBA with site and thinning history.

7.5.4 Formulation and parametrization of IBg function

Graphical inspection of graphs of IBg by A within SI classes indicated that most stands older than 10 years were past their peak PAI, with an inverse exponential relationship clearly evident across site classes.

An initial approach involved estimating the IBg of maximum density stands and scaling that increment for thinned stands (see, *e.g.* Gibson *et al.* 1971, Pienaar and Shiver 1986). The use of RDBN as a measure of relative density enabled estimates of IBg for any stand to be multiplicatively scaled relative to the IBg of a maximum density stand for that site. This approach provided a means of generalizing the response for all stands, particularly those understocked and low density conditions which are poorly represented in the karri dataset. The approach implicitly assumes that stand history will not affect maximum basal area, a premise supported by the work of Pienaar and Turnbull (1973) for pine and Bredenkamp (1977) for *E.grandis* stands. Three candidate models were selected for parametrization:

1. The increment form of the Weibull function (Yang *et al.* 1978, Zutter *et al.* 1982) was selected because this flexible function is bounded by the origin and could accommodate a biologically realistic maximum at an age less than 10 years.

$$IBg = a\,(c/b)\,(A/b)^{c-1} \exp\,[-(A/b)^{c}]$$

2. An exponential model, derived by Leech (1978) from a base Richards (1959) model, closely resembled the empirical shape of the data.

$$IBg = \exp\,(\alpha + \beta A)$$

3. A reverse logistic model, as derived by Sadiq (1983), had desirable shape properties and had successfully modelled the net B increment of red pine plantations in southern Ontario.

$$I_{Bg} = \left\{ \frac{[\exp(\alpha + \beta A + \gamma SI)]}{[1 + \exp(\alpha + \beta A + \gamma SI)]} \right\}$$

Each of these models was parametrized using the 144 maximum density stands. For each model the base fit involving A was parametrized and then SI, H, B terms were introduced as linear second stage regressors. Each model form was fitted using iteratively reweighted OLS to compensate for increasing error variance with increasing A. The models were parametrized on the full dataset, but hypothesis tests concerning the significance of additional independent variables (*e.g.* addition of SI term) were performed using standard errors computed from a reduced dataset comprising only one observation from each plot, and F tests were performed using degrees of freedom based only on the number of plots.

Thus, the base approach was to estimate

$$I_{Bg} = \underbrace{\mathrm{f}(A, SI)}_{\text{Potential}} \times \underbrace{\mathrm{f}(\mathrm{RDBN})}_{\text{Modifier}}$$

The logistic function was the most appropriate shape for the modifier term WRDBN, which was constrained to equal 1.0 when RDBN equalled 1.0, and was parametrized using data from all the thinning experiments:

$$\mathrm{WRDBN} = \{1+90.0\,[\exp(-25.1\,\mathrm{RDBN})]\}^{-1} \qquad R^2 = 0.88 \qquad (7.13)$$

WRDBN was therefore an index of the stand increment relative to the increment experienced in a maximally dense stand on the site. Taking values between 0 and 1, the effect of this modifier term was to scale the increment relative to the position of the stand on the Mϕller–curve (Figure 7.10). The trend for WRDBN to approach a value of 1.0 for relative densities greater than 0.45 is consistent with the general location of CBA in other species of regrowth eucalypts (section 7.5.2.2).

The coefficient of determination of the 'best' formulation for each model ranged from 0.43 for the Weibull formulation to 0.65 for the reverse logistic formulation. However, graphical examination of the residuals by SI, A and RDBN classes indicated that none of these models were acceptable as each exhibited substantial bias in the estimation of I_{Bg} for stands older than approximately 70 years and for RDBN less than 0.25. This was probably due in part to the limited number of observations available in these older stands.

Consequently, stepwise regression was performed using a range of stand variables (A, SI, H, D_q, WRDBN, and their interactions) to investigate alternative model forms. The final model was similar to a function used by Curtis (1967a) and incorporated the relative density term in an additive (*cf.* multiplicative) term. Fitted to all PSPs and stand

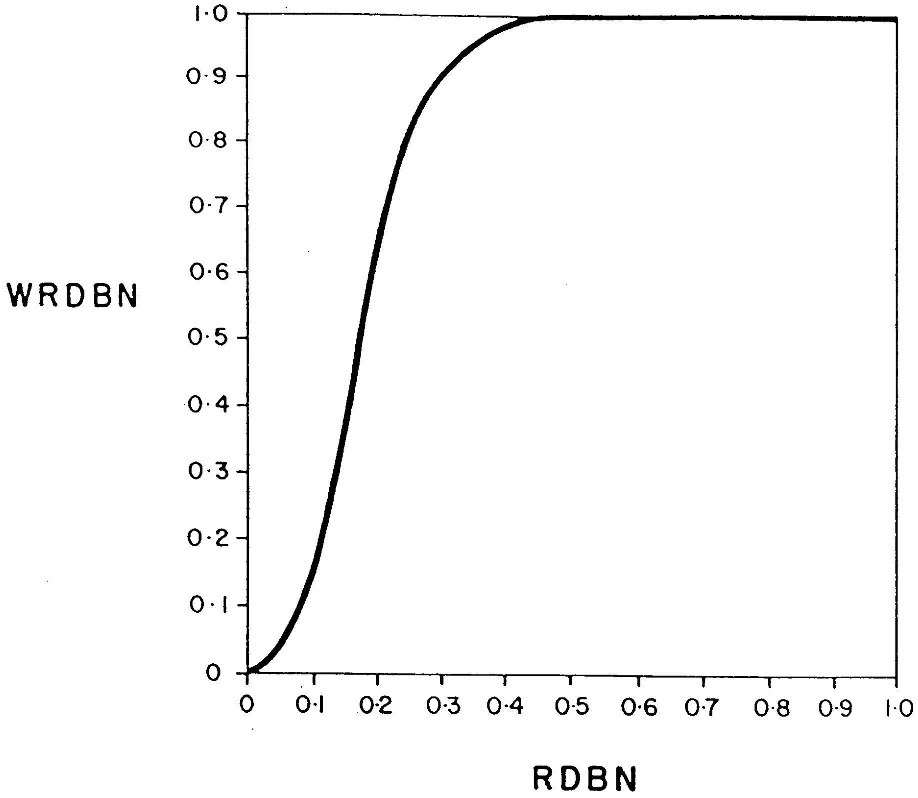

Figure 7.10 Shape of the modifier term WRDBN.

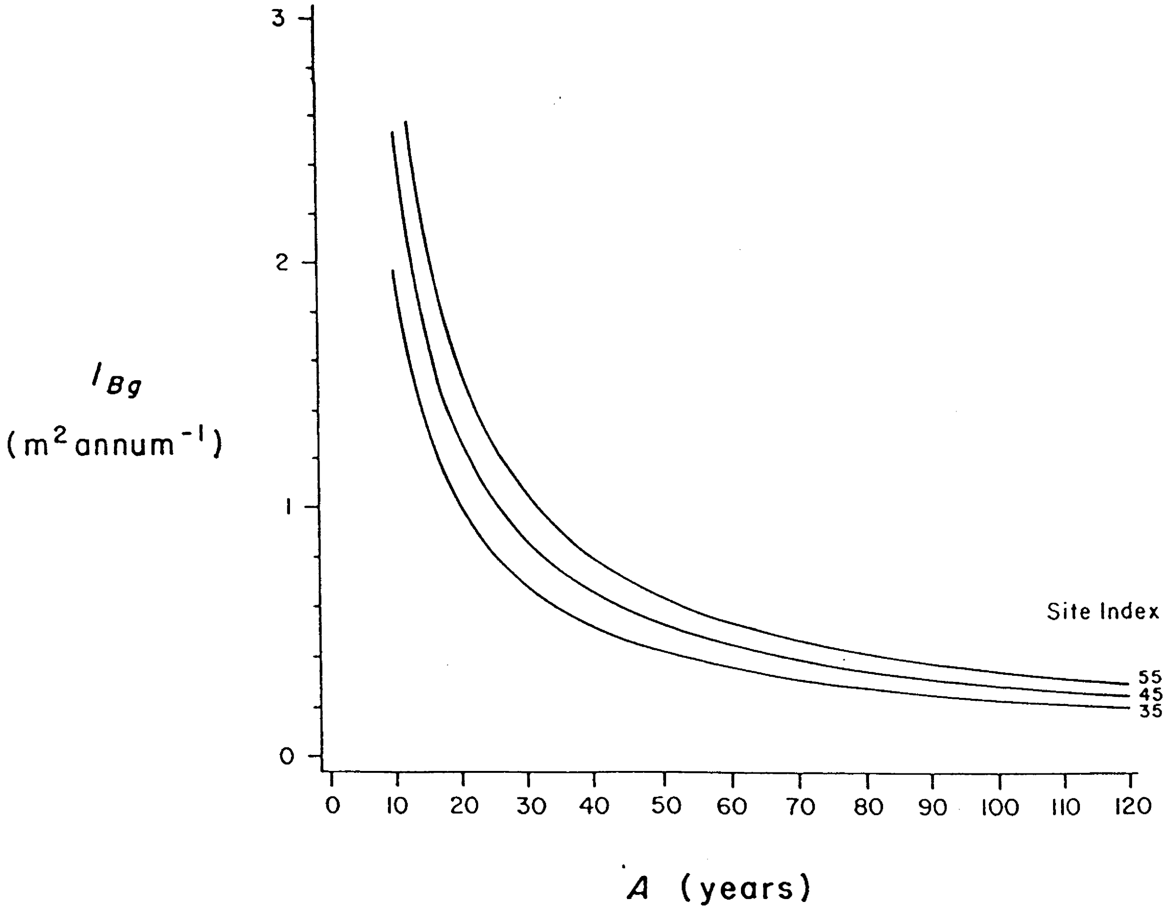

Figure 7.11 Projected I_{Bg} for fully–stocked stands (RDBN=0.8) for three site index classes.

treatment data, the model explained over 83% of the variation in the data (Table 7.3) while extrapolating sensibly across the desired range of A and SI (Figure 7.11):

$$I_{Bg} = \alpha + \beta\,(SI/A) + \gamma\,(\mathrm{WRDBN}) \qquad (7.14)$$

Table 7.3 Parameter estimates and fit statistics for I_{Bg} model (7.14). Standard errors are provided in parentheses, and were calculated using a reduced dataset comprising only one observation per plot.

Parameter estimates			Fit statistics		
α	β	γ	n	MSE	R^2_a
−0.3103 (0.1187)	0.5541 (0.0207)	0.3485 (0.0119)	237	0.2381	0.83

7.5.5 Testing and adjustment

Inspection of the residuals graphed against the independent variables revealed that model (7.14) was biased for low density stands (RDBN<0.14) younger than approximately 40 years, producing overestimates of I_{Bg} for all SI classes. Unfortunately, data for such low relative densities (which approximate open–grown conditions) were only available from the few thinning trials located on a very restricted range of site index. The available data were therefore too limited to parametrize a suitable model form for these low densities.

Accordingly, it was decided to incorporate a function to empirically constrain the growth of low density stands. This could be approached by either the development of a function constraining individual tree diameter growth (*e.g.* maximum d increment of a tree constrained not to exceed the d increment of an open–grown tree of equivalent size) or by directly adjusting the estimated I_{Bg} using an appropriate scaling function calibrated from the few trials available. The latter approach was favoured due to the lack of suitable data for open–grown karri trees across the desired range of age, site, and tree size for the model.

Examination of the thinning data suggested the following variation of the Gompertz (1825) model was appropriate to adjust for the bias in equation (7.14):

$$w = \exp\left(-1.2\exp^{-0.10A}\right) \qquad (7.15)$$

where A denotes stand age

w denotes an adjustment value of $(0.57<w<0.99)$ for $(10 \leq A \leq 40)$

Model (7.15) is implemented within KARSIM only for stands aged between 10 and 40 years with an RDBN less than 0.15. In these instances the estimate of I_{Bg} is multiplicatively reduced by the value w for each growth cycle until RDBN exceeds the 0.15 threshold. The simple scaling factor is assumed to act proportionally across all site qualities. This gross generalization was necessitated by the lack of thinning data, but no doubt represents a major simplification of thinning response across sites which may differ markedly in their response to such limiting factors as soil moisture and soil nutrient levels (Kimmins *et al.* 1990).

7.5.6 Further work required

The application of a deterministic model such as (7.14) for estimating increment is a major simplification of stand growth. In addition to stand age, site and density, annual stand increment is markedly influenced by such stochastic factors as climatic fluctuations, fire events (Banks 1982), and insect and disease predation. For example, stands of RDBN above 0.2 in the Bamess Road thinning trials (Table 3.3) have experienced annual fluctuations in I_{Bg} of up to 50% over a 10 year monitoring period, coinciding with annual rainfall fluctuations (Rayner, unpublished data). Similar fluctuations have been observed by Curtin (1968) in thinned *E.pilularis* stands.

Confirmation or refutation is required of the consistency of the Mϕller–type relationship across sites carrying mixed–species stands. Site types within the regrowth estate are known to vary markedly in their soil moisture and nutrient characteristics (Inions 1990), and presumably experience different limiting factors. Similarly, the consistency of the shape of the relationship across thinning histories has yet to be evaluated. Chapter 11 details some of the data required to test these hypotheses.

Management practices may also influence the consistency of the Mϕller–type relationship over multiple thinnings. Soil compaction arising during the original clearfell of the old–growth or consecutive thinning operations may alter the form of the relationship as well as the absolute level of stand increment. This possibility is under investigation for karri (Wronski 1984). Similarly, studies into the effect of competition from understorey species and coppicing following thinning are in a preliminary stage (Breidahl and Hewett 1992).

The generality of this approach to species mixtures exceeding 20% of non–karri species is uncertain. Exclusion of mixed–species stands up to this composition from the parametrization dataset did not significantly alter the parameters of the limiting density relationship (Chapter 6) nor the I_{Bg} model (7.14). Data collection strategies to investigate this issue are discussed in Chapter 11.

7.6 Stand ingrowth

7.6.1 Introduction

KARSIM simulates only those stems larger than 10 cm *d*, due mainly to the restriction of measurements to this minimum size class in the majority of PSPs. An estimate of annual ingrowth at 10 cm was therefore necessary. The estimation of ingrowth by complex stochastic procedures such as those adopted by Stage (1973) and Botkin *et al.* (1972) in other single–tree models are particularly efficient when ingrowth must be predicted by species composition. In the present work, however, insufficient stems of non–karri species were present to enable estimation of ingrowth by species. A deterministic approach, which ignored species composition and predicted the amount of ingrowth as a function of stand variables, was adopted.

7.6.2 Model formulation

The site evaluation study (Chapter 6) showed that within stands of comparable age, higher site qualities were associated with faster rates of segregation into crown dominance classes, and by inference, lower rates of ingrowth. Graphical inspection of ingrowth rates for the combined dataset confirmed the trend that annual ingrowth at 10 cm *d* (N_{in}) decreased markedly with increasing *SI*, and indicated that on all sites was so rare in stands exceeding 30 m *H* that for practical purposes ingrowth could be ignored beyond this *H*. Annual ingrowth decreased with increasing age, site index, and stand density.

Insufficient data were available from planted stands to confirm or reject the hypothesis that ingrowth differed between naturally regenerated and planted stands. Accordingly, a single model was parametrized for all stands.

7.6.3 Model parametrization

Alternative formulations predicting N_{in} as a function of *SI*, *A*, *H*, *B*, and RDBN, together with their interaction terms, were fitted to 72 measurements from 44 PSPs sampling the following (minimum–mean–maximum) stand values: *SI* (32–44–51 m), *A* (10–18–33 years), *H* (12–23–31 m), *B* (4–16–26 $m^2\ ha^{-1}$), and RDBN (0.12–0.51–0.68). The final model subsumed the influence of site and age into a *H* term and logically incorporated the influence of stand density on ingrowth (Table 7.4):

$$N_{in} = \exp\left(\alpha + \beta H + \gamma\, \mathrm{RDBN}\right) \qquad (7.16)$$

where

N_{in} denotes the number of ingrowth stems per hectare per annum at 10 cm *d*

H denotes stand top height (m) at the commencement of the increment period

RDBN denotes the stand relative density (stems exceeding 10 cm *d*) at the commencement of the increment period

Table 7.4 Parameter estimates and fit statistics for stand ingrowth model (7.16). Standard errors are provided in parentheses, and were calculated using a reduced dataset comprising only one observation per PSP.

Parameter estimates			Fit statistics		
α	β	γ	n	MSE	R^2_a
5.0162 (0.1790)	−0.0282 (0.0116)	−2.0896 (0.7925)	72	21.16	0.65

Model (7.16) predicts decreasing annual ingrowth with increasing site quality, age and stand relative density. Accurate estimation of ingrowth is particularly important in stands on low site qualities as ingrowth may comprise up to 50% of stand total volume in early years. Such sites generally carry a mixed–species composition. Similarly, although stand regeneration method may be a major determinant of ingrowth on some slower–growing sites, no relationship could be detected in the limited dataset used here. The testing of model (7.16) was incorporated as part of the whole–model validation described in Chapter 9.

7.6.4 Implementation

Execution of the ingrowth subroutine within KARSIM is conditional on the stand *H*, thinning history, and regeneration method. The ingrowth model is applied only while, or if, *H* is less than 30 m. As ingrowth was observed to be negligible in plots thinned to any residual stocking density (largely because stems smaller than 10 cm would have been smashed during thinning), the ingrowth subroutine is skipped if a stand has been thinned or is nominated for thinning at any age prior to attaining 30 m *H*. Finally, should the stand being simulated be either planted or at an initial stocking density representing poor stocking (RDBN<0.3 for total stem numbers at age 10) then a count is maintained to ensure that the cumulative total of mortality, ingrowth and present stem numbers does not exceed the user–specified establishment stocking density.

The estimate of N_{in} from model (7.16) is rounded to the nearest integer and that number of stems is added to the *d* array. The *d* of each stem is randomly generated to lie within the size class interval 10–11 cm by adding a uniform random variate from a computer–supplied function to a *d* of 10 cm.

CHAPTER 8 GROWTH MODEL DEVELOPMENT — TREE LEVEL COMPONENTS

8.1 Introduction

In this chapter the development, parametrization, and validation of those component models within KARSIM which operate at the tree level is described. These are the model allocating stand gross basal area increment amongst stems, the mortality model, the estimation of tree height from tree diameter, and the estimation of tree and product volumes. The chapter concludes with sections describing the implementation of thinning and economic modules within the model.

8.2 Allocation of stand basal area increment among individual trees

8.2.1 Introduction

Application of model (7.14) provides an estimate of the gross stand basal area increment. This section describes an allocation model which provides estimates of the *d*s of individual trees at the end of an increment period, enabling tree volume and product size–class distributions to be computed.

A robust approach to increment distribution in even–aged monocultures involves allocating the stand increment directly to individual trees by modelling the relationship between tree diameter increment and stand variables (Opie 1972, Woollons and Hayward 1985). This two–stage modelling approach, in which the basal area increment of individual trees in a stand were related to their basal area at the commencement of the period (first–stage) and then the parameters from these models for each PSP were related to stand variables (second–stage), was adopted in this study.

8.2.2 Selection and fitting of first–stage model (tree increment/tree size)

8.2.2.1 Shape of tree increment/tree size relationship in even–aged monocultures

The first–stage involved selecting an appropriate model form to describe the relationship between tree increment and tree size (at the commencement of the increment period) for trees within each stand. The selection of diameter increment (i_d) or basal area increment (i_b) as the dependent variable is largely a matter of convenience, as West (1980) has shown that within both thinned and unthinned stands the precision of estimates of future diameter for individual trees will be similar irrespective of the choice of diameter increment or basal area increment as the dependent variable. Most workers have modelled diameter increment (Ellis *et al.* 1987, West 1981a, 1988b).

The shape of the tree i_d / d relationship will vary with the relative density and age of the stand and can be interpreted relative to the position of a stand within the zones of a stand density management diagram. Within stands of low relative density, arising from initial espacement or heavy thinning, a period of free growth may occur in which i_d is uncorrelated with d because limited competitive interaction occurs between individual trees (Gates *et al.* 1983). As canopy closure occurs (and relative density increases) a slower growing, suppressed component develops and the i_d / *d* relationship is best described by a quadratic function (see, *e.g.* West 1980, 1981a, West and Borough 1983, Von Gadow 1984). The presence of a substantial proportion of suppressed stems is a feature of regrowth eucalypt stands in the incipient mortality and fully–stocked zones. Where a suppressed or non–incrementing stratum of stems is absent, either through exclusion in the fitting process or within thinned stands, the relationship between i_d and *d* is strongly linear. Both the slope and the intercept terms of the linear relationship have been shown to vary in thinned *E.obliqua* forest (West 1988b).

The shape of the i_d / *d* relationship will determine the change in skewness of the *d* frequency distribution in a stand. Bailey (1980a) has demonstrated that the i_d / *d* relationship must be shaped concave to the ordinate axis if it is to result, over an increment period, in the decline of the skewness of the *d* distribution which has been observed with increasing age in unthinned monocultures (*e.g.* Gates *et al.* 1983). A preliminary investigation of the tree increment/tree size relationship was therefore undertaken to examine linear, quadratic and concave forms as first–stage models for karri.

8.2.2.2 Parametrization of tree increment/tree size relationship for karri

Twenty PSPs and ten thinned plots were subjectively selected to include the range of age, density and site quality within the complete dataset. Examination of the scatterplots of i_d against *d* confirmed that the relationship between i_d / *d* and between tree basal area increment i_b / *d* was strongly linear if non–incrementing trees were excluded from the analysis. No evidence of concavity was apparent for any relative density or age. A quadratic form was clearly superior in the unthinned stands when non–incrementing stems were included. Incoll (1974) argued that because the contribution to stand growth by these non–incrementing stems was negligible they could be ignored in the modelling process without substantially biasing estimates of future stand basal area. Consequently, the candidate functions were restricted to the following simple linear forms which were fitted to each plot:

$$i_d = \alpha + \beta d \qquad (8.1)$$

$$i_b = \alpha + \beta d \qquad (8.2)$$

$$i_b = \alpha + \beta b \qquad (8.3)$$

where i_d and i_b denote the annual increment of tree diameter and basal area respectively, *d* and *b* denote tree diameter and tree basal area (respectively) at the commencement of the increment period, and α and β are parameters to be estimated.

Equations (8.1–8.3) were fitted to each plot using weighted least squares regression to compensate for heteroscedastic residuals. Only trees greater than 10 cm *d* were fitted to remain consistent with the overall model architecture. Equation (8.3) was the best predictor of increment overall when the thinned plots were included in the analysis. The R^2_a for this model varied across the plots from 0.42 to 0.93. Although the higher R^2_a values for (8.3) will be partially due to the obligatory dependence of basal area on diameter (West 1980), it was a clearly preferred fit in the thinned stands. The low R^2_a (<0.5) resulted from 'outlier' trees in some plots, presumably reflecting the chance occurrence of genetic or microsite effects.

Selection of model (8.3) as the most appropriate first–stage model considerably simplified the second–stage modelling. The model assumes that basal area increment is directly proportional to tree basal area when the origin of the relationship is shifted to the intercept basal area of b_0. The emphasis in second–stage modelling shifts to the estimation of b_0, the minimum basal area with positive increment. Variations of this approach have been used by Gibson *et al.* (1971), Incoll (1974), and Vanclay (1988a) and can be expressed as follows:

If $i_b = \alpha + \beta b$ (for an individual tree)

Then $b_0 = -\alpha/\beta$ (minimum basal area which is incrementing is the intercept of the increment relationship)

Now if N_0 represents the number of trees in a stand with a basal area in excess of b_0

Then $I_B = \Sigma(\alpha + \beta b)$ (I_B is stand live basal area increment)

$= N_0\alpha + \Sigma\,\beta b$

Thus, the relationship for an individual stand is readily determined if b_0 can be predicted from the properties of the stand and increment period, because the slope of the linear relationship is a simple ratio involving stand basal area as a proportion of the sum of basal area of stems exceeding b_0.

Model (8.3) was fitted to one randomly selected increment period of each plot in the complete dataset. Seventeen PSPs were excluded from further analysis because there were fewer than 15 trees exceeding 10 cm *d* within the plot with which to fit the regression. The remaining 211 plots had an average increment period of 3.7 years (range of 1–5 years), with a range in stand relative density of 0.12–0.94. Estimates of b_0 were computed from the α and β for each plot.

8.2.3 Selection and fitting of second–stage model

The second–stage modelling involved relating the estimates of b_0 to the stand and increment period characteristics from which they were obtained. Graphical examination of b_0 against *A*, *B*, *N*, D_q, *H* and RDBN (all values taken at the commencement of the increment period) suggested that H, D_q and N were important explanatory variables. A stepwise regression procedure was used to evaluate each of the above variables (together with combinations and transformations of them). The preferred model was (Table 8.1):

$$b_0 = \alpha + \beta \log_e D_q + (\gamma / N) + \delta H^2 \qquad (8.4)$$

Table 8.1 Parameter estimates and fit statistics for prediction of the minimum incrementing tree basal area (model 8.4). Standard errors are shown in parentheses.

Parameter				Fit statistics		
α	β	γ	δ	n	MSE	R^2_a
−0.00071 (0.00023)	0.000391 (0.00016)	0.02303 (0.01069)	0.00000037 (0.00000011)	207	0.00000011	0.85

8.2.4 Basal area allocation rule

Having determined the minimum size of an incrementing tree in any stand, an allocation rule was required which was consistent with observed stand dynamics. The simplest approach is to apportion the basal area increment in direct proportion to the tree basal area:

$$i_b = I_B\,(b / B) \qquad (8.5)$$

This approach distributes the total stand increment proportionally across size and dominance classes, and has been successfully applied in radiata, hoop and cypress pine stands (Gibson *et al.* 1971, Vanclay 1988a). This formulation, however, assumes that when simulating growth in thinned stands, the size of each tree after thinning adequately reflects its competitive position in the stand and hence its increment potential. This may not be the case in eucalypt regrowth. West (1988b) has demonstrated that both the slope and the intercept terms of the linear i_d / d relationship vary in thinned *E.obliqua* stands, indicating that tree d alone was an inadequate predictor of i_d in thinned forest.

Evidence from other thinning studies support the contention that dominant trees in thinned and unthinned stands show less response to release than do trees in an inferior canopy position (see *e.g.* Ellis *et al.* 1987, Horne and Robinson 1990). Goodwin (1990), for example, reported that the heaviest thinning (75% B removed) in three *E.regnans*/*E.obliqua* trials resulted in a 3-fold increase in the diameter growth rate of subdominant trees but only a two-fold increase for dominant trees. This relative response persisted at older ages but was of decreased magnitude. These results seem consistent with the proposition of Cannell *et al.* (1984) that the major competitive interactions in the stand occur between codominant trees. A reduction in stand density by thinning from below removes varying proportions of the subdominant and codominant strata, thereby altering the competitive interactions between trees in the stand.

The limited data available for karri supports the contention that tree increment is not directly proportional to tree size across all dominance classes. Some workers have developed complex relationships to model such allocation processes (see *e.g.* Leary 1979, Vanclay 1989b) but a simpler solution involves the incorporation of a weight parameter ω to allocate increment according to

$$i_b = I_B\,(b\,/\,B)^{\omega} \qquad (8.6)$$

where the value of ω may vary according to the nature of the species response. Values less than 1 imply the smaller trees in the stand will receive a greater share of the stand increment, values of 1 mean that a tree's increment is directly proportional to its size, while values greater than 1 assure larger trees in the stand a higher proportion of the stand increment. Examination of the data of Campbell *et al.* 1979 suggests a value of 0.93 may apply for *E.regnans*.

Graphical inspection of the range in slopes across thinned and unthinned stands of varying RDBN and site quality for the relationship i_b against b/B suggested that for practical purposes, the allocation did not vary markedly with RDBN and that a constant value of ω=0.9 was appropriate as a first approximation for karri[1].

Direct application of model (8.6) would result in a perfect correlation between tree basal area and tree growth, thereby ignoring the natural variation which would occur in a real biological population. This source of bias can be important in tree volume estimation (Stage 1973), and random variates are often introduced into the increment allocation process to preserve autocorrelation in individual–tree models (Vanclay 1992). The final stage in the development of the allocation model for karri therefore involved incorporating a suitable stochastic component in the process. The approach used by Opie (1972) was adopted in the present work. The increment of a tree was computed as

$$i_b = i_b\,(1 \pm 0.003\,SI)$$

where alternate trees in the ordered array of diameters were allocated the positive or negative variation. Opie (1972) included the site index term because a higher degree of heterogeneity was observed in the increment distribution as site index increased (Campbell *et al.* 1979). A similar effect was observed for karri and hence the term was retained in the present work.

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[1] An anonymous reviewer has pointed out that model (8.6) will produce weights which sum to 1.0 only when ω=1.0. For ω=0.9, a slight positive bias is produced. This may be corrected by dividing the weight term by the term: $\Sigma(b/B)^{\omega}$

8.2.5 Accuracy of model

The accuracy of the increment and allocation models was tested by comparing the observed *d* frequency distributions at the end of a measurement period for each plot in the validation dataset (Table 3.4) with that predicted from successive application of the I_{Bg} (7.14), b_0 (8.4) and allocation (8.6) models. The stand was initialized at the beginning of the projection period with the observed *d* distribution and stand variables for each plot. Estimates of I_B using (7.14) and then of b_0 were obtained for a stand using (8.4), and increment allocated according to (8.6). No significant difference (chi–square test at $P>0.05$) was found between the observed and predicted *d* distributions across the 32 plots over increment periods ranging from 2 to 8 years, suggesting that the stand increments had been adequately predicted and the relative increments of the trees had been satisfactorily apportioned.

This test would overstate model precision due to the very short increment periods and the initialization of the plots with observed values at the commencement of simulation (*cf.* only predicted values being available in practice). Individual biases in any of the three component models may also have been compensated by those in the other component models, while the effects of mortality were also ignored over these short increment periods. Tests of the cumulative accuracy of the model when it is applied for successive increment periods must determine if imprecise or biased estimates accrue with increasing projection length. This latter test requires complete model simulation with the few long–term plots, and was therefore incorporated into the complete model validation phase (Chapter 9).

8.3 Tree survival (mortality)

8.3.1 Introduction

Accurate prediction of tree survival (or mortality) is essential in an individual–tree growth projection system. Imprecision in mortality estimation is often cited as the major cause of poor growth model performance. Stage and Renner (1988), for example, recently compared the volume growth for 102 permanent sample plots in the Northern Rocky Mountains with projections from the PROGNOSIS model (Wykoff *et al.* 1982). Approximately 80 percent of the variability in volume projected over periods averaging 39 years was due to uncertainty in estimates of surviving stem numbers.

This section describes the application of a probability–based approach to modelling tree survival in the regrowth karri stands.

8.3.2 Choice of modelling approach

Clutter *et al.* (1983) described a variety of approaches for predicting mortality at an individual–tree or stand level. Most models derived for even–aged stands incorporate the stand density approaches of Reineke (1933) and Yoda *et al.* (1963) by estimating mortality relative to the limiting density condition. Lloyd and Harms (1986), for example, modelled the growth of individual trees and generated the mortality rate to be consistent with the self-thinning rule. An alternative approach developed by Smith and Hann (1984) used a Weibull function to model mortality and then applied a generalized self-thinning rule to generate tree size. While such approaches might maintain a degree of consistency with the application of the limiting density relationship in Chapter 7, a major difficulty with size-density approaches occurs if, as in the karri dataset, limited plot remeasurements are available from which to estimate the rate of approach of any stand to the limiting density condition. Subjective approximations based on the judgement of workers with a thorough knowledge of mortality processes within the system being modelled can still lead to biased mortality estimates. West (1991), for example, found that the adjustments adopted by Opie (1972) and Incoll (1974) in the STANDSIM model substantially over-estimated competition-induced mortality.

A further difficulty with stand density approaches is that they generally estimate only the competition-induced mortality, providing a residual stocking of a stand but no indication of which trees actually die. Empirical rules or approximations are therefore necessary to nominate dead trees (Vanclay 1989b). As well, many of the stand density management formulations have been derived for plantation systems with a very narrow range of initial stocking (Clutter and Jones 1980, Bailey *et al.* 1985, Smith 1989), and are therefore more applicable to plantation monocultures than the highly variable stocking densities characteristic of regenerated stands.

Many individual-tree level models have incorporated a probability-based approach to the prediction of tree mortality or survival. Distance-dependent models must deal with live or dead trees in a dichotomous classification, and commonly adopt an approach in which the probability of survival (or mortality) is dependent upon an individual tree's dimensions or competition index (*e.g.* Newnham 1964, Mitchell 1967, Monserud 1976). Death of an individual tree occurs if this probability exceeds some critical threshold value, usually a computer-generated uniform random deviate. In contrast, the interpretation of the probability of survival or mortality is straightforward in distance-independent or stand level models which deal with aggregate arrays of trees per hectare: the probability is interpreted as the ratio of trees which will die within a diameter class.

The approach adopted in the present work was to model the probability of individual tree survival using a logistic function as first proposed by Hamilton (1974). The probability of tree survival was estimated as a function of tree and stand parameters. The parametrization of the model used all trees in the complete karri dataset, thereby including both regular (*i.e.* density-dependent) and irregular mortality (*i.e.* arising from pests, diseases, storms, fuel reduction burns) experienced in the stands over the measurement period. This was considered more realistic than excluding irregular mortality, as is usually necessary in the limiting-density and distance-dependent approaches.

8.3.3 Selection of model form

The following base form of the logistic model was used to estimate the annual probability of survival for an individual tree:

$$\begin{aligned} P_{is} &= \{ 1+\exp [-(\alpha + \beta X_1 + \gamma X_2 + \ldots\ldots \delta X_k)]\}^{-1} \qquad (8.7) \\ &= 1-P_{im} \end{aligned}$$

where P_{is} denotes the probability of survival in the subsequent year for the i th tree

P_{im} denotes the probability of mortality

X_j denotes the j^{th} independent variable used to predict the probability of survival (j=1,2....k)

$\alpha....\delta$ denote parameter estimates

The above form may be used to predict the probability of either mortality or survival, and in practical application within an overall model either form is acceptable. Monserud (1976), observing that tree survival is a Markov process, recommended the estimation of survival as the costs of potential misclassification were diminished relative to estimating mortality.

An essential feature of a survival model for the regrowth stands is the capacity to adequately predict mortality within both thinned and unthinned stands. The logistic form of (8.7) has been successfully applied to simulate mortality in both thinned and unthinned coniferous and hardwood stands (Monserud 1976, Hamilton and Edwards 1976, Buchman 1979, Hamilton 1986, 1990), and is widely considered to be the best method available to empirically model tree mortality (Guan and Gertner 1991). The incorporation of independent variables representing not only tree size but also individual tree competition, vigour and stand density provides a means of extrapolating the probability of mortality in managed stands.

8.3.4 Data and method

The PSP and stand treatment datasets provided a total of 11,182 suitable individual tree records for analysis. A suitable tree record was one for which various candidate independent variables (defined below) could be derived and a code of 0 or 1 (representing alive or dead) could be allocated at the end of a measurement period. The full range of stand treatments, conditions, and measurement periods (Tables 3.1 and 3.3) were represented in this dataset. Problems associated with autocorrelation between successive measurements of individual trees were avoided by including only one measurement period for any plot. The data were randomly divided into two equal-sized sets by selecting all even tree numbers to be used for model parametrization and all odd tree numbers to be used for validation. Such a strategy was necessary because the validation dataset (Table 3.4) was too small for adequate testing. This approach is clearly inferior to using an independent test dataset for validation, but it was considered more important to ensure the full range of stand conditions were represented in the parametrization dataset than to randomly reserve a large portion of the data for subsequent validation.

Marri tree records comprised only 3.4% of the total (dead plus live) number of trees in the dataset, while the combined total of all non–karri species was only 5.7%. These trees were heavily biased toward the smaller–sized *d* classes. Thus, insufficient tree records for non–karri species were available to develop species–specific models, so all species were combined for parametrization purposes. Future inclusion of dummy variables to provide species–specific models is straightforward should additional data become available.

The dependent variable in equation (8.7) is a dichotomous classification, whether fitted as a mortality function (with P_{im}=0 for live trees and 1 for dead trees) or as a survival function (with P_{is}=1 for live trees and 0 for dead trees). Consequently, although nonlinear least squares regression was used to estimate the regression parameters for each model, the usual goodness–of–fit criteria (such as MSE) were inappropriate for model comparisons (Hamilton 1974). A chi–square statistic, described by Hamilton and Edwards (1976), was used to evaluate and compare the goodness–of–fit of predicted mortality to observed mortality tabulated within 5 cm tree *d* classes.

Weighted least squares was necessary to ensure efficient estimation of the vector of regression parameters, with observations weighted by $w = 1/[P_{is}(1-P_{is})]$. The occurrence of unequal measurement intervals for individual tree records was handled by treating survival as a compound interest phenomenon to convert to a common, annual base (Monserud 1976). This approach required equation (8.7) to be fit as

$$P_{is} = \{1 + \exp[-(\alpha + \beta X_1 + \gamma X_2 \ldots\ldots \delta X_k)]\}^{-I_y}$$

where I_y is the length of the increment period and the other variables are as previously defined.

Selection of candidate independent variables to describe the probability of tree survival was based on those tree and stand variables available in the dataset, and an understanding of the process of mortality in even–aged stands. A series of alternative models was formulated and sequentially fitted using combinations of the following variables: tree *d*, tree relative *d* (*d* of tree divided by stand quadratic mean diameter D_q), tree relative height (tree total height divided by *H*), *A*, *SI*, *B*, and relative density (RDBN). Various transformations (*e.g.* square root, reciprocal) of these variables were also tested. Although predicted tree growth in the previous period was likely to be a strong predictor of mortality (Monserud 1976) this variable was not included as it was not readily available from the full simulation system being developed.

8.3.5 Results

The model which best predicted the probability of survival of individual trees was

$$P_{is} = \{1 + \exp[-(1.802 - 0.0043d - 1.699\mathrm{RDBN} + 5.216\mathrm{RELDBH})]\}^{-Iy} \quad (8.8)$$

where P_{is} denotes the probability of survival

d denotes tree diameter (cm) at the commencement of the increment period

RDBN denotes stand relative density at the commencement of the increment period

RELDBH denotes d (cm) of tree divided by D_q (cm) at the commencement of the increment period

Table 8.2 shows the pattern of mortality and chi–square statistics for trees within 5 cm d classes for both the parametrization and validation datasets. The total chi–square statistics across all classes in each table of 21.46 and 18.91 may be compared with the critical value of 9.49 for 4 degrees of freedom (9–4 parameters estimated –1) at the 5% significance level. Both these values are larger than the critical value, indicating that the predicted distributions of mortality were significantly different from the observed distributions at this significance level. This result may be largely an artifact of the small number of older plots in the available dataset, as no dead trees were observed in the large diameter classes. The small amount of mortality predicted by model (8.8) for the larger diameter classes is, however, consistent with biological expectations. Moreover, additional testing of the competing mortality models during whole model validation (Chapter 9) confirmed that model (8.8) was the preferred predictor of mortality among the candidate models.

8.3.6 Discussion

Accurate prediction of tree survival when model (8.8) is applied beyond the range of stand conditions represented in the present dataset will depend upon the validity of the biological relationships incorporated into the model. Confidence is enhanced by the logical combination of variables selected for the model. Tree size provides a measure of tree vigour or future increment potential. The relative density measure RDBN defines the position of the stand in relation to the critical density zones identified on a stand density management diagram (Chapter 7). As RDBN increases, so the P_{is} decreases and the P_{im} increases (other factors held constant). The RDBN variable was a markedly superior predictor of tree survival (67% reduction in chi–square statistic) in these even–

Table 8.2 Observed and predicted pattern of mortality and chi-square goodness-of-fit statistics for the parametrization and validation datasets. Predicted survival for individual trees was computed using model (8.8).

d	Parametrization data				Validation data			
class (cm)	No. of trees	No. observed dead	No. expected dead	Chi-square	No. of trees	No. observed dead	No. expected dead	Chi-square
10.0–15.0	1187	181	170.65	0.73	1134	164	166.12	0.03
15.1–20.0	1026	84	95.24	1.46	993	100	88.75	1.57
20.1–25.0	747	52	35.32	8.27	778	50	35.44	6.27
25.1–30.0	560	24	14.65	6.13	533	23	15.52	3.71
30.1–35.0	415	7	9.06	0.48	402	5	7.21	0.69
35.1–40.0	386	2	6.05	2.75	393	2	5.33	2.11
40.1–45.0	375	2	2.78	0.22	378	1	3.13	1.46
45.1–50.0	307	3	2.22	0.28	342	4	1.89	2.37
50.1–55.0	266	0	1.26		239	0	1.36	
55.1–60.0	158	1	0.53		151	1	0.80	
60.1–65.0	97	0	0.23		77	0	0.26	
65.1–70.0	35	0	0.18		45	0	0.11	
70.1–75.0	26	0	0.28		22	0	0.17	
75.1–80.0	5	0	0.03	:	15	0	0.16	:

Table 8.2 (Continued)

d class (cm)	No. of trees	Parametrization data			No. of trees	Validation data		
		No. observed dead	No. expected dead	Chi-square		No. observed dead	No. expected dead	Chi-square
80.1–85.0	6	0	0.03	1.14a	7	0	0.06	0.69a
85.1–90.0	8	0	0.08		6	0	0.06	
90.1–95.0	7	0	0.05		5	0	0.06	
95.1–100.0	5	0	0.03		8	0	0.08	
100.1–105.0	2	0	0.01		5	0	0.05	
105.1–110.0	5	0	0.03		5	0	0.01	
110.1–115.0	1	0	0.01		3	0	0.01	
115.1–120.0	1	0	0.01		2	0	0.01	
>120.0	9	0	0.01		5	0	0.01	

a Data for all diameter classes greater than 50 cm were amalgamated into one class for calculation of the Chi–square. The 'No. expected dead' column for these classes is shown only to illustrate the trend in mortality predicted by model (8.8).

aged stands than stand density transformations based on basal area alone (B, $B^{-0.5}$, $B^{-1.0}$). This result is consistent with the choice of RDBN as an efficient estimator of stand–level thinning response (Chapter 7). Similarly, the influence of site quality on mortality rate was effectively subsumed into these other variables, as the inclusion of site index or top height terms in the survival model produced markedly inferior models. This result is consistent with other approaches to the prediction of mortality, which often report limited influence of site index terms on mortality rates (Clutter *et al.* 1983).

It was hypothesized that if inter–tree competition within these vigorous regrowth stands is indeed one–sided and primarily for light (West 1988a), then the probability of tree survival would be influenced by the relative position of a tree within a stand. The relative tree height measure was expected to better represent this influence than the diameter–based measure RELDBH. That this was not the case is probably due in part to the deterministic method of individual tree height calculation (section 3.6). Incorporation of the RELDBH term indicates that, other factors being constant, trees of larger d than the D_q have a higher probability of survival than trees with ds lower than the D_q.

Management practices which alter stand density (*e.g.* thinning) will directly affect the probabilities of tree survival through changes in both RDBN and RELDBH. Reduction in RDBN, either through thinning or natural mortality, will generate an increase in survival probabilities (hence a decrease in predicted mortality probabilities). The RELDBH of all trees within a stand will be decreased if thinning from below takes place, as the average stand d of the residual trees increases. In all instances, the RELDBH term will ensure that the smaller trees in a stand have a higher probability of mortality than the larger trees.

If the survival model adequately predicts mortality outside the range of conditions represented in the current dataset then application of the model within a complete growth projection system should reproduce stand conditions consistent with general stand development theory. For example, one test of the adequacy of the model is to examine whether or not the predicted development of unthinned stands approaches a limiting condition approximated by Reineke's (1933) stand density relationship. The results of such tests are reported under the full model validation in Chapter 9.

8.3.7 Implementation

Model (8.8) was implemented in KARSIM as follows. For a tree of given d, growing in a stand of given quadratic mean diameter and relative density, the probability of survival over the next increment period was computed using model (8.8). A value between 0 and 1 was drawn randomly from a uniform random distribution using a computer software utility and the survival of the tree determined by comparing the value with the probability of survival. If the probability of the tree surviving was greater than the selected random value the tree was assumed to live, otherwise it was assumed to die and was removed from the tree *d* array.

8.4 Tree height estimation

8.4.1 Introduction

Estimation of tree volume required the development of functions to predict individual tree heights from tree diameter and stand variables. A two–stage regression approach (West *et al.* 1984) was adopted in which an appropriate first–stage model was selected to describe the relationship between tree height and diameter within a stand, and then second–stage regressions were developed to predict the first–stage parameters as a function of such stand level variables as age, dominant height, and basal area.

8.4.2 Estimation of tree height from diameter

Desirable characteristics of mathematical models to represent the relationship between tree *h* and *d* in regrowth forests have been reviewed by Curtis (1967b) and West (1979a). Graphical inspection of *h* against *d* for a range of karri regrowth PSPs suggested that one of the following equations might be suitable to represent the *h* / *d* relationship:

$$h = \alpha + \beta d + \gamma d^2 \tag{8.9}$$

$$h = 1.3 + \beta d + \gamma d^2 \tag{8.10}$$

$$h = 1.3 + d / (\beta + \gamma d) \tag{8.11}$$

$$h = \alpha \, [1 + \exp(\beta - \gamma d)]^{-1} \tag{8.12}$$

where α, β, γ represent the parameters of the equation, and *h* and *d* are as previously defined.

Model (8.9) was used by Curtis (1967b) to predict the height of regrowth Douglas–fir trees, whilst models (8.10) and (8.11) were transformed by West (1979a) to ensure tree height equals breast height when diameter is zero. Model (8.12) is the logistic equation which is sigmoidal in shape and tends to an asymptote as *d* becomes large.

The preferred model for fitting to each plot in the combined dataset was determined by first selecting a sample of 35 test plots representing the range in stand conditions, age, and species mix within the dataset (Tables 3.1 and 3.3). Plots used in the evaluation ranged in age from 10 to 130 years and possessed a minimum of 12 trees with measured *h*s. Species other than karri were poorly represented in the measured *h* sample within the mixed–species PSPs, so separate equation forms were not calibrated for each species.

The four candidate equations were fitted to each measurement of the 35 PSPs and their fit statistics compared to determine which equation was most suited to represent the height–diameter relationship for karri. The logistic formulation, equation (8.12), provided a superior fit to the data for most plots. This choice is consistent with that of West (1982) for describing the same relationship in unthinned, 26–85 year old stands of regrowth *E.obliqua* and *E.regnans* in southern Tasmania. This equation generally possessed the lowest residual variance of the candidate equations and had an acceptable degree of bias in the parameter estimates, averaging 4.2% for $\hat{\beta}$ (the most biased of the parameter estimators) across the 35 PSPs. The residual variance and bias were consistently highest for the karri component from the mixed–species stands, indicating greater variability in the pattern of height growth within these height–stratified mixtures. Nevertheless, inspection of residual scatterplots confirmed that the fit to the data of the logistic was adequate in all plots. The next best model was the quadratic polynomial form of equation (8.10), but in addition to the higher residual variance and marked heteroscedasticity this polynomial form generated unrealistic height asymptotes when compared to the logistic formulation.

The logistic $h\ /\ d$ relationship was therefore fitted to each measurement of all plots and was initially used to derive tree volumes based on the local tree volume table (Chapter 3).

8.4.3 Prediction of first–stage parameter estimates from stand–level variables

The parameter estimates from the fit of the logistic equation to each measurement were related in the second–stage regressions to stand variables. The explanatory variables examined included A, B, N, H, SI, RDBN and Dq.

Many alternative linear and nonlinear forms of the above stand variables, and their square and interaction terms were examined. Parametrization used only one randomly selected measurement for each PSP to enable exact significance tests to be performed. The following second–stage relationships provided the best fit (Table 8.3) as described below:

$$\alpha = \alpha' + \beta' H \tag{8.13}$$

$$\beta = \exp\,(\alpha' + \beta' H + \gamma' N - \delta' Dq) \tag{8.14}$$

$$\gamma = \alpha' + \beta' \log_e H + \gamma' B \tag{8.15}$$

Table 8.3 Parameter estimates and fit statistics for height prediction functions (equations 8.13–8.15) for regrowth karri. The standard errors of the estimates are shown in parentheses.

First–stage parameter	Second–stage parameter α'	β'	γ'	δ'	Fit statistic n	MSE	R^2_a
α	1.3016 (0.4932)	0.9843 (0.0126)			299	6.94	0.96
β	0.5092 (0.1100)	0.0103 (0.0026)	−0.00026 (0.00008)	−0.0063 (0.0023)	297	0.271	0.53
γ	0.5427 (0.0222)	−0.1145 (0.0072)	−0.00032 (0.00013)		298	0.0056	0.63

Graphical inspection of the observed versus predicted first–stage parameter estimates for the validation dataset suggested the fit of equations (8.13) and (8.15) were satisfactory but that estimation of β using equation (8.14) was less precise. This first–stage parameter had had the highest bias in the first–stage regressions. Tests were undertaken to quantify the accuracy of the height prediction function.

8.4.4 Accuracy of height prediction function

The critical error (e*) for height prediction was computed as an estimate of the accuracy of the height prediction function. The heights of individual trees in each of 23 independent validation plots were estimated using equations (8.13–8.15). The difference between the estimated and observed (measured) heights for trees within each plot was then computed, and the mean of these differences calculated to give 23 mean residuals.

The critical error computed (P=0.05) from these residuals was 5.47 m. This implies the extent of inaccuracy within the model was such that 95% of tree heights would be predicted within 5.47 m. When simple linear regressions were computed to relate the mean residuals to the independent variables and their interactions, none of the regression equations showed significant (P>0.05) relationships, implying that the model provided unbiased estimates of height for the range of these variables.

8.5 Estimation of tree and product volumes

8.5.1 Introduction

Regrowth karri stands presently supply a variety of log products to differing quality, length and top diameter specifications. Estimates of total and merchantable tree volume by size class assortments are therefore required from both standing inventory and yield projections. The merchantable volume of karri stems may be defined to either a specified height (log length) or small end diameter under bark (SEDUB) above a nominal stump height.

Development of a smooth, continuous taper function which adequately describes stem shape from ground to tip and which can be readily integrated to provide volume estimates is a difficult task (Husch *et al.* 1982). Kozak (1988) identified two main approaches. The most common method involves modelling the diameter changes from ground to tip using a single function of different forms (*e.g.* Osumi 1959, Kozak *et al.* 1969). These functions are relatively easy to integrate for volume calculation and may be readily rearranged to calculate merchantable height. Unfortunately, their simplified form can often produce substantial bias in the prediction of diameters in the butt and growing tip regions of the tree.

An alternative approach identifies different functions for different regions in the stem, and joins these functions in a manner which ensures that their first derivatives are equal at the point of intersection. Polynomial formulations are typically used to represent the crown, mid–section and butt regions of the stem (*e.g.* Goulding and Murray 1975, McClure and Czaplewski 1986, Candy 1989b). Although upper stem diameters are generally well predicted with these systems the parameters of the equations are often difficult to estimate, while algebraic manipulation of the models to predict volume and merchantable height can be difficult or impossible (Kozak 1988).

Taper models can be further categorized according to their compatibility with total tree volume estimates derived from an independent total tree volume model. Compatible taper models predict the same tree volume on integration from ground to tip as that predicted by the tree volume model. Compatibility is important if estimates of total tree volume are used as an independent variable in the taper model. Further, estimates of total stem volume derived from compatible models are potentially less biased than those derived from integrated non–compatible taper models (Demaerschalk 1973).

The present taper function for regrowth karri is a non–compatible, segmented–polynomial formulation derived for estimating standing volume to a nominated height above ground (WAFD 1983). A fifth–degree polynomial is used to approximate taper between stump height and crown break, while volume estimation above crown break assumes a conoid shape. Parametrized from sectional measurements of 220 trees, the model cannot be readily integrated to calculate total stem volume, and because the emphasis in model design was on the prediction of stem diameter at specified heights above the ground, the merchantable height for a given top diameter cannot be readily calculated but must be obtained by iteration. This is particularly inefficient for calculation of variable–length product assortments within a yield simulator.

The present work investigated whether or not a suitable compatible stem taper model could be developed for KARSIM. The first stage involved the selection and fitting of a tree volume model to predict total underbark volume for regrowth trees. Two compatible taper models were then tested, but both candidate models produced highly biased estimates of stem diameter above crown break. The fitting, testing, and implementation of an alternative non–compatible taper model is described, followed by the product estimation procedures.

8.5.2 Tree volume model

8.5.2.1 Data

Data were available for 208 sample trees which had been sectioned during either stem analysis, silvicultural research, or additional sampling designed to ensure a balanced representation of trees within the range of *d* and *h* observed in the regrowth stands. They represented the following (minimum–mean–maximum) tree values: *d* (7.9–45.1–151.0 cm), *h* (11.1–36.3–69.5 m), and total underbark volume (0.01–3.47–54.02 m^3). This dataset sampled the range of site index and classification types reported in Chapter 6, and was independent of the data used to develop the present taper model. Only seven trees came from thinned stands, providing no opportunity to examine the influence of thinning on tree taper. In the short–term, however, this should not detract from the utility of models derived from this dataset because most stands to which such models will be applied are either unthinned or at most thinned once to conservative residual stocking densities.

Direct measurements of under–bark diameters were available for each tree, but the point of measurement on the stem differed among trials: 183 trees had sectional measurements recorded on a modified taper step method, while the remainder were obtained using a standard sectional method (Carron 1968, Husch *et al.* 1982). The volume of successive sections along the tree stem were therefore calculated using either Smalian's formula (taper step method) or Huber's formula (sectional method). In the taper step method, the stem section closest the ground was computed assuming it was of a cylindrical shape while the growing tip section was assumed to be of conoid shape.

8.5.2.2 Model formulation and fitting

Most tree volume models reported in the literature for predicting total underbark stem volume as a function of tree *d* and *h* are simple variants of a few base model forms. The following candidate models were selected on the basis of their reported utility for various species (Burkhart 1977, Clutter *et al.* 1983):

Constant form factor $v = \alpha d^2 h$ (8.16)
Combined variable equation $v = \alpha + \beta d^2 h$ (8.17)
Extended combined variable equation $v = \alpha + \beta d^2 h + \gamma d^2 + \delta h$ (8.18)
Schumacher and Hall $v = \alpha d^\beta h^\gamma$ (8.19)
Generalized logarithmic $v = \alpha + \beta d^\gamma h^\delta$ (8.20)

where v denotes total underbark tree volume (m^3), from ground to tip
d denotes diameter at breast height overbark (cm)
h denotes total tree height (m)

The documented trend of increasing variance in volume as tree size increased (Husch *et al.* 1982) was observed in the karri data. Schreuder and Anderson (1984) reviewed appropriate functions of d^2h which may be used in weighted regression when developing tree volume models. However, the approach of Candy (1989a, b) was used here to facilitate the direct comparison of the goodness of fit between the alternative models. This approach uses a maximum likelihood generalization of the residual sum of squares, called a deviance statistic (McCullagh and Nelder 1983), to test the significance of adding or subtracting terms from the model. The methodology involved fitting each model using iteratively reweighted least squares with weights computed assuming a poisson or gamma–like distribution for the variance of tree volume (Candy 1989b). Using this approach models (8.19) and (8.20) were reparametrized and fitted as general linear models (McCullagh and Nelder 1983) to avoid retransformation bias (Flewelling and Pienaar 1981) if fitted as logarithmic forms. Model (8.19), for example, was fitted as

$$v = \exp(\alpha + \beta \log_e d + \gamma \log_e h)$$

Examination of the Pearson residuals from these reparametrized models confirmed that the gamma function, with expected variance proportional to v^2, provided homoscedastic residuals and was subsequently adopted for each model.

8.5.2.3 Model selection and testing

Model selection was based on the residual deviance statistics ($\hat{\Phi}$) and graphical inspection of the residuals. The Schumacher and Hall (1933) model possessed the lowest mean residual deviance of all the candidate models (Table 8.4).

Table 8.4 Fit statistics for the five candidate tree volume models.

	Model	Mean Residual Deviance[a] $\hat{\Phi}$	S.E. (%) v[b]
(8.16)	Constant form factor	0.00866	9.3
(8.17)	Combined variable equation	0.00838	9.1
(8.18)	Extended combined variable equation	0.00923	9.6
(8.19)	Schumacher and Hall	0.00677	8.2
(8.20)	Generalized logarithmic	0.00741	8.5

[a] The overall accuracy of each model is presented in the form of an estimate of $\hat{\Phi}$, calculated as the mean residual deviance.

[b] Percentage variation of estimates of tree volume about 'true' volume, calculated as $100(\hat{\Phi})^{0.5}$

With the exception of the generalized logarithmic model the residuals from the other models were negatively biased for diameters exceeding 55 cm. In contrast, the Schumacher and Hall (1933) model was unbiased across the range of diameters and heights within the parametrization dataset. This model (Table 8.5) was therefore selected as the preferred tree volume model for regrowth karri. The Schumacher and Hall (1933) model has previously been selected as the best fit of a range of formulations tested for both radiata pine throughout Tasmania (Warner 1988, Candy 1989b) and white spruce in Canada (Morton *et al.* 1990).

Table 8.5 Parameter estimates for the fit of model (8.19) to the 208 stem-sectioned trees. Standard errors are shown in parentheses.

	Parameter	
α	β	γ
−10.8299	2.1068	0.9443
(0.1325)	(0.0040)	(0.0063)

8.5.3 Stem taper models

8.5.3.1 Compatible models

A number of authors have derived taper models which are compatible with the Schumacher and Hall (1933) tree volume model. Byrne (1979) derived the following compatible taper function which has proved satisfactory for estimating tree volumes for a variety of pine species (see *e.g.* Byrne 1979, Clutter 1980b, Brister *et al.* 1980):

If $v_t = \alpha_1 d^{\beta_1} h^{\gamma_1}$

and $v_m = v_t (1 - \alpha_2 d_l^{\beta_2} d^{\gamma_2})$

then $d_l = \alpha_3 d^{\beta_3} h^{\gamma_3} (h - h_l)^{\delta_3}$

and $h_l = h - \alpha_4 d_l^{\beta_4} d^{\gamma_4} h^{\delta_4}$

where v_t denotes total underbark stem volume (m^3) computed from the tree volume equation.

v_m denotes merchantable stem volume to top diameter limit d_l (m^3)

d_l denotes top diameter merchantability limit (cm)

d denotes diameter at breast height over bark (cm)

h denotes total tree height (m)

h_l denotes height from ground to the merchantability limit d_l

$\alpha_1 \dots \gamma_4$ are regression parameters

The primary advantage of this formulation is the capacity to directly estimate diameter underbark at any height and height to any diameter. However, preliminary fitting of this model to the 208 karri trees produced highly biased predictions of diameter in the crown and butt regions of the stem. The effect of buttswell and disparate taper changes associated with branching in the growing tip beyond crown break rendered this equation unsuitable for further development, even if it were restricted to sapling and pole–sized stems. Unbiased predictions in the butt region of the bole are particularly important in the regrowth stems, as this region generally contains the highest volume/value product, while accurate prediction of log volumes above crown–break is essential as new sawing technologies permit recovery of sawn timber from logs within the green crown zone (Waugh and Rozsa 1991).

The alternative approach, of enforcing compatibility by constraining the parameters of, and incorporating estimated tree volume in, the taper model has been pursued by many workers (*e.g.* Goulding and Murray 1975, Cao *et al.* 1980, McClure and Czaplewski 1986). Candy (1989b) developed a compatible, segmented, variable–form model based on Cao *et al.*'s (1980) derivation of Goulding and Murray's (1975) taper equation. This model is based on a fifth–degree polynomial in z, the relative height from tip to top diameter:

$$d_l^2(z)\, Kh/\hat{v} - 2z = \beta_1\,(3z^2 - 2z) + \beta_2\, d\,(z - \alpha_1)^2 I_1 + \beta_3\, d\,(z - \alpha_2)^2\, I_2 \tag{8.21}$$

where $I_i = 1$ for $z \geqslant \alpha_i \quad i = 1, 2$

$= 0$ for $z < \alpha_i$

d_l denotes diameter underbark (cm) to a height h_l (m)

$\hat{v}$ denotes tree volume (underbark) to tip (m^3) estimated from tree volume model

d denotes diameter overbark at breast height (cm)

$K = 0.00785$ (constant to convert d^2 to basal area)

$z = (h - h_l)/h$, relative height from tip to top diameter

h denotes total height (m)

This model was investigated for karri because the parameters could be readily constrained to ensure compatibility with model (8.19), and the formulae for calculating diameter and volume to a given height, and for height and volume to a given diameter, were readily available (McClure and Czaplewski 1986). Following Candy (1989b) a two–stage, random coefficients modelling procedure was used to fit model (8.21), where in the first stage model (8.19) was fitted to each tree and the resulting parameter estimates examined graphically for suitable second–stage regressions. The second–

stage models adopted by Candy (1989b) were appropriate, although his β_1 sub–model was altered by excluding the term for mean annual diameter increment (MD). Model (8.21) was fitted using a reduced dataset comprising only one randomly selected combination of height and diameter observations per tree. Parameter estimates and their associated standard errors are shown in Table 8.6.

Table 8.6 Parameter estimates for the fit of model (8.21) to the 208 stem–sectioned trees. Standard errors are shown in parentheses.

		Parameter		
β_1	β_2	β_3	α_1	α_2
0.2935 (0.0241)	0.2188 (0.0336)	–0.0554 (0.0271)	0.4860 (0.0658)	0.8712 (0.0349)

The percentage bias and precision of predicted diameter at a specified height, and of volume to a specified height, were calculated as the mean and standard deviation, respectively, of [100 (observed – predicted)/(predicted)] within relative height classes of 0.1. Examination of the bias and precision of predictions of diameter and volume to a specified height, and of volume and height to a specified diameter, revealed model (8.21) seriously overestimated stem diameter for relative heights exceeding 0.7 (Figure 8.1), broadly corresponding to crown break in these regrowth stems. Estimates of log volumes were also biased. The constraint of volume compatibility appeared to be compromising the prediction of stem form, a problem reported by other workers (Munro and Demaerschalk 1974). An alternative taper model was sought.

8.5.3.2 Non–compatible taper model

Largely due to time constraints, the examination of alternative formulations was restricted to forms used successfully for other regrowth eucalypt species. The following non–compatible taper model was developed in 1972 by Opie and Weir for *E.regnans* and is incorporated in the present version of STANDSIM (Campbell *et al.* 1979):

$$d_l^2 = d_u^2 (\beta_0 + \beta_1 t + \beta_2 t^2 + \beta_3 d_u + \beta_4 d_u^2 + \beta_5 h + \beta_6 h^2 + \beta_7 t d_u + \beta_8 t h + \beta_9 h d_u) \qquad (8.22)$$

where d_l denotes diameter underbark (cm) at a height of l (m) above ground

$t = l / h$

h denotes total tree height (m)

d_u denotes diameter at breast height underbark (cm)

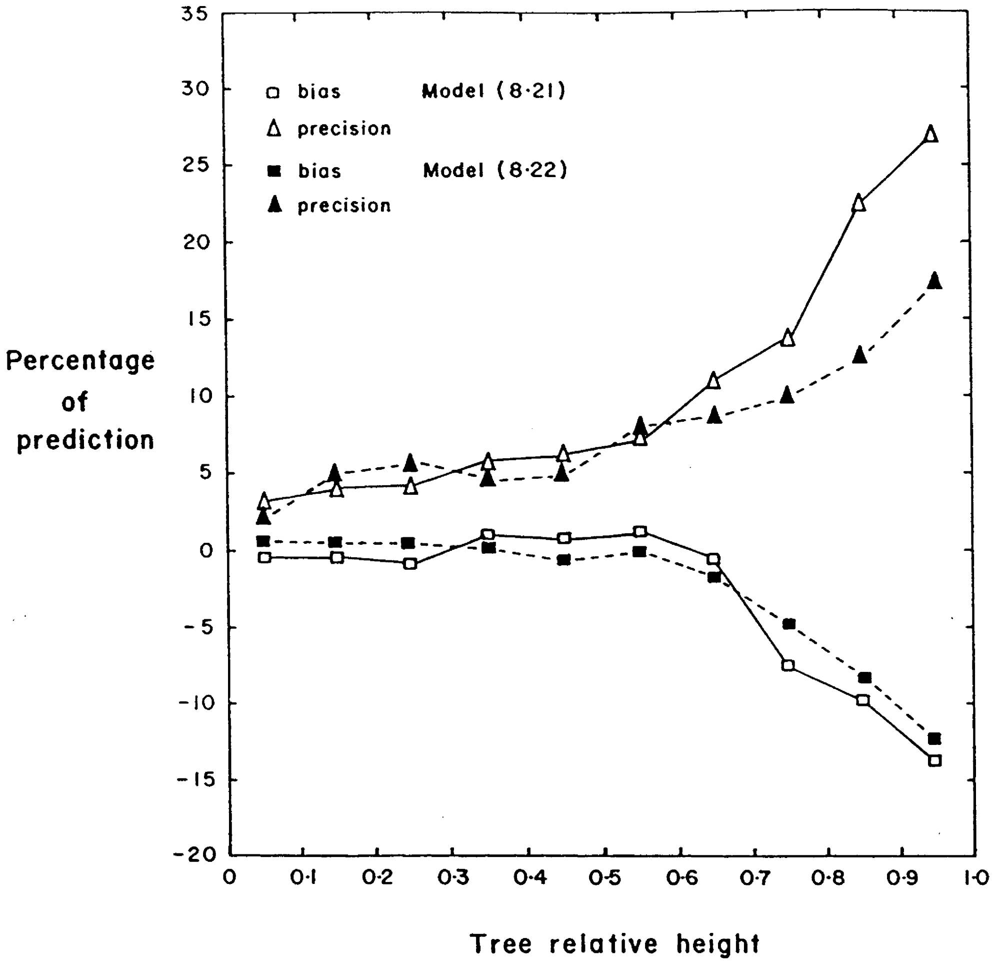

Figure 8.1 Bias and precision of predictions of diameter underbark at a specified relative height for the taper models (8.21) and (8.22).

Few details concerning the derivation of this model have been published. The function estimates diameter underbark to heights above ground by joining two polynomial functions. Separate sets of parameters are used to describe stem sections above and below a relative height of 0.2 (20% of total tree height), a point by which the influence of buttswell has dissipated for most species (Kozak 1988).

Parametrization of model (8.22) for karri stems (Table 8.7) produced a model of similar predictive accuracy to (8.21) for diameters in the lower bole sections, but of superior accuracy for upper bole sections above a relative height of 0.6 (Figure 8.1). Model (8.22) was selected for taper estimation in KARSIM, and was implemented by modifying existing source code from STANDSIM. The code was adjusted for varying stump heights, size class output and to provide for fixed-length harvesting.

Table 8.7 Parameter estimates for the fit of model (8.22) to the 208 stem-sectioned trees. Standard errors are shown in parentheses.

Relative				Parameter						
height	β_0	β_1	β_2	β_3	β_4	β_5	β_6	β_7	β_8	β_9
<0.2	1.862	−17.47	106.0	0.0049	0.000056	−0.0221	0.00030	−0.0452	0.1149	−0.0003
	(0.0899)	(1.288)	(7.426)	(0.0017)	(0.00001)	(0.0070)	(0.0001)	(0.0175)	(0.0392)	(0.00012)
>0.2	1.071	−1.326	0.2865	0.00059	0.00005	−0.0050	0.000246	0.00395	−0.0036	−0.00023
	(0.0251)	(0.0331)	(0.0194)	(0.0002)	(0.000008)	(0.0021)	(0.00004)	(0.0004)	(0.0009)	(0.00003)

Implementation of the model in KARSIM follows the sequence described by Incoll (1983) for STANDSIM. Total tree volume is first estimated using model (8.19). Model (8.22) is then applied to individual trees or mean trees within a diameter class to compute the height above stump to a specified small end diameter. This height is reduced if necessary to an even multiple of user-specified product length or its piece size increment. If fixed-length harvesting has not been specified further adjustment may be invoked to ensure that pieces larger than the minimum length but smaller than the maximum length can be cut without waste. Any remainder between the modified length and the length to the small end diameter is added to the next product length up the tree. The volume between the cut-off points is then calculated using model (8.22). Total and merchantable volumes may be output as stand totals at the end of each annual cycle, or summarized within tree *d* classes. The present version of KARSIM handles up to five product size classes for output.

8.5.4 Product estimation

Output from the taper subroutine provides tree and stand volume by size class assortments. Products overlap within these size classes, and are differentiated on the basis of quality specifications. Conversion of the volumes in size classes to product volumes is commonly approached by multiplying the size class volume by empirical out–turn factors which define the proportion of each size class which meets product specifications (size and quality). These out–turn factors have been developed as regressions which relate tree *d* and age to the percentage of gross bole volume that is utilized as each product (*e.g.* Gibson *et al.* 1974). This approach becomes difficult when, as in karri, there are many overlapping size categories for individual products.

Log quality constraints for regrowth karri stems include sweep, limb size (knottiness), length of clear grain, and the presence of kino, gum veins, or rot (CALM 1989). These attributes were unavailable for direct modelling or indirect correlation to log characteristics (Chapter 4), and in practice are unlikely to be available. Product out–turn factors can, however, be derived by combining information gathered in the computerized Logging Operations Information System (LOIS) with routine sampling of log specifications on mill landings. LOIS is a computerized payment and recording system for hardwood logging, and provides summaries of product out–turn from harvested coupes. Combined with the regular monitoring of log specifications on mill landings, these systems provide summaries of logging out–turn which can be used to determine product factors for each size assortment class. Thus, a 'look–up' table containing the proportions of the total volume in any size class which is accepted as a particular product is invoked in KARSIM. The product proportions can thus be regularly updated to reflect changes in utilization standards or the addition of new product categories for different log customers, as different customers may have the same size specifications but different quality constraints.

8.6 Implementation of thinning and economics modules

8.6.1 Thinning simulation

The simulation of thinning in models of this type is commonly approached by removing a proportion of stems from the stand according to empirical rules (Davis and Johnson 1987). Thinning in KARSIM is restricted by the nature of the data used in parametrizing the I_{Bg} model to thinnings from below, and is performed by removing a user–specified proportion of stand basal area from the array of stand diameters.

The rules governing which trees are removed from the array were derived by examining the changes in the *d* frequency distributions arising from present thinning practices in regrowth stands. Fourteen sample plots, each of 0.25 hectares extent, were located in naturally–regenerated stands prior to thinning and a complete enumeration of stems performed. Seven of the plots were machine–harvested and seven were manually felled. The relative frequencies of trees in 1 cm *d* classes in the 14 plots following machine or manual thinning to current prescription did not differ markedly. Approximately 60% of the removed basal area comprised the smallest stems in the stand, while the remaining 40% was uniformly removed from among the remaining larger trees. Inspection of the relative frequencies of *d*s for each plot within the Warren and Treen thinning trials confirmed that this empirical rule adequately described the removal process for all thinning intensities.

Hence, for any thinning, 60% of the nominated *B* to be removed is extracted from the stand *d* array by removing the smallest trees. The other 40% is uniformly removed by extracting every fourth tree in the remaining array until the total nominated *B* has been removed. A similar approach has been used by Alder (1977) and Incoll (1983).

'Strip' thinning, in which all trees the width of a harvester machine are felled and the adjacent strips of trees are thinned from below, is being considered for first thinning of the regrowth stands. Such extraction patterns improve access for fuel reduction burning as well as minimize machine harvesting costs. Incoll (1983) modelled strip thinning in *E.regnans* by assuming that the gross basal area increment of the stand following thinning was reduced by the proportion of the unoccupied area of the strip to the occupied stand area. He further assumed that the width of the unoccupied area was related to the root diameter of adjacent stems, and was subsequently re–occupied at a rate determined from root growth observations (Incoll 1979). Equivalent data to derive a crown or *d* to root size relationship for karri was unavailable, but a preliminary 'shell' for a strip thinning option was coded in KARSIM, using a simplified version of the Incoll (1983) approach. The *E.regnans* data is used as a default and a warning issued that the output is unvalidated and may be unreliable for long–term projections.

8.6.2 Economics module

Stand–level evaluation of the economic consequences of management regimes is a necessary component of a Decision Support System (Brumelle *et al.* 1991). An economics subroutine was included in KARSIM to provide the option for basic economic data to be output alongside mensurational variables. The subroutine is invoked by specifying at stand initialization the royalty price for each product category, a real interest rate, and the costs of stand establishment and subsequent tending. The discounted present net worth and the internal rate of return are computed at the end of each growth cycle, using standard algorithms (see Clutter *et al.* 1983).

CHAPTER 9 MODEL TESTING AND VALIDATION

9.1 Introduction

Model validation is a critical phase in the systems analysis sequence (Jeffers 1978). The validation process aims to not only provide the modeller with a test of the whole system but also to enable potential users to assess the reliability of the model for their intended application.

Goulding (1979) identified three stages in the validation process, *viz.* individual model and parameter evaluation, computer code verification, and whole model validation. The first two stages have been reported upon in Chapters 7 and 8, and it is the last stage, of whole model validation, that is the subject of this chapter. The emphasis in this stage is on the effects of interactions between model components, and the sensibility and limits of inferences which might be drawn from using the model.

The potential management applications of the model provide the context and define the criteria by which statistical analyses of model predictions must be evaluated (Newberry and Stage 1988). Consequently, the validation process must indicate the suitability of model behaviour and the accuracy of model predictions relevant to inventory update, harvest scheduling, and silvicultural response applications. Validation must define the range of stand conditions and the time span of projections for which the model is reliable.

No universal benchmarking procedures exist for measuring model performance (Leary 1989), largely because model utility depends on the users need (Newberry and Stage 1988), while appropriate independent test data are seldom available (Hyink 1990). Nevertheless, models must conform to minimum standards of biological and mathematical behaviour. Whole-model behaviour must not violate accepted principles of stand dynamics for the species (Leary 1989) and mathematically it must not unduly propagate error or variance in either the parameters or measured variables (Reynolds *et al.* 1981).

Largely because of the lack of a suitable independent dataset, validation of KARSIM was undertaken in two stages. The first involved an examination of the consistency of model behaviour with accepted biological principles of stand and tree dynamics. This stage identified a need for recalibration of several model components, prior to examining the accuracy, bias, and precision of model predictions. Because KARSIM comprises a number of model components which are mathematically non-compatible (*sensu* Clutter 1963), cumulative bias might be generated by successive iterations over extended periods. Given the few PSPs with long-term remeasurement histories available to detect such bias, a separate stand-level model was parametrized for unthinned forests to provide an independent estimate of stand volume for comparison with KARSIM estimates. The final section of the chapter discusses the reliability of the model for a number of potential applications.

In each section, detailed validation was performed for all stand and tree variables but for brevity greater detail is provided of *V* estimates because their accuracy depends on the accuracy of projections from all component models. Data were unavailable to perform tests of the log volumes by size class and product assortments.

9.2 Tests of conformity of model behaviour to biological theory

An individual–tree level growth model for an even–aged stand must be capable of reproducing the observed effects of competitive processes on stand structure (West 1988a). Model conformity to such relations as, for example, the self–thinning 'rule' (Yoda *et al.* 1963), Eichorns 'rule' (Assmann 1970) and Reineke's (1933) relationship are important indicators of the reliability of model behaviour. In the absence of extensive independent test data they are perhaps the only indication of model reliability when stands are extrapolated beyond the range of the data used for model parametrization.

The capacity of KARSIM to reproduce results in general agreement with such principles of stand behaviour was tested as follows. KARSIM was used to predict *N*, *B*, *V*, Dq, and *d* frequency distributions, at yearly intervals from 10 to 120 years of age, for three stands with site indices of 37, 44 and 52 m. Initial stand parameters were calculated as the mean of all stand observations for fully–stocked stands of these *A* and *SI*.

Preliminary graphical comparisons of the output of these simulations with the stand variables observed in PSPs and experimental plots suggested that the projected stocking density at ages exceeding 80 years were up to three times higher than in any stands observed in nature on sites of equivalent *SI*. Stand mean *d*, net *B* and the *d* frequency distribution were correspondingly depressed relative to the values presented in Figures 6.3 to 6.7. In contrast, the problem was not evident when thinning regimes which aimed to maintain stands on each site within 10% of the CBA were simulated. It was concluded that the survival function was underestimating irregular mortality within these stands and required revision.

9.2.1 Adjustment of tree survival model

Model (8.8) predicts a 'smoothed' or gradual reduction in stem numbers within a stand due to the combined effects of density–dependent and irregular mortality. In practice, mortality in vigorous regrowth stands is largely episodic, in which apparently 'random' drought, storm, fire, or pathogen outbreak events may trigger substantial loss of trees (Hopkins 1968, West 1981a). The extent to which these episodic reductions are incorporated in the fit of model (8.8) will largely depend upon the relative frequency of such events in the parametrization dataset. The longer the period for which records are available the more representative the P_{is} will be of this 'background' level of variation. Hamilton (1986), for example, used datasets containing PSPs with individual measurement histories of up to 70 years. Model (8.8), in contrast, was parametrized with a dataset where the mean measurement history of PSPs was only 3.8 years. Based on field observation and comments recorded within the few long–term plot histories it was reasoned that model (8.8) inadequately incorporated the influence of periodic drought within the karri forests.

The lack of PSPs with long–term measurement histories meant that an empirical adjustment, rather than a reparametrization, of model (8.8) was necessary. Such empirical adjustments must be based on sound biological reasoning (Hamilton 1990). Sequences of narrow growth rings, coincident across sites, were used as pointer years when ageing trees during earlier stem analysis work (Chapter 6). Loneragan (1979) had previously observed that major droughts, such as those of 1940, 1959, and 1969, when rainfall was 25% below the long–term arithmetic mean, caused serious disruption to the karri seed cycles. The effects of such droughting on the phenological cycle were apparent for several years. It was hypothesized that if soil moisture storage was sufficiently reduced to induce major stress on the reproductive physiology of the dominant trees, then reduced stand growth rates and increased mortality might accompany rainfall deficits of this magnitude. Data from PSP 823 ('100 year forest'), the Barness Road thinning trials and comments recorded in field books from resource and management–level inventories dating from 1920 confirmed that abrupt reductions in N and I_B were broadly correlated with severe rainfall deficit periods. The hypothesized influence of drought was incorporated into the survival model as follows.

Annual rainfall data were obtained for seventeen meteorological stations located at sites throughout the karri zone. A correlation matrix between annual rainfall at each of the 17 stations was prepared. All correlation coefficients exceeded 0.74 (significant at $P<0.05$), corroborating the consistency in ring width patterns observed in the earlier stem analysis data. Graphical inspection of the rainfall data revealed a consistent periodicity in annual rainfall deficits exceeding 25% below the long–term average for the site (Figure 9.1). The occurrence of a drought event was coincident across the entire karri region, while the historical mean probability of occurrence throughout the forest was one per 14.7 years. Accordingly, a stochastic function was added to the mortality subroutine to simulate drought events of this frequency. A drought event is simulated in any year when a test probability generated as a uniform random variate (0,1) is less than 0.07 (the annual probability of a rainfall deficit exceeding 25%). Whether or not the drought increases the probability of individual tree mortality depends upon the relative density of the stand. Stands with RDBNs exceeding 0.7 (fully–stocked) have the probability of individual tree survival decreased by a function calibrated from the Barness Road and other PSPs. This small calibration dataset suggested the decreased probability of survival was inversely related to the d of the tree relative to stand D_q, and that mortality in stands of RDBN less than 0.7 was largely unaffected by drought.

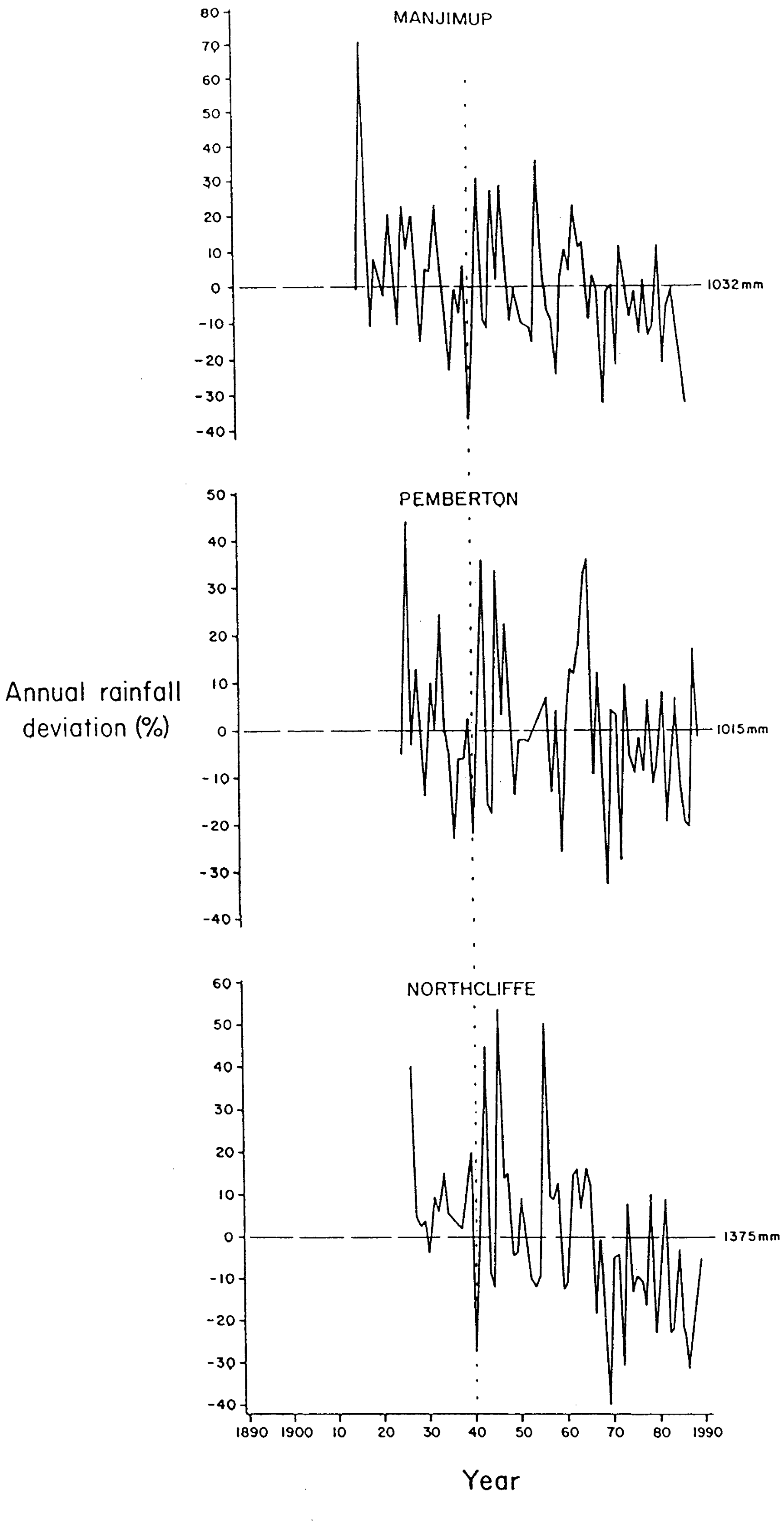

Figure 9.1 Percent deviation in annual rainfall from the long-term arithmetic average for three meteorological stations within the karri zone. Average annual rainfall for each station is 1032 mm (Manjimup – Australian Bureau of Meteorology station 009573), 1015 mm (Pemberton – station 009550) and 1375 mm (Northcliffe – station 009590). The dotted line illustrates a coincident drought in 1939/40.

The basal area increment of the Barness trials and PSPs was observed to decrease markedly for several years following a drought event. West (1979b) also observed that reduced basal area growth rates of *E.regnans*/*E.obliqua* trees coincided with drought conditions in Tasmania. In the absence of extensive data the I_B subroutine was adjusted to reduce stand basal area increment by 5% per annum for 2 consecutive years following a drought, irrespective of stand relative density.

These empirical adjustments produced consistency between KARSIM predictions and the long-term trends observed for *d* increment, *d* frequency distributions, and stocking density for most stands. Nonetheless, they are coarse approximations of a complex, interactive process which is likely to depend not only on the influence of climate but soil and biological factors as well. Seasonal moisture deficits are not the only soil factors which limit production (Kimmins *et al.* 1990), and their relative influence probably varies between nutrient-deficit and nutrient-rich sites (Landsberg 1986, Smith 1986, Grove 1987). Moreover, drought stress may predispose trees to secondary influences such as pathogen outbreaks. The 'dieback' disease of tall-open eucalypt forest in south-eastern Tasmania is thought to have been initiated by drought with subsequent attack by secondary pathogens (West and Podger 1980). Thus, although the model adjustments are consistent with observations in select karri trials, further work is necessary to refine the factors. A more general approach would involve modelling the annual variation in stand basal area and mortality as a function of climatic variation. Short and long-term data acquisition strategies for this are discussed in Chapter 11.

The inclusion of the drought effect suggests such periodic stand 'collapses' are essential to attaining the observed long-term growth rates on the remaining stems in the stand. Unfortunately, the need to adjust model behaviour in this way has two less desirable consequences. Adjustment of model behaviour to meet characteristics of the available data makes whole-model validation difficult unless a completely independent dataset is available. Secondly, the introduction of the stochastic component into the simulation provides a range of possible trajectories once stand relative density exceeds 0.7, requiring at least 15 simulations to determine a mean result. The latter problem simply makes some applications (*e.g.* inventory update) less efficient, but the former issue, of model testing, cannot be readily resolved without further data collection.

9.2.2 Evaluation of unthinned stand development across varying sites

A mean trajectory for each of the three representative stands was computed from 15 simulations following adjustment of the survival model. Graphs of the predicted mean of stand variables were inspected for conformity with the self-thinning rule, Eichorn's rule, and other stand property-property relationships characteristic of even-aged monocultures (see Bakuzis 1969). The range in simulated values for these fully-stocked stands was also compared to those in Figures 6.3 to 6.7 from the site evaluation study.

Averaged over the 15 simulations, KARSIM predicted increasing mortality, standing (net) and total *V* with increasing *SI*. Figure 9.2 illustrates this general trend for one simulation in stands of differing *SI*, and highlights the reduction in standing *V* associated with drought events. Stands on higher site qualities attained maximum density rapidly and were therefore predisposed to drought effects more frequently than those on low quality sites. This implies that as individual stands reach maximum density their progression along a theoretically 'common' maximum density trajectory, as predicted by the self–thinning rule, may not be maintained. Instead, stands will approach a limiting density but episodic mortality will reduce stocking density and generate a new trajectory toward the limiting density condition. This is illustrated in Figure 9.3, which shows that while KARSIM predicts stand behaviour consistent with Reineke's (1933) relationship, episodic mortality will place the stand in an understocked condition from which it takes some time to regain site occupancy. The extent of the understocking depends on the empirical adjustment incorporated in the mortality and I_B algorithms. Overall, the means of KARSIM projections were also consistent with other principles of monoculture development, such as Eichorn's rule, which states that total volume production increases with site quality for a given mean stand height (Figure 9.4).

A consequence of the climate–correlated droughting is that site quality becomes a dynamic variable, dependent on weather conditions, in contrast to the traditional view of a fixed site potential over such long time horizons. Explicit incorporation of climatic variability on stand growth, either through direct incorporation of meteorological factors or indirectly as in section 9.2.1, means that site becomes a variable (Gasana and Loewenstein 1984). The merit of such an approach over long projection periods is discussed further in Chapter 11.

9.2.3 Evaluation of managed stand behaviour

Thinning regimes of varying frequency (1 to 5 per rotation) and intensity (10 to 80% of *B* removed) were simulated for each of the three representative stands. Total stand volume production over a 120 year period for each thinning regime was compared to the total production of the unthinned counterpart stand of the same initial *d* distribution and *SI*.

The total production of a thinned stand (= standing volume + accumulated mortality + accumulated thinnings removals) is generally observed to be lower than the total production of an unthinned stand (= standing volume + accumulated mortality) on an equivalent site (Daniel *et al.* 1979, Smith 1986).

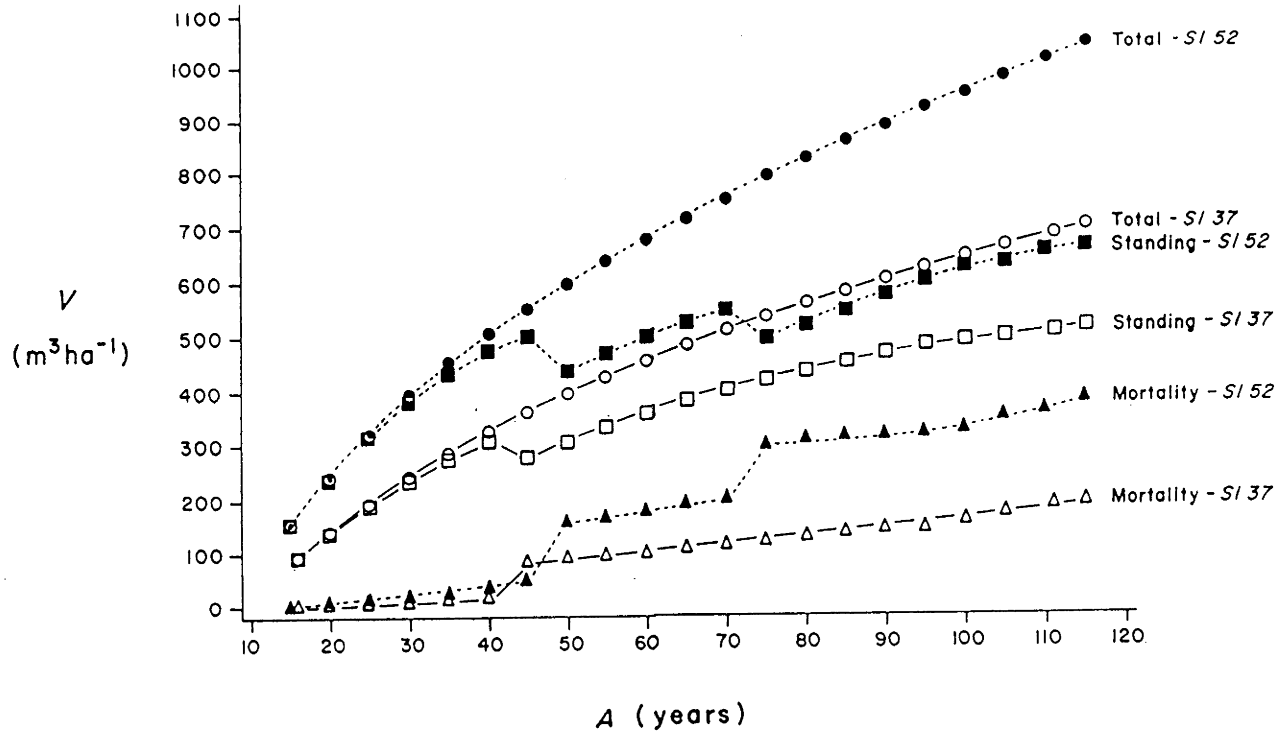

Figure 9.2 Simulated development of stand volume (to 5 cm SEDUB) with age for unthinned stands on high (*SI*=52 m) and low (*SI*=37 m) site qualities. Total volume production is the sum of the standing (live) volume and volume lost through mortality.

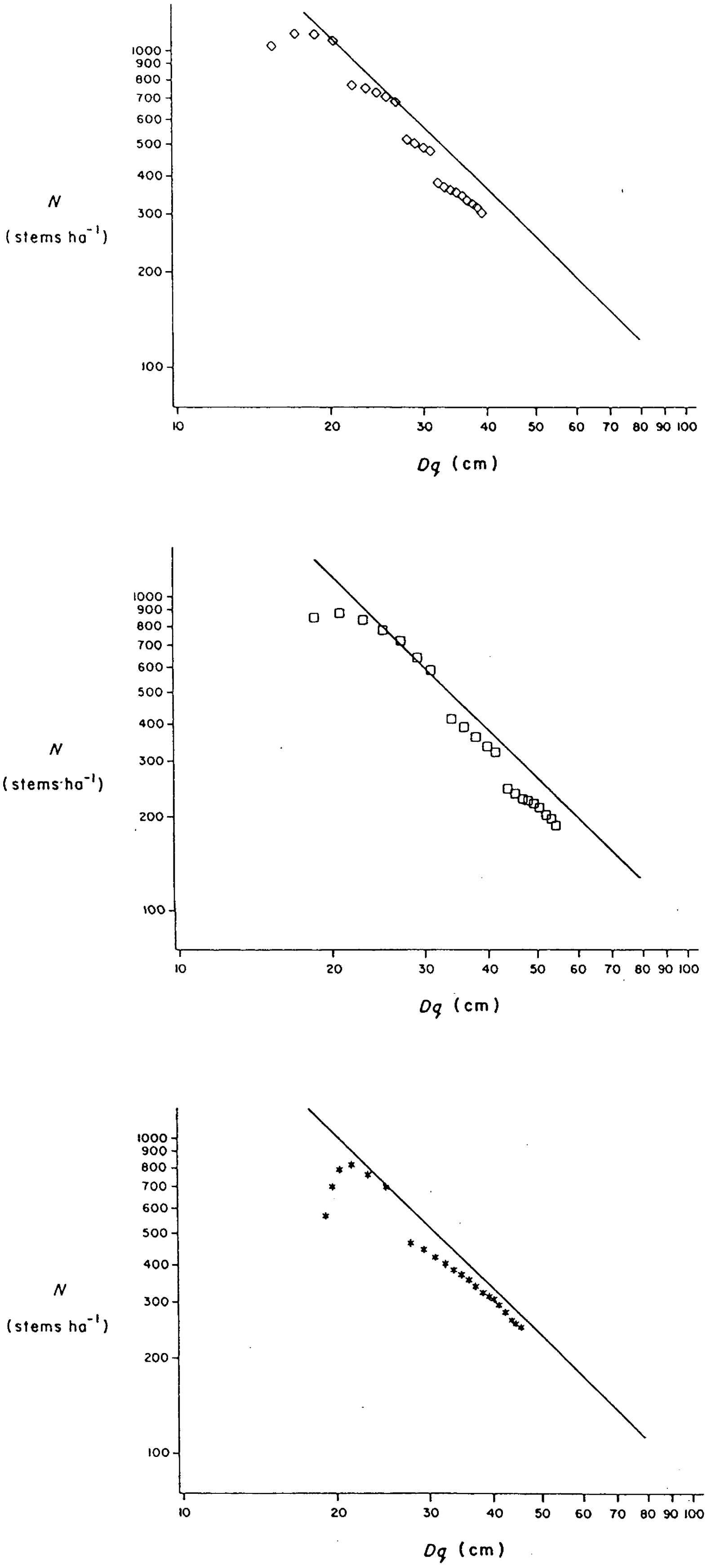

Figure 9.3 Conformity of model behaviour to Reineke's (1933) relationship. The relationship between trees per hectare and stand quadratic mean diameter for fully–stocked stands growing on sites of high, medium and low site index.

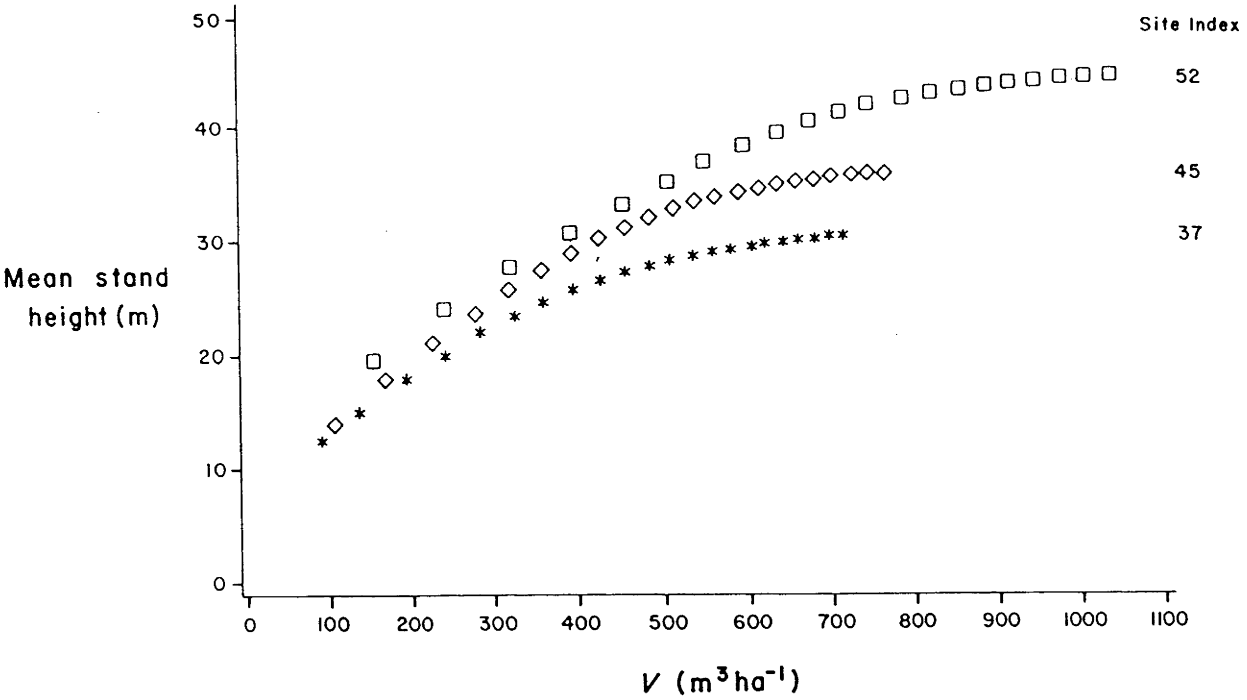

Figure 9.4 Conformity of model behaviour to Eichorn's rule. The relationship between stand mean height (m) and total volume production (m^3 ha^{-1}) for fully-stocked stands growing on sites of high, medium and low site index.

For each site, simulations of stands successively thinned to maintain the *B* above CBA (over 1 to 5 thinnings) predicted total *V* production levels which were below the mean total production of the unmanaged stands. Such a reduction would be expected if a site were under–utilized following thinning and a period of adjustment were necessary for the stand to regain full occupancy of the site. However, for a number of simulations contributing to the mean for the unmanaged stands, total *V* production was up to 5% less than that in the thinned stands (Figure 9.5). This apparent contradiction of theoretical expectations (Daniel *et al.* 1979) may be attributed to the stochastic influence of drought in the fully–stocked, unmanaged stands. Clearly, KARSIM predicted that catastrophic, drought–induced mortality reduced the stand below the full utilization of the site, and the ensuing lag time for the stand to regain full occupancy produced a decreased total production relative to stands thinned to avoid droughting mortality. This result is consistent with the concept of a variable site quality.

Stands thinned to intensities and frequencies which maintained free growth (ahead of stand competition) had, as expected, markedly diminished total production relative to their unthinned counterpart.

A final test of model behaviour, including product assortment predictions, involved examination of the output from a comprehensive range of KARSIM simulations for varying stand conditions (*e.g. SI*, initial *N*, thinning) by a panel of the five planning and silvicultural officers within CALM who were most experienced in karri mensuration and growth habits. Their collective experience and study of karri exceeded 100 person–years. In their subjective judgement the model behaved logically and provided predictions commensurate with their observations of the species. It was concluded that model behaviour was sufficiently robust to proceed to detailed testing of predictive accuracy.

9.3 Evaluation of model bias and predictive accuracy

9.3.1 Introduction

Tests of model accuracy and precision would ideally be based on independent experimental data covering a wide range of site, thinning treatments and initial stocking density, and would detail removals and product volumes. Plots providing such data would need to have been located according to proper sampling procedures to ensure they were representative of cutting unit or aggregation strata, and have been monitored over long periods (Reynolds *et al.* 1981). Independent datasets are essential to properly evaluate the predictive accuracy of a model such as KARSIM in which empirical adjustments were made to fit the data (Wallach and Goffinet 1989). In practice, such data are seldom available. Although 15% of the available PSPs and the experimental plots were reserved from model building (Table 3.4), the range of stand conditions represented in this 'independent' dataset was too restrictive to provide a comprehensive test of model accuracy. In the short–term at least, no additional independent data is

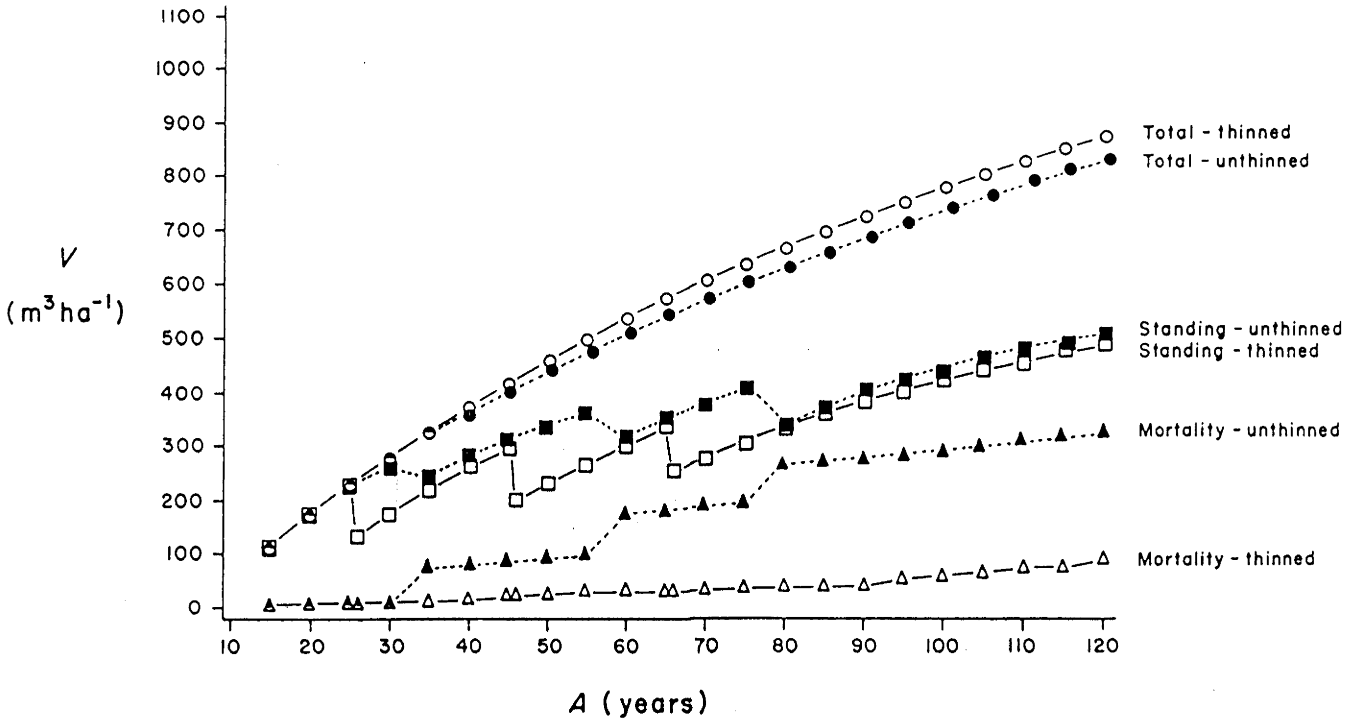

Figure 9.5 Comparison of the simulated development of stand volume (to 5 cm SEDUB) with age for an unthinned and a stand subjected to three thinnings on an 'average' site. Total volume production in the thinned stand is the sum of volume lost through mortality, volume removed in thinnings and standing (live) volume.

available for karri. A comprehensive evaluation of the predictive accuracy of the model was therefore not possible.

Nevertheless, the whole-model system should at least accurately describe the dataset used for parametrization of the component models (Hyink 1990). Consequently, the entire dataset, including the previously reserved validation dataset, were used to evaluate model accuracy, bias and precision by simulating future growth based on initial PSP conditions and comparing the predictions to observed remeasurements. The projection intervals were less than 10 years, providing an optimistic estimate of potential accuracy for short-term projections typical of inventory update applications. The predictive accuracy of longer-term simulations, typically required for harvest scheduling applications, was harder to assess as few plots had long measurement histories. Graphical and tabular comparisons were undertaken and a separate stand-level model was developed to provide an independent estimate of stand *V* as an additional check on model behaviour.

9.3.2 Accuracy, bias and precision for short-term simulations

The predictive ability of a model can be evaluated from measures of accuracy, precision, and time dependence for principal variables (Holdaway and Brand 1986). Regression methodology is frequently used for estimating the error in both stochastic and deterministic simulation models (Reynolds and Chung 1986), but it can be difficult to obtain meaningful results with small datasets or unbalanced sample sizes for the independent variables for which the error is being modelled (*e.g.* West 1983b). A preferable approach in such instances, adopted here, is the computation of confidence and prediction intervals as in Reynolds (1984). Thus, validation statistics were computed and tabulated within classes of independent variables. Observed stand values were compared with predicted values for each PSP and experimental plot within the karri dataset. KARSIM was initialized for each plot using observed stand statistics and *d* distributions within 2 cm size classes. Growth was then simulated for up to 10 years and the estimates of stand variables compared to those observed at remeasurement. The remeasurement (and hence projection interval) ranged from 2.0 to 6.1 with a mean of 3.8 years. The probabilistic nature of the droughting events meant that simulations for stands exceeding 0.65 RDBN at initial measurement required the mean of 15 simulations be used for the computation of validation statistics.

Bias was examined by computing mean residuals (observed — predicted estimates) within *A*, *SI* and RDBN classes. The standard error of the mean residual provided a measure of prediction precision, while the accuracy of predictions was evaluated by computing the critical error (e*) for the observations within each class.

Tables 9.1 to 9.3 summarize the accuracy, bias and precision statistics by *SI* and *A* classes for estimates of *N*, *B* and *V*. Because the e* statistic is not robust to departures of the distribution of residuals from normality, and tests of the normality of the residual

Table 9.1 Bias, precision and accuracy statistics tabulated by stand site index and age classes for predictions by KARSIM of stocking density. Values are in stems ha^{-1} except for the number of measurements (n). Critical error values for cells containing fewer than 10 observations may be unrepresentative, and results for cells containing fewer than 5 observations are not shown.

Site index class[a] (m)	Statistic	Stand age class[a] (years)					
		10–20	20–30	30–40	40–50	50–60	>60
<37.5	Mean bias	−16.9	25.0	−15.8	7.0	–	−18.5
	s.e. (bias)	21.8	7.7	22.1	3.7	–	32.1
	Mean predicted *N*	993.9	775.5	450.0	479.3	–	172.5
	e*	41.9	32.4	21.6	10.0	–	28.6
	n	13	6	5	5	–	9
37.5–42.5	Mean bias	28.4	–	4.5	−21.5	−9.2	–
	s.e. (bias)	17.5	–	5.9	11.9	18.8	–
	Mean predicted *N*	774.6	–	631.3	423.1	261.7	–
	e*	22.2	–	8.9	26.0	15.8	–
	n	14	–	9	7	9	–
42.5–47.5	Mean bias	15.8	−18.7	17.2	15.3	−4.7	13.5
	s.e. (bias)	17.4	12.3	13.5	9.4	5.5	6.6
	Mean predicted *N*	881.7	769.4	557.7	259.1	254.9	202.0
	e*	27.3	28.8	44.5	17.9	9.1	23.9
	n	13	5	12	30	9	5
47.5–52.5	Mean bias	−38.4	16.5	10.0	−2.5	11.7	4.0
	s.e. (bias)	23.8	30.5	8.3	5.9	6.7	1.0
	Mean predicted *N*	656.4	449.3	463.3	229.4	349.3	95.3
	e*	50.1	24.1	23.5	14.6	11.4	9.7
	n	22	6	6	25	7	5
52.5–57.5	Mean bias	22.8	–	−15.8	18.0	–	−9.4
	s.e. (bias)	16.2	–	7.3	5.7	–	7.1
	Mean predicted *N*	594.0	–	369.4	250.6	–	75.3
	e*	31.0	–	10.9	15.2	–	16.3
	n	17	–	7	6	–	7

[a] Class boundaries are mutually exclusive but have been rounded for presentation purposes.

Table 9.2 Bias, precision and accuracy statistics tabulated by stand site index and age classes for predictions by KARSIM of net basal area. Values are in m^2 ha^{-1} except for the number of measurements (n). Critical error values for cells containing fewer than 10 observations may be unrepresentative, and results for cells containing less than 5 observations are not shown.

Site index class[a] (m)	Statistic	Stand age class[a] (years) 10–20	20–30	30–40	40–50	50–60	>60
<37.5	Mean bias	2.00	−0.70	−1.86	0.10	–	−2.70
	s.e. (bias)	2.52	1.11	1.54	0.87	–	3.31
	Mean predicted *B*	21.41	35.25	30.10	35.77	–	36.41
	e*	2.09	1.78	1.99	1.06	–	2.96
	n	13	6	5	5	–	9
37.5–42.5	Mean bias	0.60	–	−1.35	1.25	0.53	–
	s.e. (bias)	0.77	–	0.35	0.96	0.86	–
	Mean predicted *B*	22.59	–	38.13	37.80	25.36	–
	e*	1.73	–	3.25	2.71	2.57	–
	n	14	–	9	7	9	–
42.5–47.5	Mean bias	1.97	−1.83	0.40	0.31	−0.04	0.96
	s.e. (bias)	0.20	1.12	0.85	0.72	0.27	1.13
	Mean predicted *B*	26.88	31.94	40.97	28.53	30.71	39.65
	e*	2.63	3.61	0.77	2.03	1.41	1.86
	n	13	5	12	30	9	5
47.5–52.5	Mean bias	−2.87	−0.60	2.29	0.77	−0.14	1.65
	s.e. (bias)	1.86	1.33	1.66	0.95	0.35	1.88
	Mean predicted *B*	23.21	30.47	40.58	30.49	41.20	49.63
	e*	1.58	1.16	2.38	1.38	2.69	3.33
	n	22	6	6	25	7	5
52.5–57.5	Mean bias	−1.55	–	0.79	−0.38	–	1.47
	s.e. (bias)	0.99	–	1.68	0.17	–	2.38
	Mean predicted *B*	21.81	–	33.40	39.05	–	47.0
	e*	1.34	–	1.21	2.53	–	2.59
	n	17	–	7	6	–	7

[a] Class boundaries are mutually exclusive but have been rounded for presentation purposes.

Table 9.3 Bias, precision and accuracy statistics tabulated by stand site index and age classes for predictions by KARSIM of net volume. Values are in m^3 ha^{-1} except for the number of measurements (n). Critical error values for cells containing fewer than 10 observations may be unrepresentative, and results for cells containing fewer than 5 observations are not shown.

Site index class^a (m)	Statistic	Stand age class^a (years)					
		10–20	20–30	30–40	40–50	50–60	>60
<37.5	Mean bias	−7.16	12.13	18.49	−22.82	–	4.80
	s.e. (bias)	5.44	8.43	23.60	9.25	–	6.45
	Mean predicted *V*	104.1	295.4	283.8	329.9	–	418.7
	e*	11.25	15.44	29.28	24.47	–	8.87
	n	13	6	5	5	–	9
37.5–42.5	Mean bias	8.25	−14.60	8.75	−17.50	−21.33	7.90
	s.e. (bias)	14.33	10.11	17.55	9.40	15.52	9.56
	Mean predicted *V*	154.5	257.3	364.5	403.4	296.5	463.4
	e*	9.21	16.90	14.47	22.31	17.13	9.72
	n	14	5	9	7	9	5
42.5–47.5	Mean bias	19.94	−4.32	−16.71	−4.97	7.71	39.96
	s.e. (bias)	7.33	9.11	7.77	12.46	12.45	28.42
	Mean predicted *V*	170.9	309.5	428.4	355.5	388.1	592.8
	e*	20.08	12.40	13.29	9.20	16.55	30.13
	n	13	5	12	30	9	5
47.5–52.5	Mean bias	−32.17	−23.93	−14.76	−14.10	32.13	−54.33
	s.e. (bias)	27.41	5.30	11.31	15.27	8.14	26.18
	Mean predicted *V*	222.8	299.9	476.9	402.7	541.0	733.2
	e*	24.66	17.99	16.87	18.66	27.45	39.89
	n	22	6	6	25	7	5
52.5–57.5	Mean bias	21.57	–	−38.61	−53.99	–	48.12
	s.e. (bias)	6.44	–	23.41	12.05	–	26.67
	Mean predicted *V*	253.2	–	439.7	606.7	–	918.8
	e*	11.63	–	21.87	25.74	–	27.36
	n	17	–	7	6	–	7

[a] Class boundaries are mutually exclusive but have been rounded for presentation purposes.

distribution were unlikely to be conclusive with fewer than 10 observations (Neter *et al.* 1985), the e* values reported in these tables for cells containing fewer than 10 observations should be taken as indicative only.

KARSIM was found to give relatively unbiased estimates across age and site classes for predictions of each stand variable. Overall, the model bias for 2 to 6 year projections was +1.5% (s.e. 1.1%) in *N* projections, −0.9% (s.e. 1.2%) for *B*, and −1.9% (s.e. 1.8%) for *V*. Segregation of the 32 PSPs in the original 'validation' dataset (Table 3.4) did not markedly alter these figures, but did of course alter values in some cells of the tables. The accuracy of *B* and *N* predictions compare favourably with those reported by West (1983b) for his model of *E.regnans/E.obliqua* regrowth in Tasmania (6 m^2 ha^{-1} for *B* and 210 stems ha^{-1} for simulation periods of up to 21 years).

The high e* in the <20 years *A* class for all *SI* in Table 9.1 reflect unbiased but imprecise ingrowth estimates. This imprecision was reflected in the relatively inaccurate *V* predictions (Table 9.3). The observed and predicted *d* frequency distributions for both thinned and unthinned stands were rarely significantly different over such short projection periods. Averaged over all plots, the Kolmogorov–Smirnov probabilities indicated there was no significant difference ($P<0.05$) between the observed and predicted distributions.

The size class interval and manner of initialization of the initial *d* distribution markedly affected the relative accuracy of *B* and *V* predictions. Aggregating the *d* class interval from 2 cm to 5 cm decreased the accuracy of *B* predictions in stands younger than approximately 40 years, an effect commonly observed in models of this type (Alder 1977, Gertner 1991). Stand volume estimates were less precise but unbiased when initial *d* distributions were generated using the Weibull *cdf* (Chapter 7).

Examination of the statistics when plots were grouped by *A* and RDBN classes revealed the model was unbiased across relative density classes and reasonably accurate (Table 9.4). The higher accuracy of estimates in stands of low RDBN (<0.4) and younger than 40 years were partly due to the adjustment of the I_B model to approximate the observed data trends for these stands (Chapter 8). Volume estimates for stands above and below a RDBN of 0.7 were of comparable accuracy, suggesting the mean of the 15 simulations for those stands with an RDBN exceeding 0.7 provided a satisfactory prediction of stand development.

9.3.3 Accuracy, bias and precision for long–term simulations

Meaningful validation statistics were unable to be computed for the few PSPs with measurement histories exceeding 10 years, due to insufficient site representation, disparate stand treatments and incomplete measurements. Comparisons between observed and predicted values from KARSIM were therefore tabulated and examined for trends. Table 9.5 shows observed and predicted variables for four plots in a thinning trial. The absence of an unthinned control plot and several other design limitations

Table 9.4 Bias, precision and accuracy statistics tabulated by relative density and stand age classes for predictions by KARSIM of net volume. Values are in $m^3 ha^{-1}$ except for the number of measurements (n). Critical error values for cells containing fewer than 10 observations may not be representative, and results for cells containing less than 5 observations are not shown.

RDBN class	Statistic[a]	Stand age class (years)					
		10–20	20–30	30–40	40–50	50–60	>60
0–0.15	Mean bias	6.00	–	–	-11.7	–	–
	s.e. (bias)	4.94	–	–	6.65	–	–
	Mean predicted *V*	60.7	–	–	220.6	–	–
	e*	7.54	–	–	9.49	–	–
	n	20	–	–	16	–	–
0.151–0.40	Mean bias	-3.93	8.60	-12.25	28.10	34.81	-16.78
	s.e. (bias)	13.47	9.44	14.72	6.33	23.55	10.22
	Mean predicted *V*	142.1	185.4	265.9	224.3	277.1	469.2
	e*	11.23	10.69	16.52	18.23	25.58	14.36
	n	18	5	11	13	10	5
0.401–0.70	Mean bias	18.89	-22.42	13.6	-0.48	-2.00	17.66
	s.e. (bias)	7.93	24.03	9.49	5.58	9.12	31.10
	Mean predicted *V*	195.1	314.8	365.5	387.7	390.7	688.5
	e*	20.15	17.45	24.04	8.24	18.60	19.20
	n	16	9	13	19	9	14
0.701–1.00	Mean bias	10.40	-18.55	14.12	17.65	-9.70	23.41
	s.e. (bias)	12.77	17.93	10.62	11.27	22.48	27.44
	Mean predicted *V*	216.6	321.3	467.8	412.4	450.1	705.1
	e*	13.71	20.68	16.41	14.84	19.25	24.66
	n	25	8	15	25	6	12

[a] Values for stands in the RDBN>0.7 class are the mean of 15 simulations per stand.

Table 9.5 Observed and predicted stand stocking densities (stems ha^{-1}), basal areas (m^2 ha^{-1}), quadratic mean diameters (cm) and live volume (m^3 ha^{-1}) for four plots thinned at age 25 to 40, 80, 120 and 160 stems per hectare. Each plot had a site index of 46.4 m and an area of 0.4 ha.

Plot number	*A*	*N*		*B*		*Dq*		*V*	
		Obs.	Pred.	Obs.	Pred.	Obs.	Pred.	Obs.	Pred.
827/1	26	40	40	6.0	5.8	43.7	42.9	-	-
	29	40	40	7.4	7.0	48.5	47.1	-	-
	36	40	40	10.0	10.4	56.4	57.5	-	-
	51	38	40	15.8	15.8	72.7	70.8	247.0	237.9
	56	38	39	18.1	17.3	77.9	74.1	302.9	288.7
827/2	26	80	80	8.6	8.0	37.0	35.8	-	-
	29	80	80	10.4	9.8	40.7	39.6	-	-
	36	80	80	13.4	13.0	46.2	45.5	-	-
	51	80	78	21.8	20.0	58.9	57.1	346.0	302.6
	56	78	78	23.9	22.3	62.5	60.3	396.9	354.1
827/5	26	122	122	10.2	9.7	32.6	31.8	-	-
	29	122	122	12.7	12.2	36.4	35.7	-	-
	36	122	121	15.5	15.7	40.2	40.6	-	-
	51	120	119	22.7	23.9	48.7	50.6	351.1	328.0
	56	116	118	24.1	26.2	51.4	53.2	382.0	371.7
827/4	26	156	156	12.5	12.3	31.9	31.7	-	-
	29	156	155	16.2	15.8	36.4	36.0	-	-
	36	156	153	20.4	18.9	40.8	39.7	-	-
	51	154	147	29.5	28.5	49.4	49.7	461.6	437.8
	56	152	147	33.2	31.9	52.7	52.6	530.8	472.2

rendered this trial inadequate for thinning response analyses, but the four plots nevertheless provide a test of the capacity of KARSIM to simulate stands following thinning for periods of up to 30 years. Stand *N*, *B* and *V* were each estimated satisfactorily, with only a weak trend toward underestimation of *B* and *V* at the highest initial stand density (PSP 827/4). Model accuracy did not vary markedly over the simulation period, and no droughting was predicted as the stands maintained relatively low relative densities throughout the projection. In contrast, the mean of 15 simulations for four unmanaged stands (Table 9.6) revealed a trend of underestimation of mortality and basal area, with consequent underestimation in D_q and *V*.

Table 9.6 illustrates that it is generally impossible to obtain precise estimates of stand variables for individual stands with empirical models of this type (West 1991). As expected, variation in stand values were largely attributable to the variable mortality over long time periods, and it was observed that at least one of the 15 simulations comprising the mean value more closely approximated the abrupt fluctuations in *N* and *B* observed for PSPs 823 and 829.

There was evidence of decreasing agreement between observed and predicted *d* distributions with increasing length of projection interval, although comparisons between thinned and unthinned stands suggested the basal area allocation model (Chapter 8) was unbiased.

9.3.4 A compatible stand-level model for volume estimation

9.3.4.1 Introduction

KARSIM contains several component models in which the regressor variables of one model are predicted from another model. The propagation of errors from one component model to another can mean that any biases inherent in various components will additively accumulate during a growth simulation, generating inconsistent estimates of future stand volume depending on the number of projection steps or the length of the projection interval (Clutter *et al.* 1983). The absence of an independent dataset of PSPs with long measurement histories made it difficult to quantify the likely extent of such bias, although recent work by Gertner (1991) has demonstrated that highly biased predictions can result from the propagation of errors between highly nonlinear functions typical of several models in KARSIM.

Models possessing the property of compatibility described by Clutter (1963) can avoid such cumulative bias, because predictions made by 'compatible' models will be the same irrespective of the number or length of the time steps involved in the projection (Clutter *et al.* 1983). Thus, one means of examining the possible extent of such cumulative bias in KARSIM was to develop a compatible, stand-level system of models which could provide an alternative estimate of future stand volume. Estimates of stand yield made with KARSIM, particularly over periods exceeding 30 years, could then be compared with those from the stand-level model. Stand and projection

Table 9.6 Observed and predicted stand stocking densities (stems ha^{-1}), basal areas (m^2 ha^{-1}), quadratic mean diameters (cm) and live volume (m^3 ha^{-1}) for four PSPs with long remeasurement histories. Plots were unmanaged, except PSP 822, which was thinned at age 53. The area of each plot was 0.4 ha.

Plot number	*SI*	*A*	*N* Obs.	*N* Pred.	*B* Obs.	*B* Pred.	*Dq* Obs.	*Dq* Pred.	*V* Obs.	*V* Pred.
819	56.0	109	84	84	39.4	40.4	77.3	78.3	–	–
		115	82	79	40.7	41.7	79.5	82.0	924.0	897.4
		120	82	75	42.7	42.6	81.4	85.0	–	–
822	49.0	74	94	94	30.5	29.4	64.3	63.1	–	–
		79	90	91	34.4	31.0	69.8	65.8	–	–
		85	90	87	40.8	32.6	76.0	69.1	689.1	586.6
		90	80	84	40.8	33.8	80.6	71.6	–	–
		96	78	82	39.1	35.5	79.9	74.3	–	–
		101	74	79	38.5	36.6	81.4	76.8	–	–
		106	66	77	35.6	37.7	82.9	79.0	–	–
		111	66	76	36.9	38.8	84.4	80.6	495.5	486.4
823	47.0	42	280	280	30.6	29.9	37.3	36.9	388.5	392.7
		52	256	247	34.7	36.5	41.5	43.4	–	–
		74	176	197	38.1	38.4	52.5	49.8	–	–
		84	164	183	47.8	41.7	60.9	53.9	–	–
		90	160	168	46.7	42.9	61.0	57.0	729.0	656.0
		101	124	150	53.9	44.1	74.4	61.2	926.5	810.1
		111	102	124	48.5	46.2	77.8	68.9	830.7	753.5
829	46.4	41	516	516	46.3	44.0	33.8	32.9	–	–
		45	516	479	49.7	45.4	35.0	34.7	–	–
		50	450	391	50.3	46.4	37.7	38.9	753.1	686.6
		65	306	278	45.8	38.0	43.7	41.7	728.4	615.8
		70	234	232	44.0	39.8	48.9	46.8	805.6	651.0

conditions giving rise to large differences (exceeding model accuracy limits) between these estimates would suggest instances where cumulative bias was a problem. Unfortunately, the lack of stand treatment data restricted the eventual stand–level model to unthinned stands, although the statistical methodology and formulations adopted are well suited to the future incorporation of stand treatment effects.

The superiority of site index as a classification of site potential (Chapter 6) suggested that traditional model forms based on stand density, age and site quality would be appropriate for predicting stand volume. A range of derivations of the Schumacher (1939) yield model (see Clutter *et al.* 1983) were considered likely candidates. Such formulations typically subsume the effects of *A* and *SI* into a *H* term, and use *B* to represent stand density effects on volume production. Consequently, the development of a compatible system required that individual sub–models predicting these variables be themselves compatible. The stand dominant height model (6.7) is compatible as estimates made with the model do not rely on earlier estimates made with it. A compatible model for the prediction of *B* was therefore required.

9.3.4.2 Net basal area increment function

A range of compatible, algebraic difference formulations of asymptotic yield functions were investigated to model stand net basal area increment. Both anamorphic and polymorphic formulations based on the Gompertz (1825), Weibull (1951), Richards (1959) and Chang (1984) functions were examined. Graphical inspection of basal area against age for the combined dataset revealed that polymorphic forms were inappropriate within the range of the current data and attention was restricted to anamorphic formulations.

The following anamorphic form of the Richards (1959) function provided the best fit, consistent with the choice of the yield form when modelling net basal area in the maximum density stands for the site evaluation study (Chapter 6):

$$B_{i+1} = B_i \left\{ \frac{[1 - \exp(-\beta A_{i+1})]}{[1 - \exp(-\beta A_i)]} \right\}^{\gamma} \qquad (9.1)$$

where B_i denotes observed net stand basal area at age A_i, and

B_{i+1} denotes predicted net stand basal area at age A_{i+1}

The parameters in model (9.1) were expected to vary with stand treatment (such as thinning) and such relationships were to be investigated in the fitting process. Model parametrization and hypothesis testing followed the statistical methodology outlined by Candy (1988, 1989a). This approach was selected as it provided an appropriate statistical framework for testing the significance of improvements to model fit by incorporating additional explanatory variables into (9.1).

Candy's (1989a) approach involved reparametrizing (9.1) and fitting it as a generalized linear model given by

$$B_{i+1} = B_i \ \exp \{ \gamma \ [\log_e (1-\exp(-\beta A_{i+1})) - \log_e (1-\exp(-\beta A_i))] \} \qquad (9.2)$$

This model was fitted using OLS to all measurements in the combined PSP and experimental database. Graphical examination of the residuals indicated substantial heteroscedasticity (variance of residuals increasing with stand age). Model (9.2) was therefore refit using IRLS and analogues of the poisson and gamma functions to model the error variance in the iterative weighting process. Inspection of graphs of the Pearson residuals (McCullagh and Nelder 1983) against the predicted increment $(B_{i+1} — B_i)$ for poisson and gamma-like variance functions indicated that the following poisson-like variance function was most appropriate for modelling the conditional variance of B:

$$\mathrm{Var}(\varepsilon_i) = \Phi \ \mathrm{Var}(B_{i+1}) \qquad (9.3)$$

$$\mathrm{Var}(B_{i+1}) = (B_{i+1} - B_i) \qquad (9.4)$$

The parameter estimates were obtained using the inverse of (9.4) as weights in the IRLS procedure.

Hypothesis testing used the quasi-likelihood ratio tests developed by Wedderburn (1974) and described by Candy (1988). The quasi-likelihood ratio tests require an estimate of a dispersion parameter (Φ) (McCullagh and Nelder 1983). The residual mean deviance ($\hat{\Phi}$) was used as the estimate in the present work, and was calculated using the derivation given by Candy (1989a) of Wedderburn's (1974) quasi-deviance statistic. This statistic is the quasi-likelihood generalization of the residual sum of squares (for normally distributed, constant error variance models) to the deviance for the exponential family of distributions (Nelder and Wedderburn 1972). F-tests based on the quasi-likelihood ratio tests are therefore analogous to the conventional F-tests.

Model (9.2) was initially fit to all stands in the dataset and then the influence of stand treatments was examined by adding additional variables. The influence of stand relative density on basal area increment was examined by replacing the parameters β and γ in equation (9.2) with linear combinations of the relative density measure RDBN. The change in residual mean deviance ($\hat{\Phi}$) from the incorporation of these terms was not significant (P>0.05), indicating no improvement to the fit of the base model (9.2). This result is at least partly due to the majority of the plots in the combined, unthinned database being fully-stocked.

Restricting the fit of model (9.2) to only the unthinned stands produced a 43% decrease in the residual deviance compared to the fit of the combined thinned and unthinned dataset. This may be attributed to the limited number of thinned stands and their few post-thinning measurements within the database. The fitting and application of the net basal area increment and consequent stand volume models was therefore restricted to unthinned stands.

Parameter estimates and their standard errors for model (9.2) are given in Table 9.7. The estimate of Φ provides an overall measure of the predictive accuracy of the model.

Table 9.7 Parameter estimates and fit statistics for net stand basal area increment model (9.2). Standard errors are shown in parentheses and were computed from a reduced dataset containing only one observation from each plot.

Parameter		Fit Statistics	
β	γ	n	$\hat{\Phi}$
0.0879 (0.0238)	2.965 (0.7213)	172	2.671

A weak trend of model (9.2) underestimating *B* for site indices exceeding 47.5 m was evident (Table 9.8), while the accuracy of predictions decreased markedly at ages beyond 60 years. The e* values in Table 9.8 were calculated using the following derivation of the Reynolds (1984) approach supplied by Dr P. West[1]:

$$e^* = [\, n\, \hat{\Phi}\, \chi^2_{1-\alpha}(1) \,/\, \chi^2_{\alpha}(n)\,]^{0.5}$$

which assumes the variance of the residuals, r (observed minus predicted), followed the following variance function

$$\mathrm{Var}(r) = \Phi\, (B_{i+1} - B_i)^2$$

where Φ is the dispersion parameter, estimated by $\hat{\Phi}$ the mean deviance.

This approximation was necessary because the assumption by Reynolds (1984) that the distribution of residuals is normal when computing e* was untenable for this compatible model: a more appropriate assumption was that $r_i/(B_{i+1} - B_i)$ had constant variance.

The *B* development predicted by model (9.2) for five PSPs with long measurement histories is illustrated in Figure 9.6. This deterministic model predicts a plateau of *B* beyond age 70 for each stand. In practice, although the rate of density dependent mortality will decrease at older stand ages (Chapter 8), irregular mortality arising from prescribed burns, drought or storm events will precipitate the observed fluctuations of *B* about the 'mean' trajectory. Such variation between the estimated stand trajectories and the observed trajectory illustrates the imprecision of the model estimates for an individual stand. In application, however, estimates would be averaged

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[1] Dr P.W. West, CSIRO Division of Forestry, Hobart, Tasmania.

Table 9.8 Bias, precision and accuracy statistics tabulated by stand site index and age classes for predictions by model (9.2) of net basal area increment for unthinned stands. Values are in m^2 ha^{-1} except for the estimate of mean deviance (Φ) and the number of measurements (n). Results for cells containing less than 5 measurements are not shown.

Site index class[a] (m)	Statistic[b]	Stand age class[a] (years) 10–20	20–30	30–40	40–50	50–60	>60
<37.5	Mean bias	0.73	−1.00	−2.18	0.95	–	−1.44
	s.e. (bias)	0.84	1.91	0.70	0.39	–	1.11
	Mean predicted *B*	19.61	32.95	33.88	34.82	–	34.98
	e*	1.51	1.34	1.73	1.38	–	1.73
	$\hat{\Phi}$	1.11	0.98	1.72	1.11	–	1.63
	n	9	6	5	5	–	6
37.5–42.5	Mean bias	0.78	–	0.14	0.16	0.86	–
	s.e. (bias)	0.66	–	0.57	0.40	1.03	–
	Mean predicted *B*	20.63	–	39.73	40.64	31.73	–
	e*	1.61	–	1.04	1.14	3.06	–
	$\hat{\Phi}$	1.19	–	0.59	0.75	4.59	–
	n	12	–	6	5	9	–
42.5–47.5	Mean bias	−0.06	−1.23	−0.09	0.52	1.01	−0.39
	s.e. (bias)	1.05	0.96	0.46	0.72	0.43	0.99
	Mean predicted *B*	24.53	33.17	41.06	41.71	33.41	40.91
	e*	1.85	1.87	1.04	2.79	2.60	4.09
	$\hat{\Phi}$	1.73	2.02	0.53	3.42	3.54	9.66
	n	8	5	9	11	7	5
47.5–52.5	Mean bias	−3.21	−1.02	−0.60	−0.01	−0.04	−0.23
	s.e. (bias)	0.96	1.54	0.66	0.41	0.49	0.38
	Mean predicted *B*	27.52	31.49	41.19	43.56	41.93	44.03
	e*	1.58	1.93	1.25	1.45	1.50	3.08
	$\hat{\Phi}$	1.19	2.04	0.90	1.15	1.18	5.47
	n	10	6	5	6	7	5

Table 9.8 (continued)

Site index class[a] (m)	Statistic[b]	Stand age class[a] (years) 10–20	20–30	30–40	40–50	50–60	>60
52.5–57.5	Mean bias	−1.46	-	−1.58	0.17	-	0.29
	s.e. (bias)	0.43	-	1.47	0.11	-	1.69
	Mean predicted *B*	33.69	-	34.98	38.87	-	46.70
	e*	0.97	-	0.14	0.63	-	4.95
	$\hat{\Phi}$	0.49	-	0.01	0.22	-	14.18
	n	7	-	7	6	-	5

[a] Class boundaries are mutually exclusive but have been rounded for presentation purposes.
[b] Critical error and mean deviance values for cells containing less than 10 observations may be unrepresentative.

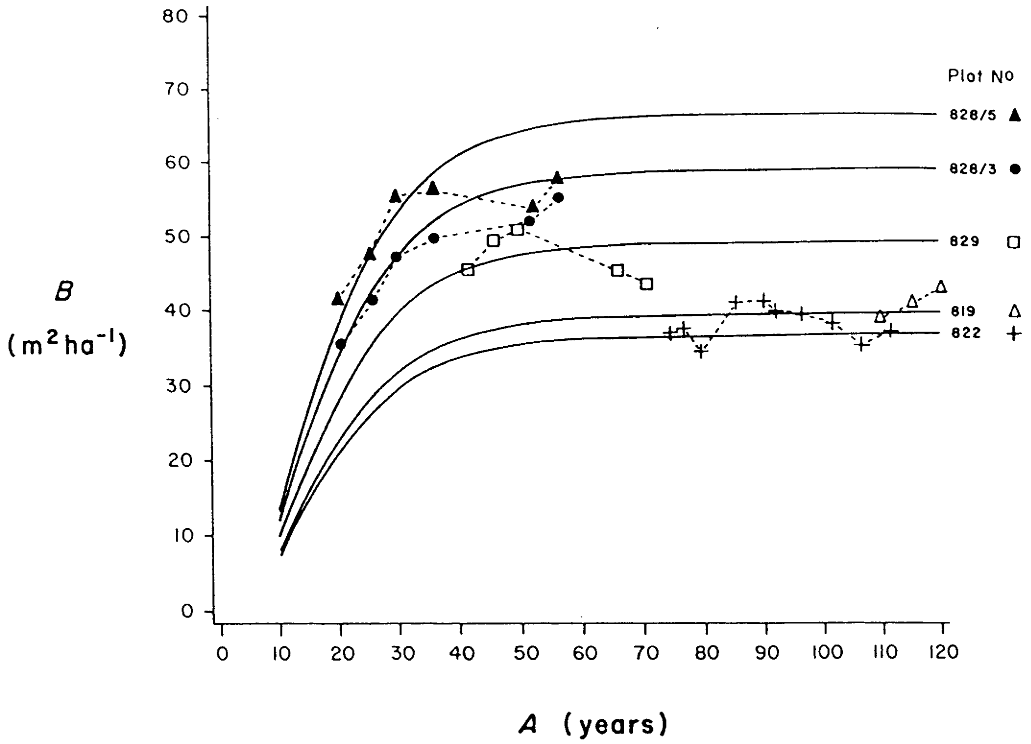

Figure 9.6 Observed and predicted (model (9.2)) stand basal area development for five PSPs. Predicted development (solid line) was initialized with plot values observed at the commencement of stand measurement.

for many individual stands in a planning unit of the forest, markedly increasing the final precision of forest-level estimates (DeVries 1986).

9.3.4.3 Stand volume model for unthinned stands

A range of derivations of the basic Schumacher (1939) yield model were investigated using combinations of the stand variables A, H, SI and B. The preferred fit model was a particular form of the yield function previously used by a number of authors, including Borders and Bailey (1986) and Candy (1989a):

$$\log_e V = \alpha + \beta \log_e B + \gamma \log_e H \qquad (9.5)$$

where V denotes predicted stand volume (m^3 ha^{-1}) to 5 cm SEDUB,
B denotes observed net stand basal area (m^2 ha^{-1}) for stems $\geq$10 cm d,
H denotes stand top height (m)
and α, β, γ represent parameters to be estimated

To avoid the difficulties associated with eliminating the bias generated if logarithmic estimates produced by (9.5) are back-transformed (Flewelling and Pienaar 1981), model (9.5) was reparametrized and fit to all unthinned stands as

$$V = \exp(\alpha' + \beta' \log_e B + \gamma' \log_e H) \qquad (9.6)$$

The unweighted OLS solution indicated increasing residual variance with increasing predicted volume, and examination of the graphs of the Pearson residuals suggested a poisson-like variance function would adequately model the error variance. Model (9.6) was refit using IRLS with a poisson-like variance function (Table 9.9).

Table 9.9 Parameter estimates and fit statistics for stand volume model (9.6). Standard errors are shown in parentheses and were computed from a reduced dataset containing only one observation from each plot.

Parameter			Fit statistics	
α'	β'	γ'	n	$\hat{\Phi}$
-1.407	0.7801	1.234	185	7.933
(0.1446)	(0.0459)	(0.0512)		

Predictions of V by model (9.6) were unbiased across the A and SI classes, although the relative precision and accuracy of predictions varied markedly between classes (Table 9.10). As expected, greater precision and accuracy were observed for those stands in cells about the mean of the dataset. Figure 9.7 illustrates the variation about the predicted *V* trajectory which might be observed when individual stands are initialized with *A*, *H*, and *B* values and the future *V* estimated using model (9.6). The lack of tree height observations for most plot measurements meant that fewer *V* estimates were available for each plot compared to the *B* records shown in Figure 9.6. The few measurements shown in Figure 9.7 suggest that the precision of future *V* estimates made with model (9.6) will decrease for an individual stand with increasing age and length of projection period. As with the *B* predictions, the observed fluctuations of *V* about an 'average' trajectory can be largely attributed to episodic mortality.

9.3.4.4. Comparison of volume estimates from KARSIM and the stand–level model

Combining models (6.7) and (9.2) within model (9.6) enables future *V* to be forecast from initial *B*, *H* and *A*. Importantly, *V* estimates generated by model (9.6) will not accumulate bias over varying projection intervals, since future *V* is predicted from only *B* and *H*, both of which are estimated from compatible models. Projections made from the whole system or their component equations will therefore be consistent and independent of the time step involved in the prediction.

Stand volume estimates produced by KARSIM may be subject to cumulative bias problems if the difference between KARSIM estimates and those generated from model (9.6) exceeds the accuracy of model (9.6). The e* values in Table 9.10 provide a benchmark for future comparisons of model performance. Comparison of the e* values in Table 9.10 with those in Table 9.3 does not provide a clear indication because estimates in Table 9.3 were derived from short projection periods. Further data are necessary to evaluate the bias in long–term projections.

9.4 The range of model reliability

A growth model can be deemed adequate if it is sufficiently accurate for the requirements of the user (Newberry and Stage 1988). However, when no alternative models are available for a species, the temptation to use the only available model can lead to it being applied beyond the range of model reliability suggested by the validation process. For this reason, and to assist potential users to evaluate the suitability of KARSIM for a particular application, the following overview of model reliability is necessary.

The critical error values in Tables 9.1 to 9.4 provide a quantitative measure of model accuracy for short–term projections, while the satisfactory agreement between observed and predicted variables in Tables 9.5 and 9.6 suggests model accuracy is satisfactory for long–term simulations. The levels of model accuracy reported in these tables include errors in the input data as well as the contributions from the KARSIM

Table 9.10 Bias, precision and accuracy statistics tabulated by stand site index and age classes for volume predictions of unthinned stands using model (9.6). Values are in $m^3 ha^{-1}$ except for the estimate of mean deviance (Φ) and the number of measurements (n). Results for cells containing less than 5 measurements are not shown.

Site index class[a] (m)	Statistic[b]	Stand age class[a] (years) 10–20	20–30	30–40	40–50	50–60	>60
<37.5	Mean bias	-3.36	54.11	-15.17	-6.31	-	7.12
	s.e. (bias)	5.77	44.06	20.16	9.06	-	31.73
	Mean predicted *V*	65.51	214.29	257.50	292.11	-	359.62
	e*	6.62	28.47	15.71	12.35	-	37.19
	$\hat{\Phi}$	1.94	12.48	4.77	1.82	-	11.54
	n	9	6	5	5	-	6
37.5–42.5	Mean bias	8.73	-16.42	-2.47	-11.91	-7.95	3.43
	s.e. (bias)	6.45	13.18	9.25	12.03	8.01	9.66
	Mean predicted *V*	99.82	170.90	327.27	418.37	389.88	452.67
	e*	9.38	26.83	18.73	22.70	23.44	22.61
	$\hat{\Phi}$	8.77	6.49	3.84	4.82	1.82	0.56
	n	12	5	6	5	9	5
42.5–47.5	Mean bias	18.02	1.82	-29.34	15.44	-10.62	-51.77
	s.e. (bias)	8.25	18.64	11.79	9.78	6.60	35.5
	Mean predicted *V*	107.44	257.92	393.27	475.84	447.88	524.35
	e*	16.44	10.74	24.33	15.28	18.93	37.85
	$\hat{\Phi}$	5.69	6.57	10.58	4.92	2.16	26.13
	n	8	5	12	11	7	5
47.5–52.5	Mean bias	28.99	-25.01	-18.66	-24.85	-25.09	64.72
	s.e. (bias)	21.14	13.31	9.19	6.05	6.25	24.18
	Mean predicted *V*	159.06	265.71	430.10	522.74	570.53	686.43
	e*	23.85	18.93	24.76	25.41	26.29	44.13
	$\hat{\Phi}$	31.81	3.11	2.58	2.68	1.94	17.72
	n	12	6	10	6	7	7

Table 9.10 (continued)

Site index class[a] (m)	Statistic[b]	Stand age class[a] (years) 10–20	20–30	30–40	40–50	50–60	>60
52.5–57.5	Mean bias	−15.66	–	−57.98	85.87	–	77.94
	s.e. (bias)	9.28	–	31.80	13.40	–	6.77
	Mean predicted V	203.44	–	425.15	572.67	–	886.44
	e^*	25.09	–	40.79	52.38	–	68.96
	$\hat{\Phi}$	1.42	–	14.82	11.68	–	18.12
	n	7	–	8	6	–	5

[a] Class boundaries are mutually exclusive but have been rounded for presentation purposes.

[b] Critical error and mean deviance values for cells containing less than 10 observations may be unrepresentative.

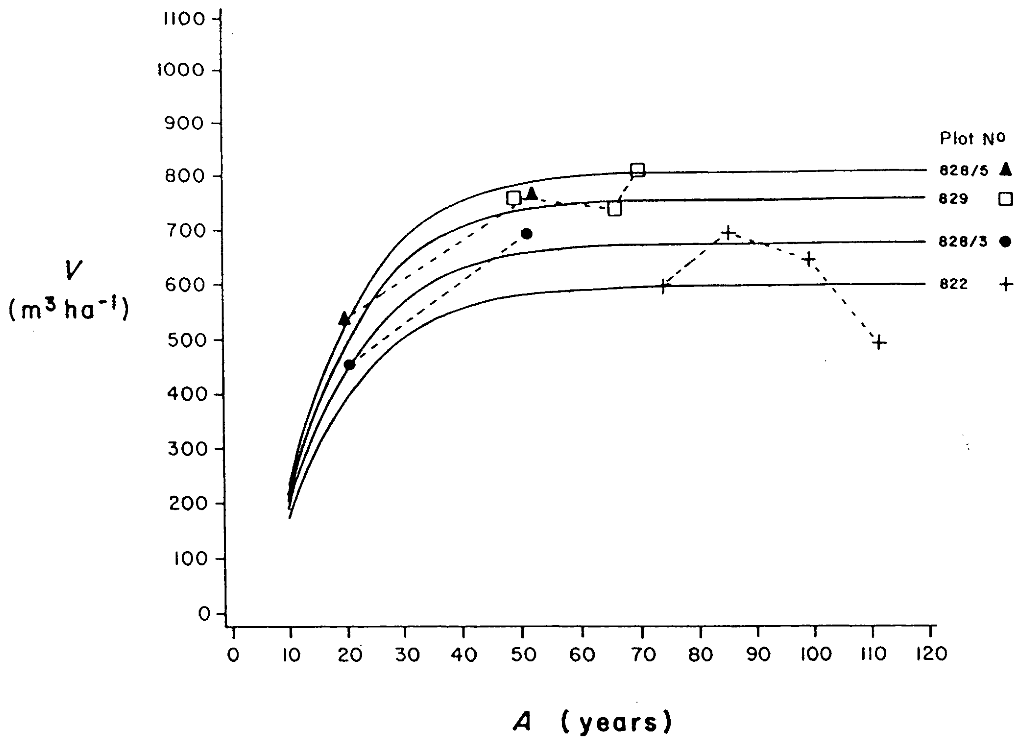

Figure 9.7 Observed and predicted (model (9.6)) stand volume development for four PSPs. Predicted development (solid line) was initialized with plot values observed at the commencement of stand measurement.

components. As errors in input data can have a greater influence on model precision than model behaviour (Mowrer 1989), any changes to mensurational procedures (plot size, instruments) may be expected to alter these values (Moeur and Ek 1981). The stand–level model (9.6) provides an additional check on KARSIM predictions.

However, the use of the parametrization dataset for all these tests will have provided an optimistic evaluation of model performance. Extrapolation of the model beyond the range of stand conditions represented in the parametrization dataset could produce very unreliable predictions (Jeffers 1978). An indication of model reliability for conditions beyond the data range is provided by the stability of parameter estimates in the component models (Gertner 1991). Unfortunately, parameters in many of the component models, particularly the ingrowth component, were highly sensitive to the random or selective deletion of as little as 10% of the data used for parametrization. For example, marked changes occurred in the parameter estimates of the ingrowth model if data for plots younger than 15 years were rejected and the model refitted. This problem cannot be overcome without additional data, and emphasizes the need for caution when interpreting results from simulations of stand conditions beyond those in the parametrization dataset.

The validation tests suggest KARSIM is probably most reliable for growth projections of 5 to 30 years commencing from ages of 15 to 50 years. The reliability of KARSIM projections over periods exceeding 30 years has not been determined. However, the few studies which have examined error propagation between model components have shown that variance propagation in models of this type can seriously restrict model reliability beyond two to three 10–year projections (Mowrer and Frayer 1986). Continual monitoring and comparisons of KARSIM projections with the stand–level model and actual yields is imperative, as projections of up to 100 years are necessary when regulating the yield of karri. Model reliability for stands exceeding 20% by N or B of non–karri species is uncertain, while projections of stand growth beyond 150 years are not recommended due to the absence of data from such stands in the parametrization set. Model estimates should be most reliable for unmanaged or stands managed to 'conservative' thinning regimes. Regimes which maintain stands for considerable periods in free growth conditions were not represented in the dataset. Extrapolation of the model for intensive plantation development would require additional modules to simulate the observed changes in branch retention and bole length at low stocking densities.

Overall, the validation tests suggested that for stand simulations within the model range the degree of bias in V estimates will vary depending on whether or not KARSIM was initialized with observed stand statistics (of appropriate measurement precision) or generated by the model, the age at the commencement of the simulation, and the length of the projection period. The reliability of long–term projections will depend markedly upon the capacity of the model to predict stand mortality (Stage and Renner 1988), and although the incorporation of a stochastic drought occurrence successfully explained variation in the present dataset, reduced accuracy of model predictions would arise from altered climatic conditions (*e.g.* arising from the possible greenhouse effect), altered site or establishment procedures, or intensive tending involving fertilizer applications.

That KARSIM predicts stand behaviour in general accord with known biological patterns of monoculture development is not surprising. Such consistency was achieved in the absence of extensive data by making a number of hypotheses and assumptions concerning stand and tree growth (see Chapter 4). These assumptions must be considered when using the model to examine alternative silvicultural treatments for stands. Model simulations present the consequences of these hypotheses and assumptions, thereby limiting our capacity to draw new inferences about empirical reality (Landsberg 1986). KARSIM cannot, for example, provide any new insights into the theory of stand dynamics that are more useful than those derived from the studies underlying model formulation.

CHAPTER 10 PRELIMINARY APPLICATIONS

10.1 Introduction

Individual-tree level growth models can be powerful tools within Decision Support Systems (Davis and Johnson 1987). Their application within such systems will, however, be reduced if the data necessary for model initialization is not readily available. In the karri, as in many hardwood forests in Australia, the information systems for inventory, site stratification mapping and yield monitoring are evolving from old-growth oriented systems to ones which cater for the regrowth estate. Consequently, the immediate applications of KARSIM were constrained by the fragmented nature of the site stratification and inventory information available for the regrowth estate. Nevertheless, KARSIM provided a hitherto unavailable capacity to assist both operational and strategic-level planning and to explore stand-level treatment options.

In this chapter a range of preliminary applications of the present version of KARSIM are briefly described. A study to determine the optimum economic rotation length for unthinned regrowth stands is described in the first section. This study is a simple example of the possible financial applications of the model. An evaluation of the present thinning prescription for karri is then outlined, followed by the use of the dominant height and stand-volume estimation models to assist the assignment and scheduling of first thinning in the regrowth stands. In the final section, the simulation of 'optimal' thinning regimes for forest-level yield regulation is described. For this application KARSIM was used to predict not only timber yields but also the likely changes in forest structure over time horizons exceeding 100 years, in order to assist the planning for other forest values in multiple-use forest. Each of these applications provided a further validation of model behaviour, assisting the process of continual improvement in model design as applications highlight limitations in model generality or output.

The emphasis in each section has been to describe the application of KARSIM rather than present detailed results *per se*, as in most instances they are specific to the databases and planning processes within the Dept. of CALM.

10.2 The optimum economic rotation age for karri

10.2.1 Introduction

The economics module in KARSIM computes the net present value (NPV) and internal rate of return (IRR) for the stand at each cycle of a simulation. Such output can be used for a variety of stand-level investment analyses, including the calculation of break-even product royalties and sensitivity analyses of these calculations to variation in cost or cost groups (Ferguson and Dargavel 1978), examination of the profitability of existing or alternative silvicultural practices (West and Inglis 1984) or determination of the economic optimum rotation length (Campbell 1974, Taylor and Fortson 1991). These stand–level analyses may be thought of as micro–economic case studies, providing useful insights into the economic efficiency of silvicultural alternatives. They are essential precursors to the formulation of forest policy and practice (Ferguson and Dargavel 1978, Brumelle *et al.* 1991). Determination of the optimum economic rotation age for regrowth karri stands, and the main factors influencing this age, was selected as a simple example to illustrate a potential application of the financial module.

10.2.2 Optimum economic rotation age

Comprehensive reviews of the various criteria for selecting the optimal economic age for harvesting a forest are provided in Johansson and Löfgren (1985) and Oderwald and Duerr (1990). The Faustmann–Pressler–Ohlin theorem (see Johansson and Löfgren 1985) and alternative theorems (Oderwald and Duerr 1990, Hultkrantz 1991) treat forests solely as sources of wood, saleable in competitive markets, ignoring the externalities of environmental problems or multiple–use considerations. The results of the following analyses are therefore of most relevance to pre–investment estimates of the long–term profitability of possible timber management options (Spilsbury 1990).

The optimum economic rotation age (OER) for a stand is the age at which NPV is maximized (Clutter *et al.* 1983). It is calculated as the present value of cash flows from an indefinite series of rotations, and is usually determined by selecting the stand regime which provides the largest NPV from analyses of a range of representative stands (Clutter *et al.* 1983). Numerous possible combinations of thinning regimes, rotation lengths, and potential residual stocking density levels at each age, together with site preparation treatments such as varied initial espacement, could be examined for the regrowth karri stands. Such comprehensive analysis, however, is an enormous task if heuristic simulation techniques are adopted, and more general approaches, such as the use of dynamic programming techniques, have been developed to explore this problem (Davis and Johnson 1987). Schreuder (1971), Brodie and Kao (1979), and Valsta (1988) have all used dynamic programming to examine the problem of simultaneously determining the optimal thinning schedule and rotation length for an even–aged forest. The development of a dynamic programming model for karri was beyond the scope of the present work. Consequently, the following example was restricted to determining the OER of unthinned stands growing on public land. In these circumstances, the costs accruing from taxes and land purchase may be ignored in the analysis, and the net present value of an infinite series of rotations, termed the Soil Expectation Value[1] (SEV), may be calculated as (Davis and Johnson 1987):

$$\mathrm{SEV} = N_A \,/\, (1+i)^A - 1 \tag{10.1}$$

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[1] Synonymous terms are the Land Expectation Value (LEV) and the Bare Land Value (BLV).

$$N_A = V_A P_A + \Sigma\, V_t P_t\, (1+i)^{A-t} - \{ [M\, (1+i)^A - 1] / i \} - E\, (1+i)^A - \Sigma\, C_{jt}\, (1+i)^{A-t} \qquad (10.2)$$

where

SEV denotes the net present value of an infinite series of rotations (\$ ha^{-1})
N_A denotes the net return (\$) at stand age A (years)
i denotes the annual interest rate (decimal)
V_A denotes volume (m^3 ha^{-1}) harvested at age A
P_A denotes royalty (\$ m^{-3}) for timber harvested at age A
V_t denotes volume (m^3 ha^{-1}) harvested as commercial thinnings at age t
P_t denotes royalty (\$ m^{-3}) for commercial thinnings at age t
M denotes annual maintenance cost (\$ ha^{-1})
E denotes stand establishment cost at year zero (\$ ha^{-1})
C_{jt} denotes cost (\$ ha^{-1}) of cultural treatment j occurring at age t

The terms V_t and P_t in equation (10.2) were redundant in the present study of unthinned stands. The source code in KARSIM was modified to calculate SEV values by dividing the stand NPV by the term $(1+i)^A-1$ to compute the discounted sum of a continuing series of rotations (equation 10.1).

Equation 10.1 assumes that prices are elastic, that the real value of costs and revenues will be constant over time, and that markets will be available for all products at all times (West and Inglis 1984). These assumptions appear reasonable in this study, because (1) the Dept. of CALM is an almost exclusive seller of karri logs, (2) both prices and costs tend to rise with inflation, and (3) integrated markets exist for all size and quality classes of log produced during karri harvesting.

The SEV of a stand is generally calculated using deterministic cost and yield regimes, with sensitivity analyses used to indicate the variability in values if these assumptions are relaxed. In practice, stochastic climatic factors, such as periodic droughts, will affect timber yields (Chapter 9). Campbell (1974), however, developed a Monte Carlo simulation model to stochastically simulate the growth and management of *E.regnans* stands in Victoria. His calculated optimum rotation age for regrowth stands of 30–35 years was relatively insensitive to most sources of uncertainty except the interest rate. Stand NPV estimates, however, were significantly lower for the stochastic model compared to those from a conventional deterministic analysis. He concluded that explicit consideration of uncertainty and risk preferences was of limited importance in the analysis of the rotation length decision. Thus, the present work used deterministic regimes, and assumed current management practices and costs, when determining the EOR for unthinned karri stands growing on a range of site qualities.

10.2.3 Data

Karri stands are regenerated using one of three methods, *viz.* natural regeneration from seed–trees, planting with nursery–raised open–rooted seedlings, or direct seeding. Direct seeding is seldom used over extensive areas because of the prohibitive cost of karri seed. The phenological cycle of karri generally determines which of the other two options is used on a given site, as the cheaper seed–tree method is preferred whenever sufficient seed is available in the crop trees (CALM 1987b). Consequently, naturally-regenerated and planted stands were examined separately in the following analysis.

10.2.3.1 Yield regimes

KARSIM was used to estimate yields, at yearly intervals from 10 to 120 years of age, for three representative stands with site indices of 37, 44 and 52 m. The model was initialized using the mean H, B, N and d frequency distributions of all PSP observations for fully–stocked stands of each regeneration method, A and SI. Yield predictions did not differ markedly between naturally–regenerated or planted stands, and the effect of regeneration method on yield was therefore ignored in the subsequent analysis. Stand volume was partitioned into three product categories, consistent with current operational practices: First grade sawlogs (minimum SEDUB=30 cm), medium–sized sawlogs (minimum SEDUB=20 cm) and chiplogs.

10.2.3.2 Costs and returns of operations

Hypothetical but plausible data were used for the costs of all operations due to the commercial sensitivity of actual costs. The costs were based on financial records kept by the Dept. of CALM and may be considered representative for each operation (Table 10.1). They were expressed in 1991 dollars.

Table 10.1 Management costs for naturally–regenerated and planted karri stands.

Year	Operation	Direct cost ($ ha^{-1})	
		Natural	Planted
0	Slash preparation	60	60
0	Regeneration burn	55	55
1	Plants, planting, fertilizing		230
2	Infill	25	25
2	Landing rehabilitation	15	15
0–A	Annual maintenance	2	2

The annual maintenance cost is an annualized expenditure related to research, surveys and inventories for the estate, and was assumed to be incurred at the commencement of each year of the rotation. Planting and fertilizing costs in planted stands assumed an initial stocking density of 2000 spha. All values in Table 10.1 are direct costs, to which an overhead of 130% was applied to account for the salaries and operating expenditure of administrative staff, building, vehicle and machinery depreciation, and fire protection programs.

Royalties from the harvested timber were the only returns considered in this work. Present royalty charges were used. The following charges, which incorporate a price/size differential, apply to all logs harvested from the regrowth forests: first grade sawlogs \$ 34.00 m^{-3}, medium–sized sawlogs \$ 25.80 m^{-3}, and chiplogs \$ 15.00 m^{-3}.

10.2.3.3 Financial analysis

A real interest rate of 4% per annum was used for base analyses, consistent with rates recommended in similar studies (Leslie 1989, Brumelle *et al.* 1991, Rawlins 1991). The influence of varying the interest rate, and all other cost factors, on the OER was examined in sensitivity analyses. In this approach, all cost items were held constant while the factor being investigated was varied by 10, 20, 30 and 40% above and below the values given in Table 10.1. The influence of the royalty price/size differential on SEV and OER was also investigated by using the chiplog royalty rate for all products.

10.2.4 Results and discussion

This dataset indicated that for all combinations of site quality, royalty structure, operational costs, cost overheads and interest rates, naturally–regenerated stands were always more profitable (higher NPV), with shorter OERs, than planted stands (Table 10.2). This was a direct consequence of stand establishment costs being \$ 230 ha^{-1} cheaper for naturally–regenerated stands relative to planted stands. This analysis, however, implicitly assumed that the product proportions of future yields from both stand–types will be identical. The marked difference in profitability between these methods emphasizes the need to minimize establishment costs and to use seed–trees to establish regeneration wherever and whenever possible.

The OER ages were longer than the rotation of maximum volume MAI for each site quality and regeneration method. This was probably due to the increasing royalty prices as stand age (hence average tree size) increased (Clutter *et al.* 1983). The predicted age of MAI culmination for a naturally–regenerated stand on a site of index 44 m was 21 years, a value consistent with the observed development of an 'average' fully–stocked stand as summarized in Table 6.8 and Figure 6.6.

Table 10.2 Economic optimum rotation age (years) for unthinned representative stands growing on low (*SI*=37 m), medium (*SI*=44 m), and high (*SI*=52 m) site qualities. SEV values (\$ ha^{-1}) are shown in parentheses.

Regeneration method	Site index (m)		
	37	44	52
Natural	27 (1677)	25 (1992)	22 (3418)
Planted	29 (1230)	26 (1504)	24 (2947)

The OER age increased with decreasing site quality. This effect was largely due to the higher total volume productivity of stands on higher site qualities rather than a higher proportion of trees attracting the first grade sawlog royalty. Simulations using the chiplog–only royalty for all stands reproduced this trend of increasing OER age with decreasing site quality. The OERs for each stand were 2–6 years younger than the values in Table 10.2 when a chiplog–only royalty was used.

Sensitivity analyses revealed the interest rate had the most influence on the OER and SEV values. For example, the OER and SEV values for the planted stand on *SI*=52 m varied from 29 years and \$ 8819 ha^{-1} at an i of 2% to 20 years and \$ 825 ha^{-1} at an i of 7%. The trend and order of magnitude of these changes were consistent across all combinations of site and regeneration method. The OER was insensitive to variations of less than 30% in the other cost factors (including overheads and annual maintenance charges).

As indicated previously, the results from these representative stand analyses are most appropriate to an evaluation of the future profitability of stands established and managed as plantations for timber production. In such instances, maximum returns would accrue from stands harvested solely for chiplogs on rotations of 19–24 years. If land were purchased for the stand, then the revised SEVs could be calculated by simply deducting the land cost from the SEVs in Table 10.2. The relevance of these stand–level analyses to multiple–use forests managed to concurrently sustain a range of non–timber benefits is the subject of considerable debate (Leslie 1989, Spilsbury 1990). Moreover, the relative profitabilities of stand management regimes can vary markedly depending upon the choice of decision criterion. Spilsbury (1990) demonstrated the varied rankings of alternative management regimes which could result from the use of SEV, Benefit–cost ratio or forest rent criterion for the same stands. He concluded that use of the NPV criterion favours the 'traditional' coniferous plantations, while use of benefit–cost ratios as the measure of financial viability highlights the efficiency of investment for more 'natural' hardwood management systems. In practice, forest–level analyses which incorporate broader considerations, including the availability of labour, capital and non–timber values are most appropriate for economic evaluation of management alternatives for public forests (Ferguson and Dargavel 1978).

The impact of thinning regimes on the OER remains to be examined. Enhancement of the NPV of a stand might be expected with thinning (Ferguson and Dargavel 1978, Rawlins 1991), but a thorough analysis should incorporate a possible decline in stand productivity due to soil compaction from consecutive thinnings (Wronski 1984), and include the potential degrade in future log quality resulting from damage to retained stems during thinning.

10.3 Evaluation of the present thinning prescription for karri

Thinning in karri is presently controlled by the residual basal area for a stand of specified top height (Table 10.3).

Table 10.3 Thinning prescription for high quality regrowth karri stands.

H (m)	Retained B (m^2 ha^{-1}) After first thin	After second thin
30	14	N/A
35	17	20
40	18	22
45	20	24
50	21	26
55	22	27

Source: Bradshaw 1992. Silvicultural Specification 1/92, Dept. of CALM

This prescription was developed using hand–drawn graphical analysis of very limited data, and aims to thin to densities "that will maintain volume increment per hectare consistent with maximizing value increment" (Bradshaw 1992). KARSIM provided a general framework which could be used to examine whether or not maximum stand volume increment was maintained at the densities prescribed in Table 10.3.

The general reliability of the prescription was examined by following the simulated progression of hypothetical stands through the various zones on the karri stand density management diagram (Figure 7.6). The development of five representative, fully–stocked stands on site indices of 35, 40, 45, 50 and 55 m when thinned according to the prescription was compared to the position of the CBA zone. It was found that the prescribed residual densities for first thinnings were appropriate to maintain stand volume increment. This was not unexpected as the prescription aims to thin to the codominant stratum, thereby ensuring a retained *B* exceeding the CBA (Bradshaw[2], *pers. comm.*). Less agreement was found between KARSIM simulations and the prescribed residual densities for subsequent thinnings. The prescription presumes more conservative second and subsequent thinnings are necessary to maintain maximum basal area increment and maximum sawlog increment. Simulations across the site index range suggested the residual densities for second and subsequent thinnings may require adjustment for stands growing on site indices below 40 m. Actual thinning response data is required to test whether it is the prescription or KARSIM which requires recalibration, as the possibility that the thinning response predicted by KARSIM is biased for stands on low site qualities should not be overlooked.

A separate investigation of the prescription examined the feasibility of commencing a second thinning in regrowth stands aged 40–60 years. Almost all stands in this age class have been first thinned, and a wide range of residual stocking exists, partly due to natural gaps in these stands resulting from the retention of culls during the regeneration practices of the 1930's. A second thinning which exacerbates understocking would result in an irrecoverable loss of growth and a lower clearfell yield. These stands are important to sustaining the supply of medium–sized sawlogs from thinnings in the short–term, but are of critical importance in the long–term as they will be the largest contiguous areas of mature regrowth available for clearfelling. Maximizing the total stand volume available at clearfell from these stands must be an essential objective in any karri yield regulation strategy (Bradshaw and Lush 1981). Concern over the timing of the thinning to ensure its economic viability, while not jeopardizing stand increment, prompted this investigation.

KARSIM was used to simulate the future growth of 15 PSPs located in these stands. Each PSP had been subjected to a first thinning at ages ranging from 48 to 53 years. These plots were representative of the variability in site and residual densities of the thinned stands. The predicted development of each PSP was plotted on the stand density management diagram (SDMD) (Figure 7.6) to determine when a stand had regained full stocking and an economic minimum yield could be removed according to the present prescription.

The results suggested that stands with site indices exceeding 45 m which had been thinned to the prescribed residual density (Table 10.3) should be within the minimum *B* limits for a second thinning by age 65. The second thinning yields predicted by KARSIM were also consistent with inventory estimates prepared for the 1987 Timber Strategy (CALM 1987a). Stands which were 'under–stocked' as a result of heavier than expected first thinning or natural gaps did not attain the minimum economic *B* for many years, highlighting the need for a detailed stratification of thinned stands by *H* and

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[2] Mr F.J. Bradshaw, Manager, Silviculture Branch, Dept. of CALM

residual density classes to determine the precise extent and location of stands suitable for scheduling. Preliminary work on such a stratification, using photo-sampling techniques similar to those described by Biggs and Quain (1992), has commenced.

10.4 Operational planning

10.4.1 Introduction

Integrated harvesting schedules are prepared on an annual and four year horizon for the karri (CALM 1992). These plans define such features as the location, extent, and estimated yields from logging areas, together with associated roading and protection requirements. The estimated yields from these stand-based operational schedules are consistent with strategic 15 and 100 year stratum-based harvesting schedules. Integrated logging operations are scheduled within both old-growth and regrowth forest to meet the total supply commitments for up to 15 log products. Component models of KARSIM were used to assist the assignment and scheduling of thinning operations within the regrowth stands, and to provide preliminary estimates of the yield from those stands scheduled for first thinning.

10.4.2 Assignment and scheduling of thinning treatments

The site index curves provided a regional site stratification which was used as follows to assess the availability of stands for thinning. The present thinning prescription uses stand top height as the criterion to indicate the suitability of a stand for thinning: thinning does not commence until the maximum possible branch-free bole is attained for crop stems, taken to be when H reaches 30 m. Model (6.7) predicts future H at a future A given observed H and present A. Thus, an estimate of the future A at which any observed young stand reaches 30 m H (and is therefore available for thinning) can be obtained from model (6.7) by substituting values for present H, present A, and a future H equal to 30 m. Stand top height and stocking density measurements were obtained in stands aged 15–30 years using a combination of systematically located photo-plots and ground plots. These measurements were performed by the Ground and Air Survey section of the Dept. of CALM using techniques developed in the recent jarrah inventory (see Biggs and Quain 1992). The A, H and location details for each plot within a stand were entered onto computer and model (6.7) solved to predict the A (hence calendar year) when the stand would be available for thinning. The output from this program was then used in conjunction with 1:12,500 scale maps to manually schedule the potential availability of stands for first thinning during the 1991 to 2006 planning period.

Preliminary work is underway to input the sampled H measurements directly into the Dept. of CALM's Geographic Information System. Measurements from the photo-plots would then be used to initialize model (6.7) and provide map-based projections of stand availability.

10.4.3 Estimation of yield from first thinnings

Thinning prescriptions for the regrowth stands prescribe a residual *B* for a given *H*. Because the first thinning in the young regrowth stands presently removes only chiplogs (to 5 cm SEDUB), the stand–volume estimation model (9.6) may be used to provide an estimate of the yield from first thinning.

Model (9.6) requires initial estimates of *A*, *B*, and *H* for a stand. Each of these variables can be estimated for the current regrowth estate from regeneration records and temporary ground or photo–plots, or in the case of simulations, by specifying initial stand basal area, age and site index. Estimates of the first thinning yield may then be obtained by differencing volume estimates made with model (9.6) for the same *A* and *H* but different *B*s.

Preliminary estimates were prepared for sample stands within scheduled cutting management units, and will be compared with the actual volume removed when thinning occurs.

10.5 Strategic planning: regulation of yield from the karri forest

10.5.1 Introduction

The CALM Act (1985) requires the preparation of harvesting plans, and their periodic revision, "to ensure the multiple use and sustained yield of that resource for the satisfaction of long–term social and economic needs" (section 56 (1) (a) CALM Act 1985). Whether simulation or optimization provide the best approach to such planning is the subject of considerable debate (Johnson and Tedder 1983, Rose 1984, Davis and Johnson 1987), but until recently the applications of either modelling approach have considered only timber values in multiple–use public forests.

Timber harvest scheduling defines a sequence of logging activities to achieve, over a specified planning horizon, a specified supply objective. Computerized harvest scheduling systems, using advanced mathematical programming techniques, have been developed for several hardwood forests in Australia. Type I linear programming formulations (Johnson and Scheurman 1977) have been applied to schedule harvests for both mixed–age and even–aged eucalypt forests in Victoria (Paine 1966, Weir 1972). More recently, Osborn (1988) used nonlinear programming techniques to determine optimal harvest schedules for Tasmanian hardwood forests, while Dargavel and Turner (1989) and McKenney (1990) applied FORPLAN (Johnson *et al.* 1986) to develop schedules for the Otways forests in Victoria. Typically, however, harvest scheduling in eucalypt forests, including the karri, has been accomplished using heuristic simulations, rather than optimization procedures, to evaluate alternative cutting sequences.

Early harvest schedules for karri were prepared for individual permit or supply–areas, with an annual allowable cut estimated using von Mantel's method (Rayner and Williamson 1984). This method of yield regulation considered the current volume of the growing stock only, and as with methods based on both the growing stock and its increment (*e.g.* the Austrian and Hanzlik's formulae), was adopted to initiate control in the virgin old-growth forests. The foundations of the present yield regulation system were introduced in the 1970s with the commencement of integrated logging operations (arising from woodchipping) and the concurrent adoption of a land-use zoning system in multiple-use forests. A grid-cell based GIS was developed and an intensive management-level inventory of the entire karri estate was performed to support intensified planning, capitalizing on the dramatic improvements in computational efficiency and data acquisition provided by computer technology.

The key factors which vary the sustainable level of timber (and other values) are the rate of harvest of the old-growth, and the rotation length and management regimes adopted for the present and future regrowth stands. The sustainable yield estimates prepared by Bradshaw and Lush (1981) used basic yield tables within broad forest-type strata. A revision presented in the 1987 Timber Strategy (CALM 1987a) incorporated improved yield tables and further refinement of the GIS, but was hindered by the lack of site stratification and a limited capacity to examine more than a few management regimes.

This section provides an overview of the latest revision of the harvest schedule for karri. The development of a site stratification for the regrowth estate (Chapter 6) and the availability of KARSIM enabled major advances in the yield regulation process, allowing a wide range of stand treatment options and hence yield regulation alternatives to be evaluated in the planning process. Heuristic simulations were used to develop alternative cutting sequences. This revision was undertaken as part of the recently published review of forest management practices in the south-west forests of Western Australia (CALM 1992).

10.5.2 Definition of desired forest structure and cutting unit strata

10.5.2.1 Target forest structure

It was not possible in the time available for the revision to formulate and solve an optimization model. In the absence of advanced mathematical programming techniques, harvest scheduling is usually linked to a target-forest concept (Clutter *et al.* 1983). The final choice of harvest sequence is then largely influenced by the ultimate structure (age-class composition) of the target forest and the time-frame within which this structure will be achieved. In the karri, a target forest structure was required which could sustain all forest values in perpetuity. Insufficient data were available to consider the stand structures, forest conditions and the rotation lengths that might suit non-wood values. However, given the adequacy of existing conservation reserve systems (Christensen 1992), and comprehensive visual resource zoning (CALM 1992), it was reasoned that management of the forest for a sustained yield of wood might also largely sustain other values if the rotation lengths were sufficiently long and varied to encompass the physical or biological rotation of each overstorey species. The definition of a target forest was based on the 'natural' forest structure, assuming that to maintain the oldest stage of forest development, each preceding stage should be equally represented. Thus, taken across the entire forest estate, there would be sufficient area of forest in each stage of development to ensure sustension of all stand age/size classes.

Definition of the target forest structure was based on the relative age and species composition of the entire karri forest, including the karri within National Parks and conservation reserves because, although these were unavailable for timber production, they nevertheless contribute to the sustension of habitat, visual and other values. The desired forest structure was defined in terms of the relative proportions of the forest estate which would be desired in age classes over time. This was translated in the harvest scheduling process into constraints on cutting unit availability in those forests available for timber harvesting. The rationale leading to the definition of the target forest is described in CALM (1992). The forest structural goal was defined by a strategy team, and the author's contribution to this process included the quantification of the changes in stand size–class structure over time using KARSIM, interpretation of stand age and structural relationships in karri (Rayner 1992), and the critical evaluation of the feasibility of proposals in the harvest scheduling process.

10.5.2.2 Cutting unit strata

The delineation of cutting unit strata within forest areas available for timber production was approached as follows. Stands within land–use categories available for harvesting were identified using a component of the Departmental GIS, a grid–cell based system (see Pearce *et al.* 1992) which stores forest thematic maps such as forest type, cutting history and land tenure and provides composite maps by overlaying selected themes. Strata were defined by species composition and cutting history for old–growth forests, while the regrowth forests were stratified on the basis of their year of regeneration, stocking density (three classes based on RDBN for fully–stocked, adequate, and low), thinning history, and site quality.

The site index curves developed in Chapter 6 provided for the first time a quantitative basis for stratification of the regrowth by site quality. However, the availability and reliability of top height measurements varied markedly between age classes of the regrowth estate. Stand *H* had not been measured for many stands older than 50 years, while portions of younger and thinned stands had been systematically sampled using photo–plots (section 10.4) or ground plots. Consequently, where *H* samples were available, site classes were based on model (6.7), but where few measurements were available stands were aggregated into one of three site index classes (37, 44, or 52 m corresponding to low, medium and high site qualities). The proportion by area of any stand in each of these classes was subjectively determined from a combination of field observation, local knowledge, and the available measurements.

The site quality composition of future (post–1991) regrowth stands could not be readily inferred from the species composition of the harvested old–growth (Chapter 6), and in practice, in any one year the proportion of site classes will be determined by the harvest sequence adopted by the regional planner. A uniform site quality of *SI*=44 m, being the median value observed in the PSP dataset, was assumed for all even–aged stands generated by future harvesting.

The area of each stand in each stratum was determined from the GIS output. These estimates were corrected where necessary to compensate for the area lost to roading and non–regenerated tracts.

10.5.3 Definition of management regimes

10.5.3.1 Yield estimates for old–growth stands

Standing volume estimates only were required for the unlogged old–growth stands, as increment was assumed to balance mortality. Volume estimates were computed from management–level inventory data. Because the inventory data had been collected to the utilization standards prevailing 10 to 15 years ago, the estimates of volume per hectare for each of four product categories in each old–growth forest stratum were adjusted by product estimation factors to reflect current operational out–turn.

Standing volume estimates in selectively cut–over stands were also based on management–level inventory, with growth calculated from a network of Continuous Forest Inventory plots.

10.5.3.2 Yield regimes for regrowth stands

Ideally, a network of inventory plots located within each cutting unit according to proper sampling procedures, would have been used to initialize KARSIM to develop yield regimes for each cutting unit. Unfortunately, limited inventory has been performed in many of the regrowth stands. Notional or representative regimes were therefore developed for both existing and future strata. Adopting a nominal 100 year rotation length, individual regimes were developed which aimed to maximize stand volume production for each cutting stratum. KARSIM was used to heuristically determine thinning regimes which brought a stand basal area to just above the CBA whenever a minimum economic thinning (based on present operational costs and machinery) would permit. The present thinning prescription and SDMD served as guides. This process generally resulted in only two thinnings for stands on low site qualities (*SI*=37 m), three for average (*SI*=44 m) and four thinnings for stands on high quality (*SI*=52 m) sites prior to clearfall at age 100 years. The regimes for poorly stocked stands excluded thinnings, and incorporated an adjustment to product proportions to reflect an expected high proportion of trees with large, persistent limbs which would militate against recovering sawn timber from the bole of small trees.

KARSIM was initialized at age 10 with representative stand values for each stratum. Initial stand variables were calculated from PSP or inventory observations for the stratum or, if these where insufficient, hypothesized from the SDMD. For example, the relative density of fully-stocked stands was initialized at an RDBN of approximately 0.6, a value considered representative for a fully-stocked stand in the field. Understocked stands commenced simulation from an RDBN of 0.3, which approximated the stocking levels recorded in the photo-plot and ground survey of such stands. The yield regimes for stands regenerated prior to 1963 where adjusted to reflect the varying proportions of cull trees retained in these stands during earlier stand regeneration practices.

A total of 35 regime/stratum combinations were defined. Table 10.4 provides an example of 3 regimes developed for representative, fully-stocked stands on three site qualities. For all regimes the break-down of tree volume into SEDUB size classes assumed full product segregation (*cf.* fixed length harvesting). Volumes within the size class assortments were multiplied by current product proportion factors to define product categories (Chapter 8).

Table 10.4 Yield regimes for even-aged karri.

Site index (m)	Age (years)	Operation type[a]	Product volume (m^3 ha^{-1})[b] First S/L	Med. S/L	Chiplog
37	30	T_1	-	15	62
	60	T_2	19	38	38
	100	CF	274	39	78
44	25	T_1	-	5	88
	45	T_2	11	48	48
	65	T_3	32	32	42
	100	CF	294	42	84
52	20	T_1	-	-	73
	35	T_2	10	45	45
	50	T_3	31	31	41
	80	T_4	33	17	33
	100	CF	449	64	128

[a] T_i denotes the i th thinning, CF denotes clearfell.

[b] Product size specifications were as follows: Minimum length 2.4 m, maximum length 12 m, and minimum SEDUB of 30 cm (first grade sawlog), 20 cm (medium-sized sawlog) and 5 cm (chiplog). Product quality specifications are detailed in CALM (1989).

10.5.4 Harvest scheduling

Alternative harvest schedules were prepared using previously written FORTRAN programmes and micro-computer spreadsheet systems. The scheduling was performed in collaboration with Mr P. Stirling, Regional Planning Officer, Dept. of CALM.

The yield was regulated on the basis of sustaining in perpetuity the maximum possible level of gross bole volume supply, within the constraint of attaining the forest structural goals. A 100 year (one rotation length) planning horizon was adopted. Supply constraints included the need to meet existing contractual arrangements for each product for the next 10–15 years, and a requirement to maintain at least one quarter of the annual total sawlog harvest from trees larger than 60 cm *d*. Availability constraints included the need to retain from harvest as much of the presently available old-growth forest as possible to enhance visual amenity and wildlife habitat requirements. Similarly, although an 'oldest first' priority was adopted for harvest scheduling, clearfellings of the oldest regrowth stands presently available (regenerated pre-1960) needed to be minimized to enable these stands to grow on to become the future 'old-growth'.

The minimum rotation length of 100 years had to be relaxed in order to obtain feasible solutions within the forest structure constraint. The final strategy adopted a compromise whereby a proportion of the available area for stands regenerated in each year since 1974 (including future stands) was excluded from clearfelling to grow on beyond a 100 year rotation, and a similar proportion was scheduled for harvest at rotation lengths no shorter than 80 years. All understocked strata were clearfelled by age 60.

Graphical and tabular output were obtained for each harvest schedule investigated. The age class distribution of the forest at 10 yearly intervals throughout the planning period was also examined to assist evaluation of the structural objectives. Figure 10.1 shows the maximum sustainable yield by various product categories under the adopted harvest schedule. Further details of this schedule may be found in CALM (1992).

10.5.5 Discussion

The definition of a target forest for yield regulation purposes is usually confined to those areas available for timber harvesting. The present work has differed by defining structural goals for the entire forest estate, and then translating these objectives into temporal constraints within the yield regulation process. This approach may be considered a compromise when insufficient information is available to explicitly define the future yields of non-timber values from multiple-use forests. The method assumes, however, that sustaining the overstorey forest structure will ensure the sustension of all forest values, a premise requiring considerable research and time to confirm or refute

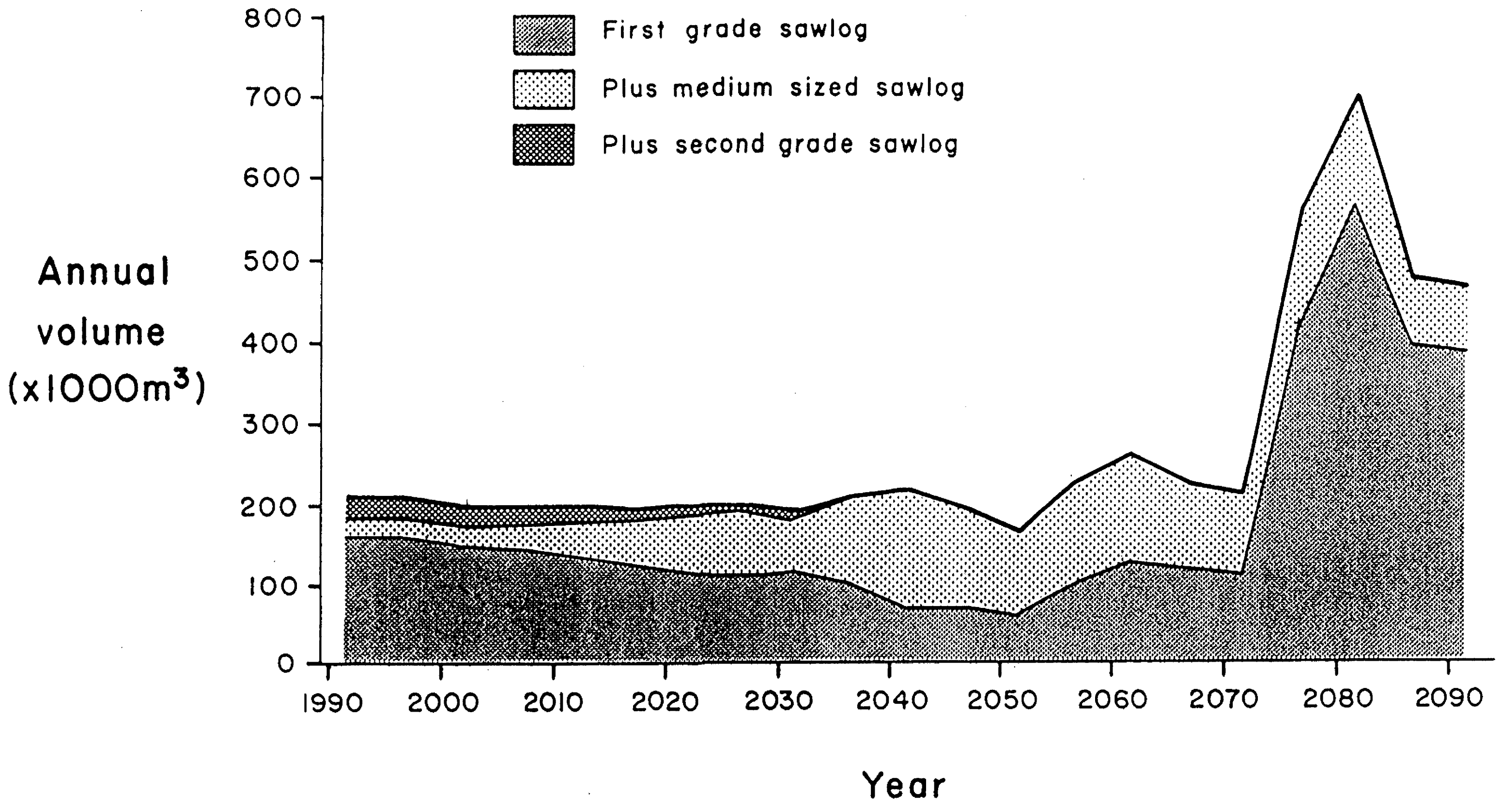

Figure 10.1 Projected sustainable karri yield.

for any species or value (see, *e.g.* Moeur 1985). Moreover, the use of a simulation approach means that the strategy is unlikely to be optimal, even for timber.

For these reasons, other computerized iterative techniques, including traditional linear programming formulations, should be investigated for harvest scheduling in karri. Alternatives include systems based on binary search methods (see Johnson and Scheurman 1977), which have been applied to comparable harvest scheduling problems in the old–growth forests of the Pacific Northwest in USA (Walker 1976, Tedder *et al.* 1979, Lyon and Sedjo 1986). These models compute approximately optimal solutions using a procedure which iteratively adjusts harvest levels according to assigned *a priori* harvesting priorities for each stratum. Walker (1976) used an 'oldest–first' priority, comparable to the assignments used in the present karri work. Some binary search models can be considered generalized forms of the Model II linear programming formulation (Johnson and Scheurman 1977), and optimal solutions would be obtained if the harvesting priorities assigned *a priori* to the forest strata were identical to those that would be established by linear programming (Garcia 1990).

Linear programming formulations are a further alternative, with demonstrated flexibility to accommodate the complexity of multiple–use planning in Australian forests (Duguid *et al.* 1990). FORPLAN–type models have, however, proved expensive to develop, and a major difficulty in the karri would involve the building of yield models to quantify the temporal change in non–timber values under different management regimes (Jackson 1983, Navon 1987). Nevertheless, these techniques would provide improved capacity to perform comprehensive sensitivity analyses of the optimal yield schedules. Sensitivity analyses are expensive with the present karri system.

Irrespective of whether simulation or optimization models are used for yield regulation, the spatial feasibility of scheduled timber harvests should be examined before adopting a forest plan. Long–term, strata–based harvesting schedules have typically ignored the spatial feasibility of the temporal solutions generated by either simulation or optimization approaches. However, evaluation of the spatial feasibility in short–term, area–based operational planning is essential in native forests managed for multiple–use. Adjacency constraints on karri forest harvesting arise from the need to maintain fuel reduction buffers in old–growth stands and to protect fire–sensitive regrowth, visual amenity requirements, seasonal access restrictions related to soil protection and disease risk, and the optimum economic location of roading. Particularly important is the capacity to evaluate the location of wildlife habitat reserves and linking corridors to ensure adequate provision is made for long–term continuity between the age and stand structure classes (Wardell–Johnson and Nichols 1991).

Elsewhere, attempts have been made using mixed integer, nonlinear programming, or random search techniques to deal with a limited number and type of adjacency constraints in harvest scheduling (O'Hara *et al.* 1989, Roise 1990, Nelson and

Brodie 1990). Given the complexity of the task in multiple–use forests, perhaps the approach most suited to the karri situation is the use of GIS–based software such as SNAP II (Scheduling and Networking Analysis Program) to examine the feasibility of scheduled harvests. Developed by Sessions and Sessions (1991), a random search technique is used within a GIS environment to interactively examine adjacency constraints and habitat connections in the harvest scheduling process. Encouraging results have been obtained in a number of case studies (*e.g.* Dahlin and Sallnas 1992), although some developmental work would be necessary to export data from the Dept. of CALM's GIS into the SNAP II structure. The spatial feasibility of a temporally feasible harvest schedule developed using either mathematical programming or simulation techniques would then be examined as a further extension of model sensitivity analyses.

CHAPTER 11 GENERAL DISCUSSION[1]

11.1 Introduction

KARSIM, like other stand simulation models currently used by Australian forest organizations (Aust. For. Council 1987), has been parametrized for an individual species within a particular geographic zone. Model development was based on existing silvicultural and mensurational data, and limitations in model generality or behaviour largely arose from the restricted range of site, stand condition and treatment, age, and measurement interval of the present PSP and experimental dataset (Chapter 3). Future enhancements to the model therefore require the collection of additional data to both extend model generality and to test the assumptions incorporated within the functional forms of component models. In this chapter, the present limitations of KARSIM are discussed and data acquisition strategies necessary to implement proposed model improvements are outlined. Although the issues identified are specific to KARSIM, they are discussed in the wider context of the present status and possible future trends in growth and yield modelling of Australian eucalypt forests.

In the first section of the chapter the limitations of, and proposed enhancements to, the present version of KARSIM are outlined. Because the collection of growth data for the construction or subsequent extension of a model are expensive tasks, a comprehensive strategy is necessary to ensure that any data collected is appropriate to assist the development of the next generation of models. The likely future trends in eucalypt modelling are therefore considered prior to a general discussion of the data required to monitor KARSIM performance and improve its generality. The implementation of an appropriate data acquisition strategy is then discussed in the context of developing an integrated Decision Support System for karri.

11.2 KARSIM limitations and proposed enhancements

11.2.1 Species generality

The restriction of the model to stands with less than 20% (by stocking or basal area) of non-karri species is a major limitation, as substantial areas of even-aged, mixed-species stands will develop as old-growth harvesting extends into more mixed quality sites. Extension of the model to incorporate species-specific parameters for each algorithm, particularly for marri, is essential.

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[1] Sections of this chapter have been published as:

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Rayner, M.E., and Turner, B.J., 1992. Eucalypt growth models: past and present. In: G.B. Wood and B.J. Turner (Editors), Integrating Forest Information Over Space and Time. Proc. IUFRO Conf., 13–17 January 1992, Canberra, Australia, pp. 53–62.

Unfortunately, the dynamics of mixed–species stands are particularly complex and poorly understood for most eucalypts (Jacobs 1955, Florence 1984). Few studies have quantified mixed–species dynamics in sufficient detail to serve as a guide to model development. West (1981b), for example, has published the only detailed comparison of mixed–species growth rates for eucalypts in even–aged stand structures. In the absence of such comparative data the generalization and interpretation of mixed–species stand dynamics is extremely difficult, and in practice a highly empirical modelling approach will be necessary rather than a potentially superior, detailed examination of system principles (Leary 1970). Elsewhere, species–specific parameter estimates have been successfully applied in some individual–tree, distance–dependent models for uneven–aged, mixed–species stands (Monserud 1975). This approach excludes the explicit treatment of species interaction components, such as allelopathic or site improvement effects exerted by one species on another. It is probable, however, that such interaction effects would be insignificant for most combinations of karri with other species, and that any exceptions could be handled in a straightforward manner during simulation.

KARSIM's structure could be readily adjusted to accommodate additional species. The tree *d* array could be extended to a two–dimensional species by *d* array. Generation of the initial *d* distribution for each species would require the simulation of bimodal *d* frequency distributions, possibly by generalizing the present Weibull *cdf* to a segmented form similar to that developed by Cao and Burkhart (1984). The prediction of ingrowth by species composition could be achieved by stochastically allocating the species identity of ingrowth stems (see, *e.g.* Vanclay 1989a). The stand dominant height and taper functions for regrowth marri could be modelled using species–specific parametrizations of present KARSIM functions. Each of the species occurring in mixture with karri is amenable to annual growth ring dating (Rayner, unpublished data), facilitating the use of stem analysis to obtain suitable data for these calibrations. These data would also enable investigation of interspecies site index relationships. Similarly, the basal area allocation model for individual tree growth could be assumed to be of the same form for all species. Species–specific allocation and mortality parameters could be readily calibrated as further data accrues.

11.2.2 Generalization of the stand density/stand increment relationship

Thinning in KARSIM was taken into account by incorporating a variable representing the level of competition, in a manner which approximated the Møller hypothesis regarding the effect of stand density reduction on stand increment (Chapter 7). A critical assumption was that the Møller hypothesis holds true across the range of site and species composition to which the model is applied. The thinning experiments used to examine the stand density/stand increment relationship sampled only pure karri stands on higher quality sites, and the validity of this hypothesis in stands on low quality sites or containing higher proportions of non-karri species is therefore uncertain. It is most likely valid for mixtures containing species of similar growth habits to the karri, such as yellow tingle and bullich.

11.2.3 Empirical adjustment of algorithms and the use of short-term increment data

The use of empirical adjustments, which essentially act as overriding correction factors to the model, were necessary to overcome the data limitations. Such adjustments to the I_{Bg} model for low density stands, and the tree mortality and I_{Bg} model for droughting effects could, however, seriously limit model generality and extrapolation. Further calibration of the I_{Bg} model in low density stands aged less than 40 years is a major priority if the effects of heavy early thinnings on stand yield are to be fully evaluated. The profitability in eucalypt regrowth of management regimes featuring heavy thinnings which commence at ages as young as 5 years have been emphasized by Florence (1988) and Rawlins (1991). Properly designed experiments will be necessary to investigate the I_{Bg} model, while data from long-term monitoring of mortality in all PSPs and experiments should improve the tree mortality function.

A related problem, common to all component models, was the possible bias in parameter estimates introduced through the use of data measured over short time periods. The extent of such bias will largely depend on the representativeness in the long-term of the climatic conditions prevailing over the period of the PSP measurements. Abbott *et al.* 1991 suggest there has been a trend of reducing annual rainfall (by up to 10%) in the karri region since 1980, the period of measurement of most PSPs. This could render the present parametrizations biased. The bias introduced by using short-term measurements for tree mortality estimation, and the necessary empirical adjustment, were described in Chapter 9.

11.2.4 Simulation of stands aged less than 10 years

The commencement of stand simulation from age 0, rather than age 10, would enhance model utility. The simulation of silvicultural treatments involving early non-commercial thinning ('spacing') would require this facility, as would investigation of the influence of varied initial stocking density in planted stands. Complete information on stand development would also be desirable for financial and yield analyses. Direct extension of the tree list approach adopted in KARSIM would be inefficient when simulating all stems in naturally-regenerated stands, as up to 30,000 individual trees can be present on some sites at year 1 (White 1974). The simulation of stand-level variables only below age 10 is a possible solution. The present mortality and stand dominant height models could be readily extended, while the ingrowth model would become redundant.

11.2.5 Tree and product volumes

KARSIM cannot directly model the influence of stand density and treatment on bole (and hence log) quality. Such information is essential for proper evaluation of the economics and yield potential of alternative silvicultural regimes. Attempts to correlate visible bole defects with sawn recovery and log value have emphasized the importance of delineating green and dead knot zones in the eucalypt stem (Waugh and Rozsa 1991, Brennan *et al.* 1991). Thus, an additional model in KARSIM would predict at least the tree crown depth and maximum live branch diameter at bole, to be used in defining products from total tree volumes. A suitable approach might be to define a third element in the tree array, identifying an individual tree in the simulation process by its *d*, species, and a crown length/branch size index. This index would be used in conjunction with a set of grading rules and the present product proportion table to define log volumes by size and quality assortments.

The tree volume and taper models in KARSIM were parametrized using forest-grown trees from unthinned stands (Chapter 8). Recalibration of these models will be necessary as an increased proportion of the regrowth estate is thinned. Changes in stem taper arising from thinning or fertilizing have not been examined in karri, but appropriate data should accrue from thinning experiments. A recently published non-compatible taper function for *E.obliqua* (Goodwin 1992) would be expected to fit karri and associated species well, and should be compared to the present KARSIM function in future revisions.

11.2.6 Thinning type

There is some evidence to suggest that for eucalypts, the stand-level response to strip thinnings will be different to that from a uniform thinning from below (Incoll 1979). Data are therefore required to describe the I_{Bg} and allocation response to any changes in thinning type which may be introduced operationally. The present approach for strip thinning, being based on the root influence zone (Chapter 8), may be an adequate first-approximation in karri, but requires further data to define the root size/crown size relationship for individual trees. Similarly, the possible reduction of stand and tree basal area increment due to coppice competition following thinning was not incorporated in KARSIM, although considerable coppice can be observed in some stands following thinning. If present, this effect could be modelled as a reduction in *B* increment as a function of the time-since-thinning.

11.2.7 Effect of fuel reduction burning on tree survival and log quality

Fuel reduction burns are likely to commence in some regrowth stands prior to their first thinning. Operational trials indicate that such low intensity fires will have a similar effect to a thinning from below, with suppressed and subdominant trees being killed (McCaw 1986). The inclusion in KARSIM of such a 'fire thinning' (Incoll 1974) is therefore relatively straightforward if sufficient data on the relationship between tree mortality and site, fire intensity and tree size is available. The probabilistic approach to tree mortality is ideally suited to this application, as some larger trees will be killed by flare–ups where fuel levels adjacent to the tree are very high. The subsequent degrade of the butt logs in surviving stems would also need modelling, perhaps by defining a product degrade proportion (0–100%) as an additional element in the tree array, which could be used to adjust tree volumes for past fire events or branching/spacing degrade. The possible transient, post–fire increases in *B* increment resulting from nutrient mineralization (Banks 1982) could, if observed, be readily incorporated in KARSIM in a manner similar to the drought influence on *B* increment (Chapter 9).

11.2.8 Site amendment

The broadscale application of fertilizer is unlikely in regrowth stands managed for multiple–use, because of concerns of possible changes in the floristic composition of the understorey (Christensen 1992). It seems likely, however, that restricted fertilizer programs would target select site qualities, necessitating the capacity within KARSIM to simulate the effect of varied timing, intensity and frequency of fertilizer applications on tree form and stand increment. Because of the complexity of site–fertilizer interactions, substantial data would be necessary to develop empirical models capable of predicting response to such a range of combinations (Miller 1981). In the interim, the effects of site alteration on the entire stand's development might be estimated by simple changes in the stand dominant height growth curve. For example, the increased rate of self–thinning and segregation of trees into dominance classes observed by Grove (1987) following the application of a combination of nitrogenous and phosphatic fertilizer to an unthinned regrowth karri stand is consistent with an increase in stand site index. Thus, in the absence of detailed data on stand response to fertilizer regimes, an increase in site index might be used to simulate response to fertilizer. Under some conditions the effect of fertilizer on stand growth might be short–lived, requiring the simulation of a gradual reversion to the pre–fertilizer site quality (Turner *et al.* 1978). The improved tree growth observed from the innoculation of open–rooted karri seedlings with ectomycorrhizal fungi (Bougher *et al.* 1987) might also be modelled in this way, while a decrease in site index might be hypothesized for site deterioration resulting from, for example, soil compaction arising from thinning operations.

11.2.9 Simulation of other forest attributes

KARSIM was designed to simulate the timber yields of commercially important species (Chapter 4). The complexity of harvest scheduling in multiple–use karri forests (Chapter 10), however, illustrated the desirability of simulating the stand dynamics of non–timber and understorey species directly within the growth model. The capacity to simulate understorey succession and abundance can provide a basis for quantifying related non-timber attributes such as fauna habitat, water and recreation potential. These models are constructed on the proposition that the influence of management practices on the suitability of a stand for wildlife habitat, the composition of the understorey, or the sequence of succession all depend on how the overstorey vegetation changes with time and treatment.

Presently, most operational models of eucalypt stands simulate only timber attributes. Concurrent simulation of understorey species or other forest values has been restricted to distance-dependent gap or mechanistic models (Shugart and Noble 1981, Squire 1987). Elsewhere, however, distance-independent models have been developed which, in conjunction with overstorey models, can provide a detailed estimate of the vegetative structure of a single stand through time under different silvicultural prescriptions (Wykoff *et al.* 1982, Moeur 1985, Keane *et al.* 1990). The distance-independent design of KARSIM would require considerable adaptation to incorporate other values, particularly the effects of fire on understorey dynamics. Simulation of live and dead fuel accumulations, fire behaviour, and fuel reduction would be necessary, however, to evaluate the effects of protection strategies upon such values as faunal habitat and floral succession.

11.3 Future trends in karri and other eucalypt modelling

Most of the present limitations of KARSIM can only be overcome by the collection of additional data. An appropriate sampling and data acquisition strategy must not only provide for the ongoing extension of the present model, but must ensure the data is adequate to support development of the next generation of models. This requirement is discussed below in relation to likely future trends in modelling the growth of eucalypts.

11.3.1 Developments in eucalypt modelling in the short-term

Several factors have determined the recent direction of eucalypt modelling in Australia. The nature and management intensity of the eucalypt forest resource is rapidly changing. The area of old-growth forest available for timber production is steadily decreasing due to harvesting or the transfer of forests to land-use categories unavailable for logging. Even-aged regrowth stands are becoming a significant component of the hardwood resource, requiring harvesting and processing technologies for much smaller diameter trees than have traditionally been acceptable to industry. These changes, together with substantial interest in the establishment of industrial plantations of high-yielding species on previously cleared farmland as an alternative source of hardwood for industry, have focussed attention on the development of management regimes for even-aged stands. Growth models are required for simulation of stand response to thinning regimes, fertilizing schedules and in some instances site preparation treatments. The extensively managed mixed-age, mixed-species forests also present a complex range of simulation requirements involving stand response to selective tree removal or crop tree release.

Presently, however, only STANDSIM (Opie 1972) and KARSIM can simulate multiple thinning and varied initial espacement treatments in regrowth eucalypt forest. No operational models are available to explicitly model the effect of intensive site preparation techniques or tending on plantation growth for any species (*cf.* Turner *et al.* 1978), although a number of private forest organizations are currently developing databases for their eucalypt plantation estates (White 1988).

Unfortunately, as Florence (1988) asserted, the sampling designs for many of the current growth plots and thinning studies for most of the commercial even–aged stands do not provide a good database for detailed studies on stand dynamics and thinning responses. Modelling these stands is typically constrained by disjoint ranges in stand treatments and site variation represented in trials and growth plots. Similarly, the statistical design of forest experiments has historically focussed upon hypothesis testing rather than response–surface parametrization (Box *et al.* 1978) in which stand treatment extremes may be included. Older trials are often limited by the extent of stand history information available or by inappropriate tree and stand variables having been recorded.

In the short–term, the present emphasis on highly empirical models for both operational planning and the simulation of silvicultural treatments is likely to continue. Existing empirical models will therefore continue to be updated and extended as additional data accumulates. Greater detail will be required in simulating those tree and stand attributes which influence log quality, and further integration of stand predictive models into broadly based utilization modelling systems will occur. These systems require simulator output by both log size and quality assortments. Consequently, branching and canopy description will become increasingly important in model design.

It is likely to be some time before the precision of growth estimates from current mechanistic models are able to match those from empirical models which have been parametrized from forest–wide inventory and growth plot databases (Leech 1984, Burkhart 1990). The limited availability of experimental data necessary to calibrate the prototype mechanistic models is a major constraint on their use for broadscale projection of forest estates. Nonetheless, tree– and stand–level models of this category have successfully reproduced the stand dynamics of fully–stocked, even–aged monocultures growing on specific experimental sites (Mohren *et al.* 1984, West 1987, McMurtrie *et al.* 1990a). In addition to being valuable research tools (Landsberg and McMurtrie 1984), the immediate application of mechanistic models will probably involve the hypothetical simulation of the many alternative (extreme) silvicultural response options to assist the selection of optimal stand strategies for input to existing forest–level planning systems.

Significant potential exists for process model approaches to expand our biological knowledge and provide insights into suitable formulations for traditional, empirical models. Any improvements in our physiological knowledge of eucalypt growth processes generated by mechanistic models will probably be most readily incorporated into single–tree, distance–dependent empirical models. Linder *et al.* (1985), for example, emphasized the need for research into the structure and dynamics of eucalypt canopies to further refine mechanistic models. Such knowledge is also required to improve approaches to modelling inter–tree competition, crown and canopy architecture and branching characteristics within empirical model formulations.

11.3.2 Longer term developments

Long–term developments in modelling will probably see greater emphasis on developing an understanding of the biological and environmental determinants of forest production, in contrast to the historical emphasis on size/age relationships for even–aged stands. Such 'hybridization' of the traditional empirical and recent mechanistic approaches to model construction has been advocated as the only way to meet the information demands of future forest managers (Kimmins 1985). This new generation of models will see renewed emphasis upon relating growth or productivity either indirectly to complex environmental gradients through site classification and evaluation, or directly to individual environmental factors such as soil nutrient status and forest macro–climate.

11.3.2.1 Site classification and evaluation

Most even–aged eucalypt estates are presently stratified by forest type (species composition) and site index. This single–index approach to site productivity rating has not proved entirely satisfactory for eucalypt growth modelling. Incoll (1983) excluded site index as an explanatory variable for prediction of *E.sieberi* basal area increment in STANDSIM, whilst West (1981a) found limited explanatory power for this variable and omitted it altogether from his single–tree, distance–independent model for *E.regnans*. The site index concept has also proved difficult to adapt for irregular forests (Goodwin 1988, Monserud 1988, Vanclay and Henry 1988). A major constraint in generalizing mechanistic models is the availability of site description attributes to replace the 'site index' variable used presently in empirical models (West 1991). Thus, dissatisfaction with site index, together with the need for site evaluation for new plantations and the potential benefits of indirect site classifications to multiple–use management (Chapter 6), will continue to provide an incentive to develop indirect classifications of timber productivity.

The comprehensive evaluation of the utility of the indirect site classifications for karri, and the subsequent superiority of site index, highlight the difficulty of developing indirect classifications at a level of resolution suitable for use in stand yield projection (Chapter 6). Similar difficulties might be expected for other eucalypts occupying similarly restricted ranges in edaphic, climatic and elevational variables. The prognosis may be more optimistic where species are introduced over large areas which contain considerable variability in these factors, such as in the expanding plantation estates. For example, stratification of sites on soil chemical and physical attributes has provided acceptable productivity groupings for some radiata pine plantations in Australia (Turvey 1983, Turner and Holmes 1985) and South Africa (Louw 1991). Nix *et al.* 1992 have recently compared the potential productivity of candidate eucalypt species across Tasmania by relating stand site index to climatic, terrain and soil attributes within a geographic information system. Their use of a simple growth model to simulate potential forest growth as a function of climate was an innovative extension of the use of regional climatic data by Booth and Pryor (1991) to predict the bioclimatic suitability of sites (but not yield potential) for particular acacia and eucalypt species on a continental scale. Nevertheless, considerable research is still required to link forest–level climate data to stand–level micro–climate. Beadle and Inions (1990) illustrated one approach to this problem when they developed a set of polymorphic–nondisjoint site index curves for short–rotation plantings of *E.globulus* on Western Australian farms. Eight environmental attributes, four of which reflected water availability, were able to explain almost 85% of the variation in site index at 60 sites. Such promising results may be partly attributed to the wide range in climatic conditions and geography within their study area.

The alternative approach, of modelling directly the site descriptors and their influence on stand growth, will also be a major emphasis for research in the immediate future.

11.3.2.2 Direct incorporation of site descriptors

The use of environmental parameters as driving variables in growth models is presently limited by the resolution (time and spatial scale) and nature of available meteorological and edaphic data for eucalypt forests. Incorporation of micro–climatic parameters into growth models requires evaluation of the appropriate time step (annual, seasonal, or other) to meet the precision required of yield estimates from the model. The appropriate scale at which the complex interactions of radiation, temperature, moisture, and edaphic processes must be incorporated into models requires further definition (McMurtrie *et al.* 1990b). In the longer term, mechanistic models may assist identification of those site factors which will be most discriminating when incorporated into empirical models or for developing indirect site classifications. For example, the incorporation of edaphic and climatic variables in many site classification procedures provides each variable with equal weighting in many of the regression/multivariate techniques used. Sensitivity analyses of mechanistic models may help identify relative weightings for those variables of key importance or discriminating power in eucalypt physiology, and suggest appropriate time steps (annual or other) at which such attributes would need to be incorporated to improve prediction.

In the short-term, those variables readily monitored from meteorological stations will most commonly be incorporated as predictors within empirical models. Correlations between monthly and annual rainfall statistics and periodic basal area increment have been reported for some eucalypt stands (Webb 1966, Fisher 1978), although the incorporation of rainfall as a regressor in models has sometimes provided only marginal improvements in the precision of yield estimates (Nautiyal and Couto 1984). This might appear to be the case for the regrowth karri, where a simple formulation of stand age, site index and relative density explained over 83% of the observed variation in I_{Bg} (Chapter 7), leaving only 17% to be partitioned by additional explanatory variables. However, the need to accommodate the effects of climatic variability within individual-tree level models was exemplified by the necessary adjustments for drought in the tree mortality and I_{Bg} models (Chapters 8, 9). Failure to account for drought effects could lead to highly biased estimates of stand variables over long projection periods.

An example of the trend toward incorporation of climatic parameters and increased detail in site description is provided by the modelling component of the Silvicultural Systems Project (SSP) (Squire 1987) being undertaken in Victoria. This project aims to evaluate the range of silvicultural systems applied in eucalypt forests. The proposed individual-tree, distance-dependent model will be sufficiently general to simulate the spectrum of even-aged and irregular mixed-species stand structures (Squire 1987). It is envisaged that the area to be modelled will be characterized by constants such as altitude and aspect, with state variables describing individual trees, other vascular plants, fauna, soil and litter effects. Stochastic variables may include wildfire, annual rainfall, pest and disease attack. Most parts of the model are planned to operate on an annual time step and it is envisaged the final model will be used to predict ecological and economic outcomes over multiple rotations of the eucalypt stands.

The use of time-dependent climate variables as additional predictor variables in growth models introduces site potential as a variable, dependent upon future climatic patterns. This approach is consistent with the basis of mechanisitic models. Landsberg (1986) suggested the productivity of a site should be modelled mechanistically as an expression of soil nutrient and hydraulic characteristics, and such models should include climatic variables to account for the probability of drought periods and the average insolation.

The use of rainfall values cannot be expected to explain all variation in observed stand growth, but it does provide a basis for 'localizing' regional growth models by adjusting the model to local conditions (Leary and Hamlin 1988). If, for example, the actual amount of rainfall where likely to be monitored over an increment period then this information could be used directly in model formulations. Alternatively, even an estimate based on historical records of the long-term moving average of annual or seasonal rainfall might serve to localize model projections. The high correlation between meteorological patterns at weather stations throughout the karri forest suggest such an approach should be investigated for the I_{Bg} and H models (Chapter 9).

11.4 Data required for monitoring and model improvement

The design and construction of future eucalypt models will, in the short–term, largely depend on the quality of data acquisition strategies now in place. The capacity to extend the generality of KARSIM will therefore require advances in our knowledge of tree and stand dynamics as well as the implementation of a revised data collection strategy. Such a strategy must integrate the data required for monitoring present model performance with that required for future model development. These future modelling requirements for karri will probably include a need for increased detail of products within trees, wider generality to mixed–species stands, and stand treatments for which empirical data are unlikely to be available for many years. An individual–tree level model will remain the best alternative to meet these requirements.

Integration within the data collection and modelling strategy means, for example, that the sampling design for future inventory can facilitate the development and application of growth models, as inventory databases are generally used as a basis for projections, whether they be for inventory update or to project into the future (Ek 1990). The basis of site stratification for both inventory and stand simulators should therefore be designed to be compatible from the outset. Problems of incompatibility often arise when site classification procedures used in the response model are statistically incompatible with the sampling procedures used in forest inventory (Hegyi 1981). For example, although site index or site form (Vanclay and Henry 1988) has traditionally been used in eucalypt models to discriminate between variation in the productive capacity of sites, this variable is rarely mapped over large forest areas to a similar sample intensity or precision as that on which the site index relationship was based.

11.4.1 Monitoring

Monitoring of model performance by comparing model predictions with stand out–turn is critical to the updating and ongoing credibility of a growth model (Goulding 1979). The importance of monitoring KARSIM predictions has been emphasized in earlier chapters. The comparison of KARSIM predictions with harvested and retained volumes within test plots provides one test of model accuracy (Chapter 9). Appropriate sampling designs and their associated data structures for comparing the growth, standing volumes, and removals between thinned and unthinned stands are detailed in Byrne and Stage (1988). In the short–term, these plots must sample the range of site, species and thinning–type necessary to test all component models within KARSIM. First–thinning yields estimated using model (9.6) should also be compared with harvested volumes. Model (9.6) might also be used to compare harvest or inventoried volumes for unthinned stands, and hence provide an indication of cumulative bias in

KARSIM (Chapter 9). Should new thinning technologies be introduced, comparisons of product and *d* frequency distributions following thinning would be necessary to recalibrate the empirical rules in KARSIM which nominate that portion of the stand to be removed during a thinning (Chapter 8).

Long-term monitoring should aim to detect changes in site productivity over consecutive thinning operations, the development of fungal degrade following damage of stems during thinning, and to compare yields obtained on an operational scale in the field with those recorded in carefully tended experiments (see, *e.g.* Tennent 1988).

11.4.2 Model improvement

A revised and expanded data collection strategy, incorporating improved sampling schemes, revised experimental designs and increased site description, will be necessary to enhance KARSIM. Ferguson (1983b), Tennent (1988), Vanclay (1988b) and Rose and Ugalde (1988) have each reviewed some of the plot design, mensurational and sampling issues to be addressed when collecting growth data for model development. Although detailed recommendations concerning each issue are beyond the scope of this section, a brief outline of factors to be considered is provided below.

11.4.2.1 Sampling

The primary objective when collecting growth data for model development must be to obtain appropriate data for quantifying response surfaces (*cf.* hypothesis testing) (Ferguson 1983b). It is therefore essential to complement traditional inventory data on the existing forest estate with data from structured experiments representing the extremes of site and treatment variation envisaged for the species. Both the PSP and experimental plots must sample the complete range of site, stand condition and treatment in order to develop a satisfactory growth model (Curtis and Hyink 1985). The site evaluation work reported in Chapter 6 suggested the present PSP system for karri is biased toward fully-stocked, naturally-regenerated, pure karri stands, while the few thinning experiments sample only the higher end of the site quality range. Consequently, a revised sampling frame should specify the priorities associated with establishing additional plots by species composition, age, regeneration method and site quality. Although site index provided a superior productivity stratification (Chapter 6), the detailed site description provided by the indirect classifications provides a further guide for locating experimental plots. For example, the edaphic and climatic classifications could be used to identify possible microsite limiting factors if fertilizer experiments were desired on sites of contrasting moisture and nutrient status. Stand site index might also provide a preliminary sample frame for siting experiments to calibrate current mechanistic models. Long and Smith (1984), for example, hypothesized that stands which are undergoing self-thinning are those which have achieved an upper limit in the amount of foliage supported. If this is true, and the relationships between tree parts documented by Causton (1985) are relevant for karri stems, then stand site index will indicate different equilibrium leaf area indices, a major variable in mechanistic formulations (Linder 1984).

Such a revised sampling matrix could identify desired combinations of site quality and species composition for locating experiments, but insufficient area of a particular combination may exist in the present regrowth estate. The lack of marri data, for example, is partly due to the limited site and age representation of present mixed-species stands. Appropriate old-growth sites would need to be introduced into the short-term harvest schedule to establish a suitable range of experimental locations. Similarly, the sampling strategy should schedule the installation of new plots to accommodate forseeable changes in site quality or stand treatments. Additional PSPs are necessary in planted stands, particularly those regenerated within the last 10 years, as average site quality may have decreased as poorer quality forest has been harvested. Initial stocking density of the planted stands has also increased during this period from 1250 to 1600 and 2000 spha.

An objective method for evaluating the capacity of future sample schemes to improve the predictive ability (*cf.* parameter estimates) of a model was described by Gertner (1987). The Bayesian procedure uses an estimate of the mean variance of prediction in the response region where the model will be used to determine if additional measurements will improve the structured, precalibrated model. The procedure could be used to target the range and number of observations necessary to improve those KARSIM components which were parametrized using OLS regression.

The siting of experiments must be consistent within the inventory and PSP sampling frame. Because the establishment and maintenance of experiments is particularly expensive, and the extrapolation of their results to other sites and times is always difficult, consideration should be given to not only the replication of treatments within an experiment but also replication of similar experiments at a number of sites throughout the forest estate to which the results are to be extrapolated. Such replicates might comprise smaller 'satellite' experiments and utilize a reduced treatment representation sufficient to incorporate the extremes of the treatments applied in larger experiments.

11.4.2.2 Experimental design

Experimentation and stand simulation modelling must be viewed as complementary, with the experimental data serving to validate the postulates incorporated in the model design. A variety of experimental designs are necessary to gather data for modelling individual-tree level response to inter- and intra-species competition processes resulting from density variation (*e.g.* thinning, espacement, crop tree release) and site amendment (fertilizer addition or site preparation). The popular factorial ANOVA designs are valuable for testing such hypotheses as the validity of the

Mϕller hypothesis across site and species mixtures, but they are usually limited in the number of treatments they examine by the availability of land, and are therefore of restricted utility for parametrizing response surfaces (Bailey and Ware 1983).

A set of ANOVA thinning experiments, complemented by smaller 'satellite' trials, could be established across the site and species composition range to test stand density/stand increment relationships. The control plots within those experiments established in mixed-species stands would also provide data to compare the relative productivity of mixed stands and quantify *H* growth relationships (or their correlation to karri *H*) for other species. Data from the ANOVA thinning experiments could also provide the flexibility to investigate those modelling approaches which simulate tree growth as a function of modified potential (maximum) growth if one of the treatments maintained the trees in a free-growth condition. This approach provides an alternative to empirically testing multiple thinning regimes.

Alternative experimental designs for quantifying individual-tree response to stand density variation include the Nelder and Scotch Plaid designs (Nelder 1962, Zavitkovski *et al.* 1982). Although the utility of data collected from these single-tree, systematic designs for modelling stand-level response has been debated (Adlard 1980, Woollons 1980), variants of these cost-effective designs have proved particularly useful for validation of both distance-independent and distance-dependent individual-tree models (Ek and Dawson 1976, West 1991). Previous difficulties in aggregating the individual-tree plot data to stand level when developing individual-tree simulators might be addressed using APA indices (see, *e.g.*, Chapter 4 and Daniels and Burkhart 1988). Both the Nelder and Scotch Plaid designs can produce initial data in a relatively short time, and the Scotch Plaid can be readily adapted for use in existing older stands (enabling major efficiencies in the land area compared to the ANOVA designs). The designs are particularly efficient for obtaining crown and branch data suitable for utilization studies (Powell 1988).

The need to replicate stand treatments in time is often subjugated by the need to establish new experiments or improve the site range of present treatments. The purpose of replicating experiments in time is usually to capture the variability arising from climatic fluctuations. Gathering climatic data at key experimental sites provides an indirect way of examining possible variation over time. Tree ring analyses are another (Booth *et al.* 1988b, Rayner 1992). Dendrochronology can be used to extend data series from both PSPs and experiments, particularly when algebraic difference models are being developed, as only two measurements are required (Chapter 6). Garcia (1992) has recently developed an efficient sampling scheme for selecting trees for increment cores to obtain an unbiased estimator of past (stand) *B* increment. Tree ring analysis may also be useful for comparing the frequency of local drought events (indicated by pointer years) to regional rainfall records to localize the *B* increment and tree mortality functions (Chapter 9). Alternatively, the data could assist the development of the type of stochastic basal area function incorporated by Stage (1973) in the PROGNOSIS model.

The size and shape of growth and experimental plots can be important determinants of data quality. In Chapter 7, for example, only those plots larger than 0.006 hectares had sufficient stem numbers (>30) in young regrowth stands to adequately quantify the *d* frequency distribution using the Weibull distribution. The expense, land area and duration of forest experiments reinforce the need to use optimum plot sizes, but further studies are required on the precision of the estimation of growth and its dependence on plot size, preferably using long–term remeasured plots in which the spatial position of trees is known. Fixed–size permanent plots are best for individual–tree models (Curtis 1988), as they avoid the discontinuities in estimates of stand variables which can arise when plots are expanded between measurements (Chapter 3).

11.4.2.3 Variables recorded

Definition of desirable tree, stand and site variables to be recorded in existing and future growth plots is difficult, as the maintenance of flexibility and independence between modellers in future modelling approaches is desirable (Leary 1988). As well, future management objectives, and hence model requirements, may vary from multiple–use to industrial plantations.

Measuring only those variables routinely recorded in forest inventory can seriously restrict future model designs. For example, recent attempts (Goodwin 1988) to adapt a distance–independent single tree model for irregular, mixed–species eucalypts have highlighted limitations in both the sampling design and variables recorded in typical Australian continuous forest inventory (CFI) plots when applying the recent advances in empirical modelling. The rectangular shape of many CFI plots militates against the use of standard distance–dependent models, whilst the limited range of measured tree attributes severely restricts the design options for such components as crown development functions. Such problems are common when inventory procedures are designed to describe current levels of the resource, with little emphasis on predicting consequences of treatment (Stage 1981). DeVries (1986), for example, has demonstrated that where CFI using sampling with partial replacement is undertaken, there is no single sampling scheme that is optimal for estimating both current population levels and subsequent growth. Consequently, whilst the CFI networks are capable of providing adequate estimates of some components of forest growth, they are inappropriate for the collection of both growth and resource–level inventory information. Turner (1988a), however, cautioned against a complete abandonment of CFI plots and their replacement with designed experimental and special yield plots, arguing that in many eucalypt forest types these are the only data likely to be available for some years.

Although either stand or tree–level inventory data can be used for model validation, individual–tree level data is necessary within growth and experimental plots to retain flexibility for future modelling approaches (as later aggregation to stand–level is straightforward). In addition to standard mensurational variables (tree diameter, total height, bark thickness) information relevant to product differentiation (such as the size and frequency of branches) will be necessary to meet utilization modelling objectives. Such product–related data might be measured for a sub–sample of trees in the plot, providing tree injury and bole descriptions suitable for later correlation to defects and sawn timber recovery (see, *e.g.* Brennan *et al.* 1991, Strelein and Boardman 1992). The height to crown break may be useful to indicate the extent of a potentially green knotty core from the dead knot zone in ash related species (Waugh and Rozsa 1991), and hence log quality zones within the stem. Measurements of the depth of green crown under the range of stand age and densities is also potentially important in modelling crown biomass parameters. Wood density and fibre yield may be important additional variables in plantations managed for pulpwood.

Specific improvements to present mensurational techniques in the karri PSPs and experiment plots (Chapter 3) would include the adoption of consistent axes when measuring crown radii, the use of binocular clinometers or telerelaskops to improve sighting for height and crown break measurements, together with the recording of base–line bearings and distances to minimize the subsequent differences in sighting the growing 'tip' of a tree. Bole description should be performed for a sample of stems.

Tree variables must be measured, as subjective estimates are unacceptable for growth estimation (Chapter 3). This may necessitate fewer samples being obtained or the use of sub–samples within plots. All tree species within a plot must be adequately sampled to ensure species–specific parameters can be estimated for future models. Similarly, the traditional emphasis on recording only those trees exceeding a minimum diameter size limit (which later becomes redundant as modelling objectives change) must be avoided. The spatial location of trees must be recorded to facilitate remeasurement and provide for future distance–dependent modelling approaches. Understorey species should be sampled if modelling of biomass accumulation and regeneration processes are to be incorporated into future models. Depending upon the progress of mechanistic modelling research, close attention should be paid in structured experiments to measuring stand and tree level variables (*e.g.* leaf area indices) necessary to capitalize on this approach. McMurtrie *et al.* (1989) have recently identified those key variables required in eucalypt mechanistic models, whilst Benson[2] (*pers. comm.*) has reviewed the appropriate mensurational techniques for such models.

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[2] Mr M. Benson, CSIRO Division of Forestry and Forest Products, Canberra

11.4.2.4 Site description

A revised data acquisition strategy for karri must include greater site description in all PSPs and experiments. The definition of an appropriate set of site descriptors for incorporation into predictive models, or as a basis for site classification, should be based upon knowledge of the particular species site requirements. Unfortunately, greater knowledge is available on the soil nutrition requirements and physiological processes for introduced species such as radiata pine than for most eucalypt species (see, *e.g.*, Cromer 1984). Definition of a minimum site description set is therefore tentative.

One approach to selecting the appropriate site variables to be recorded is provided by Kimmins *et al.* (1990), who considered the interaction between moisture and nutrients to be important in the control of forest growth. They infer that detailed description of site attributes should be governed by the limiting factor concept *i.e.* soil moisture attributes such as soil structure should take precedence on dry sites and in climates which produce severe growing–season moisture deficits, whereas nutrient attributes (parent material, chemical analyses) will be more important for growth and yield prediction on moist sites and in humid climates.

As a minimum, existing soil, landform, climatic, vegetation and site index classifications should be recorded for all PSPs, monitoring and experiment plots (Rose and Ugalde 1988). Collection of meteorological data at frequent intervals for each experiment and PSP site is prohibitively expensive, but may be necessary for select experiments to provide sufficient information to correlate to the readily available forest–wide climatic variables such as monthly or annual rainfall data. The high correlation between annual rainfall recorded at meteorological stations throughout the karri zone (Chapter 9) suggests that only key stations might be sampled.

Current forest–wide climate systems such as BIOCLIM (see Booth *et al.* 1988a) require latitude, longitude, and elevation to access information for any plot location. This information is also required to derive such mechanistic variables as the incident solar radiation for a site (Landsberg 1986). Physiographic features such as aspect and slope should also be recorded.

Within areas of uniform climate, the nature and efficacy of soil variables is likely to vary between species and forest types. Abrupt changes in species composition within natural eucalypt stands have been related to soil properties (Florence 1981). Limited success has been achieved, however, when correlating detailed soil chemical and physical properties to site productivity at a level of resolution sufficient to form a basis for yield projection strata for either eucalypts (Hall 1956, Turner 1966, Carmean 1984, Bowman and Kirkpatrick 1986, Chapter 6) or other species (Duncan 1979, Tesch 1981, Monserud 1990). Detailed soil chemical analyses of sites in natural stands may only be appropriate in experimental plots where comparative data is required for treatment comparisons (*e.g.* fertilizer trials).

The floristic composition of a stand has been considered to be an integrated expression of those edaphic and climatic factors influencing site productivity in undisturbed (Daubenmire 1976, Spurr and Barnes 1980) and managed (Keenan and Candy 1983, Inions *et al.* 1990) forest stands. Rarely, however, have classifications based solely on floristics provided yield projection strata of sufficient resolution for most growth and yield modelling applications in natural forest stands (Havel 1980b, Tesch 1981, Mathiasen *et al.* 1987). Thus, while existing vegetation types should be recorded in growth plots to assist evaluation of the classification, routine recording of understorey floristics and abundance may only be justified when required for purposes other than timber projections, such as in wildlife habitat inventories (see, *e.g.* Davey 1989).

11.4.2.5 Frequency of measurement

The frequency of remeasurement of PSP and experiment installations is an integral component of a data collection and monitoring program. The remeasurement schedule should ideally be tailored to the specific site/age growth rates (Gertner 1981) to ensure that growth exceeds the measurement error for the major variables (Chapter 3). While this can be readily determined for PSPs in unmanaged stands, the frequency of measurement of experiment plots for thinnings or single–tree plots may need to grade from very frequent to infrequent as a function of the time since stand treatment. The construction of models capable of simulating understorey abundance in karri would need plot remeasurement schedules to be determined on the basis of understorey life–cycles as well as the measurement error in traditional timber attributes.

Model design and statistical issues will also influence the selection of an appropriate measurement interval. For example, using data collected over intervals longer than three years to approximate annual increments may introduce bias for fast growing species. Similarly, modellers often use reduced datasets for model parametrization to overcome the statistical difficulties associated with hypothesis testing when using multiple measurements from individual sampling units (West *et al.* 1984). There seems little point in collecting frequent remeasurements for each plot if many are later discarded in the statistical analysis – in some instances it might be preferable to expand the number of plot replicates over site and time.

11.5 Timing and implementation of a data acquisition strategy

The extent to which KARSIM is updated, enhanced, and additional experiments established will be largely determined by the perceived priority for this task at the policy level within the organization, and hence the magnitude of the resources allocated to the work. With the increasing controversy and concern over management practices and priorities of use in public forests (Turner 1988b), it is essential that KARSIM be improved and a comprehensive data collection strategy be put in place. This strategy must specify the long-term nature of data collection to attract sustained support throughout the organization. A staged approach might proceed as follows.

In the short-term (0-5 yrs), tree ring analyses and continued measurement with additional variables (product, crown) would extend the measurement history on existing PSPs and experiments. The measurement frequency of those PSPs on over-represented sites might be extended to 'free up' resources during this period. A revision of the sampling strategy would aim to improve the site representation of the PSPs while identifying key sites for the establishment of new experiments. The present old-growth logging plan would be adjusted to ensure the availability of desired sites. Additional thinning and espacement experiments, together with appropriate monitoring trials, would be established.

In the medium-term (5-15 yrs), data from the thinning and espacement trials could be used to either recalibrate or revise those model formulations dealing with the effect of thinning on stand increment, *d* distribution, and tree taper and product distributions. Sufficient data would accrue by the end of this period to enable alternative individual-tree modelling approaches to be examined. Additional PSPs could be established in regenerated stands on site-types previously under-represented in the older dataset.

In the long-term (20+ yrs), a major review of the mortality and thinning models would be possible.

This data acquisition strategy must be viewed in the wider context of developing, during this period, a fully integrated Decision Support System for karri. While the complete details of such a system have not been defined, data collection and model development must capitalize on the emerging technology for systems development. For example, integration of the karri inventory, growth and experimental data within a database management system would provide several advantages. Revisions of KARSIM could then be integrated within the database system, making operational application of the growth model much more efficient, because all initialization and development data would be stored in a common database (Ek 1990). Future ties to the CALM geographic information system would also be facilitated. This approach was used to develop a Forest Resources Information and Yield Regulation system for softwood plantations in Victoria (DCE 1991). The growth model was developed and written entirely within the database management system, providing flexibility for the direct entry of measurement data and the production of up-to-date resource statements, the simulation of stand strategies and yield scheduling. Development of growth models within a database system would also streamline the construction of computerized decision aids such as expert systems (Kourtz 1990) and the production of greatly enhanced model output using computer graphics (Burkhart 1990).

The successful implementation of this approach would require close integration of silvicultural, research and inventory programs. Uniform measurement standards both within and between programs would be essential to ensure a consistent database was developed.

CHAPTER 12 CONCLUSIONS

Advanced forest-level planning techniques will be needed to meet the increasing complexity and intensification of management in Australian eucalypt forests. Stand growth models are fundamental to such systems. A review of the literature on growth and yield models developed for both pure and mixed-species eucalypt stands indicated that modelling approaches have evolved from the traditional stand-level, empirical formulations through to individual-tree level simulators and recent mechanistic approaches, in progressive attempts to extend the species or stand treatment generality of models (Chapter 2). The chronological sequence of advancements in model design has broadly parallelled international developments in growth and yield theory. The review highlighted the similarity of current datasets for the regrowth eucalypt estates, and that the present lack of models for many forest types placed serious constraints on the use of advanced forest-level planning systems.

As stated in Chapter 1, the aim of this study was to develop a model which could quantitatively describe the growth and productive potential of regrowth karri stands under varying management regimes. However, aspects of this research have wider implications. Renewed interest in the establishment of eucalypt plantations and the intensification of management of existing regrowth estates (Kerruish 1991) has emphasized the need for growth models which can explore stand treatment options. This study provides a timely example of an approach to model development with a dataset typical of those collected by most forest organizations. The contribution has been in the synthesis and drawing together of component models, as some of the mathematical formulations have been adapted from previously published simulators.

Adopting a systems analysis approach to model development, the first phase of the study critically evaluated the quantity and quality of the available karri data (Chapter 3). This evaluation revealed serious deficiencies in mensurational standards and practices which seriously constrained the choice of model design. Alternative model designs were examined and an empirical, individual-tree level modelling approach was selected as appropriate to meet the karri information objectives (Chapter 4).

The stratification of a forest estate into land units of similar potential productivity is an essential stage in model development and land-use planning. An algebraic difference approach was used to formulate nine dominant height/age models for karri, and tests revealed an anamorphic Weibull-based formulation was the most accurate in estimating future stand height. The algebraic difference formulations and the sampling and mensurational techniques employed provide a comprehensive methodology for developing site index curves (Chapter 6). For example, the existence of a bias in tree height estimates derived from graphical methods in stem analysis was confirmed for karri, and correction factors were tested to correct for this bias

(Appendix 1). Such bias has hitherto been overlooked in eucalypt mensuration. Similarly, the recognition of regional patterns in tree ring widths was a useful tool for standardizing tree ageing during stem analysis. The site index curves proved superior to separate edaphic, landform, climatic and vegetative classifications for stratifying site productivity in these forests (Chapter 6). None of the indirect classifications were able to adequately stratify maximum density stands into differing ($P<0.05$) stand volume, basal area, or stocking density productivity classes within which the correlated dynamics of stand development could be consistently interpreted. This result emphasized the need for careful definition of the sampling hierarchy in land classification and in the selection of appropriate site descriptor attributes when developing indirect classifications for eucalypts.

Separate models for stand accretion, ingrowth and mortality were parametrized using data from mostly naturally-regenerated karri stands. Component models for estimating tree volume, taper and product assortments were also developed. Despite a paucity of stand treatment data and a predominance in the dataset of fully-stocked stands, thinning effects were simulated by incorporating in the I_{Bg} model a measure of the level of stand competition in a manner which approximated the Mϕller hypothesis, essentially generalizing a Stand Density Management Diagram (Chapter 7). This approach is a valuable first approximation if stand treatment data are limited.

An individual-tree, distance-independent simulator, called KARSIM, was constructed by building upon designs adopted by Curtis (1967a) for regrowth Douglas-fir and Opie (1972) in regrowth ash eucalypts. Whole-model validation revealed the importance of incorporating the effects of stochastic climatic events, such as drought, on stand development (Chapter 9). Ignoring the impact of such events on stand growth and mortality could lead to substantial bias in volume estimates for unmanaged eucalypt stands, even over the relatively short rotations envisaged for plantations. This work reinforces the view that site index can only be considered deterministic if future climatic patterns remain similar to the historical patterns underlying the stand growth observations used for model parametrization.

Validation tests confirmed that despite many biological assumptions and empirical adjustments, KARSIM was a satisfactory predictor of stand variables for both managed and unmanaged regimes. The lack of an independent dataset for model validation was partially overcome by developing a separate, stand-level model for estimating total stand volume, thereby providing an 'independent' check on long-term projections from KARSIM (Chapter 9).

The utility of the present version of KARSIM was demonstrated across a range of stand treatment and planning investigations (Chapter 10). The development of the site stratification for the regrowth estate (Chapter 6) and the availability of KARSIM enabled major improvements on previous yield planning processes. As part of a major review of forest management strategies in W.A., the model played a central role in revising the sustainable yield for karri.

Considerable monitoring and improvement of the prototype KARSIM will be necessary to meet future planning information needs. A data collection strategy was outlined for karri which, in keeping with probable future trends in eucalypt modelling, incorporated expanded sampling frames, better site description, and uniform mensurational standards (Chapter 11). Aspects of this strategy should be relevant to any organization involved in the development of individual-tree level models for eucalypts.

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APPENDIX 1 ESTIMATION OF TRUE HEIGHT FROM KARRI STEM ANALYSIS DATA[1]

1.1 Introduction

Stem analysis is a technique commonly used in eucalypt mensuration for obtaining height/age data for the derivation of height growth and site index curves (see *e.g.* Lindsay 1939, Tas. For. Comm. 1964, Incoll 1974, Kilgour 1982, Goodwin and Candy 1986).

A potential bias in the estimate of tree height corresponding to a given age in a cross–cut section can arise from sectioning of the stem, and a number of studies have investigated the extent of such bias for temperate and coniferous species (Carmean 1972, Dyer and Bailey 1987). The bias arises because the true total height of the tree at the age corresponding to the ring count at the cross–cut will usually be located some distance above the cross–cut. Dyer and Bailey (1987) have shown the sensitivity of parameter estimates for height/age models to the use of uncorrected data.

This study aimed to determine if such bias existed in stem analysis data for regrowth karri. Six published algorithms, derived for coniferous species, were compared for their capacity to estimate the length of the "hidden tip" in this eucalypt species.

1.2 Method

1.2.1 Data

A total of 30 logs, each of four metres in length, were randomly selected from dominant trees sampled for stem analysis as part of the site index study (section 6.2). Each log was randomly selected within a tree from sites subjectively selected to represent the site range of existing regrowth stands. The range of tree and stand parameters represented by the sample are summarized in Table A1.1. No tree contributed more than one log to the dataset. Ten logs were sampled from each of the butt (<5 m from base of tree), bole, and crown (above crown base) zones of the trees.

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[1] This Appendix has been published as: Rayner, M.E., 1991. Estimation of true height from karri (*E.diversicolor*) stem analysis data. *Aust. For.*, 54: 105–108.

Table A1.1 Minimum–mean–maximum values of log, tree, and stand variables from which logs were sampled for sectioning to determine the position of the "hidden tip". Total sample size is 30 logs.

	LOG	TREE	STAND
Crown–end diameter (cm)	..9–27–52		
Butt–end diameter (cm)	10–31–55		
Breast height diameter (cm)		20–46–74	
Total height (m)		17–37–52	
Stand basal area (m^2 ha^{-1})[a]			16–34–48
Stand age (yrs)			20–54–77

[a] Live stems ≥10 cm breast height diameter.

Each log was sequentially sectioned from the base to the crown end at 2 cm intervals to locate the position of the first hidden tip above the base cross–cut. The location of the hidden tip was observed by counting a decrease of one in the number of growth rings relative to the number of rings on the base cross–cut. Growth rings on all sections were counted on three radii by two independent assessors using magnifying lenses. Four logs were discarded from further analysis because assessors differed in their opinion of the position of the hidden tip.

The height, number of growth rings, and radius of each growth ring from the pith were recorded for both the base section and the hidden tip section. In addition, the inside–bark taper was calculated for the base section, thereby providing all data necessary for application of the candidate algorithms.

1.2.2 Algorithms tested

The 'true' height of the tree at the age corresponding to the ring count on the base cross–cut was the height to the base of the cross–cut plus the height to the hidden tip (Figure A1.1). This height (*i.e.* including the hidden tip) was measured for each log section and then estimated using each of the following candidate algorithms. These algorithms have been comprehensively described by Dyer and Bailey (1987), whose terminology and notation is reproduced here for consistency:

Let r_i = total number of growth rings at the i^{th} cross–cut
j_i = the j^{th} growth ring on the i^{th} cross–cut, with j=1, 2 ... r
h_i = tree height at the i^{th} cross–cut
H_{ij} = estimated total tree height at age t_{ij}
t_{ij} = age of the tree associated with the j^{th} inner ring at the i^{th} cross–cut
= total tree age − $r_i + j$
w_i = radius to inner i^{th} ring

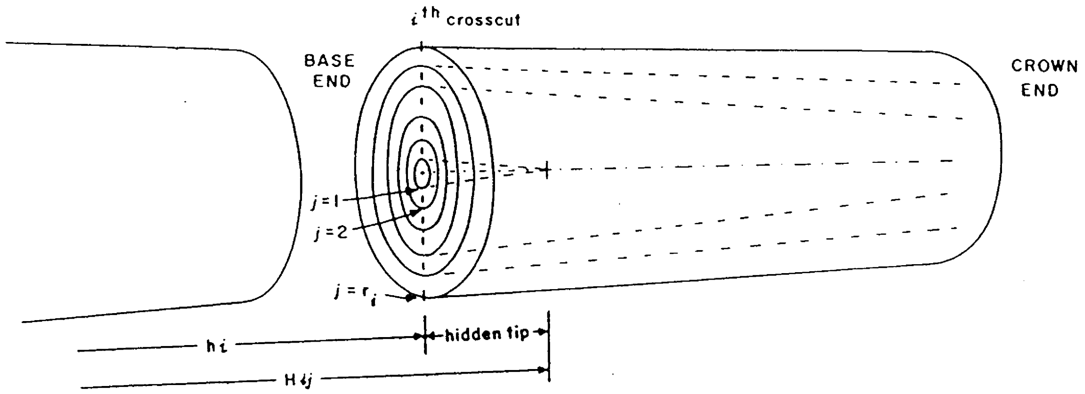

Figure A1.1 Diagrammatic representation of a cross–cut section illustrating the position of the hidden tip and the notation employed in describing each candidate algorithm.

α = angle of inside bark taper for top–most section
w_j = radius to the j^{th} inner ring where $j=1, 2 \ldots. k$
w_k = radius to the k^{th} inner ring
k = number of inner rings

Then the six methods may be expressed mathematically as follows.

1. Graphic

$$H_{ij} = h_i$$

i.e. the height of the tree is the sum of the log section lengths to the particular cross–cut. This method does not allow for a potential hidden tip.

2. Graves (1906) (cited by Dyer and Bailey 1987)

$$H_{ij} = h_i + j\,(h_{i+1} - h_i) / (r_i - r_{i+1})$$

i.e. this method proportions a section equally among the inner rings of a cross–cut by assuming the height growth is constant for each year that ends in the section containing the hidden tip.

3. Lenhart (1972)

$$H_{ij} = h_i + j\,(h_{i+1} - h_i) / (r_i - r_{i+1} + 1)$$

i.e. this method assumes height growth ceased at equally spaced points throughout the section.

4. Carmean (1972)

$$H_{ij} = h_i + (h_{i+1} - h_i) / [2(r_i - r_{i+1})] + [(j - 1)\,(h_{i+1} - h_i)] / (r_i - r_{i+1})$$

i.e. assumes annual height growth is constant for each year for which height growth is contained within a section, and that on average a cross–cut will occur at the mid–point of a year's height growth.

5. Newberry (1978) (cited by Dyer and Bailey 1987)

$$H_{ij} = h_i + (\mathrm{Tan}\ \alpha) w_j$$

i.e. assumes the inside bark taper for the current year's growth forms a similar triangle with the taper of that portion of the tree from the cross–cut to the top of the tree.

6. Ratio (cited by Dyer and Bailey 1987)

$$H_{ij} = h_i + [(h_{i+1} - h_i)(w_j / w_k)]$$

i.e. assumes the length of hidden tip is proportional to the ratio of the annual rings corresponding to years when height growth ended within a section.

Student's *t*–statistic was used to test whether the residuals (observed height minus predicted height) for each algorithm differed significantly from zero.

1.3 Results

Both the Graphic and the Newberry algorithms significantly underestimated the length of the hidden tip within a stem section (Table A1.2). In contrast, the Graves and Ratio algorithms produced a significant overestimate of the length of the hidden tip within the log. The Carmean and Lenhart methods both provided estimates of tree height at a section which were not significantly different ($P<0.05$) from the actual height.

Table A1.2 Summary of residuals (observed minus predicted) for the position of the hidden tip within a karri stem section. An asterisk (*) indicates the mean of the residuals was significantly different from zero at the 0.05 probability level.

Method	No. of Observations	Min. value	Max. value	Mean value	Mean of absolute value	Standard Deviation	*t* Statistic
		....	.......metres.......	....	....	....	
Graphic	26	0.05	2.00	0.64	0.64	0.45	7.32*
Newberry	26	0.14	0.84	0.46	0.46	0.21	7.35*
Carmean	26	−0.35	1.28	0.11	0.25	0.35	1.60
Lenhart	26	−0.70	0.92	−0.12	0.26	0.33	−1.89
Graves	26	−1.40	0.57	−0.42	0.48	0.48	−4.50*
Ratio	26	−2.65	0.07	−1.21	1.21	0.69	−8.89*

The residuals of the Lenhart and Carmean methods were investigated further to determine if either method was superior. Skewness and kurtosis statistics were comparable, suggesting either algorithm was statistically acceptable for hidden tip estimation within this dataset.

Similar results were obtained when the sections were grouped according to the position in the stem from which they were sampled *i.e.* either the butt, bole or crown zones. However, the statistical power of the tests were limited due to the restricted sample size in each category.

1.4 Discussion

This work provides evidence that for at least one eucalypt species significant bias may result from the use of stem–analyzed height data which is uncorrected for the "hidden tip". Biased parameter estimates would result from height/age models parametrized with such uncorrected data.

Both Carmean's (1972) and Lenhart's (1972) methods were acceptable for estimation of 'true' tree height within this sample dataset. The different assumptions of each method concerning the position of each hidden tip wholly or partially contained within a section appear to be of limited practical consequence for dominant karri stems. This contrasts with the findings of Dyer and Bailey (1987) for *Pinus taeda*. In their study, Carmean's method also produced the most accurate results of all methods tested, but Lenhart's method significantly overestimated the length of the hidden tip, whilst in the present work no significant difference between the estimated and actual heights was detected using this algorithm. This may be partly due to the limited sample size (less than 30 degrees of freedom) in the present study, or alternatively, the assumptions upon which Lenhart's method is based may be robust for eucalypts. Lenhart's (1972) method assumes that the points where height growth ended are equally spaced throughout the section, whilst Carmean's (1972) method assumes that on average a cross–cut will occur in the middle of a year's height growth, and that the annual height growth is constant for each year for which height growth is wholly or partially contained within the section.

Dyer and Bailey (1987) speculated that Carmean's method would be superior for other log lengths, species, and for breast height ages. The present work supports this contention (albeit Lenhart's was also suitable), particularly as the growth habits, size, and tree form of karri differ markedly from the coniferous species used in previous investigations.

1.5 Conclusion

The bias inherent in using the Graphic method to determine tree height corresponding to the number of growth rings at a cross–cut necessitates application of an algorithm to determine the length of the hidden tip. Six alternative algorithms were investigated, and either the Lenhart (1972) or the Carmean (1972) correction appears most appropriate for dominant regrowth karri stems. This result is consistent with findings for other species.

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