APPLICATION OF A PROCESS-BASED MODEL FOR PREDICTING AND EXPLAINING GROWTH IN EUCALYPTUS PLANTATIONS

by

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STATEMENT OF ORIGINALITY

The thesis "Application of a process-based model for predicting and explaining growth in Eucalyptus plantations" is original and has not previously been submitted for a degree or diploma in any institution of higher education.

The thesis reports on, and uses, results of a major experimental program carried out in a catchment area (The Watershed Project) in Aracruz, ES, Brazil. I was responsible for initiating and designing that project and had primary responsibility for carrying out and supervising most of the measurements. Many of the data used in this thesis were obtained from measurements made with assistance from technical staff under my supervision. I have been entirely responsible for the data analysis reported in this thesis. Some of my colleagues from Aracruz had responsibility for aspects of data collection. Their contribution is detailed in the Acknowledgments.

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ABSTRACT

This thesis examines the feasibility of using a process-based model as a practical management tool for predicting forest growth and explaining the main factors that affect the productivity of *Eucalyptus* plantations in Brazil. The 3-PG model (Landsberg & Waring, 1997) was adopted for the study. The principles underlying the model and the features of the sub-models are outlined. The model was parameterised for *Eucalyptus grandis* hybrid plantations, based mainly on data collected in an experimental catchment (Microbacia, MBE) of 286 ha. Model performance was compared with data collected monthly in the catchment and in permanent sample growth plots measured annually in other areas, covering about 181 000 ha of plantation owned by Aracruz Celulose in eastern coastal of Brazil. The features of the experimental areas and data collection procedures are presented in detail. Intensive measurements of climate from a dense network of 19 automatic weather stations, unequally distributed across the Aracruz estates, provided accurate data to generate weather information for any area and allow analyses that provided important insights into the effects of drought periods and of vapour pressure deficit on tree growth. Biomass partitioning was determined from data obtained by destructive sampling of trees which, associated with physiological measurements, provided the information needed to understand observed differences between genotypes (clones). These observed differences could be attributed primarily to differences in biomass partitioning and secondarily to differences in stomatal conductance. The results allowed identification of differences between clones in carbon allocation to roots. Using data from an irrigation and fertilization experiment, where water and nutrients were not constraints on forest growth, a reliable empirical value of canopy quantum efficiency - the efficiency with which the tree canopy converts radiant energy to carbohydrates - was established for this species. A sensitivity analysis was carried out identifying the most important parameters from the forest management point of view.

Application of the model using the parameter values determined in the MBE study allowed accurate description of the growth patterns of stands in terms of mean annual increment, total stand volume, basal area, diameter at breast height, leaf area index and available soil water. For areas other than the MBE the goodness of fit between peak mean annual increment, and mean annual increment to harvest, estimated using generic parameter values, and observed peak and mean annual increments in ten regions, was high ($r^2 = 0.93$, $P < 0.05$, SE = 1.44 m^3 ha^{-1} $year^{-1}$ and $r^2 = 0.81$, $P < 0.05$ SE = 2.25 m^3 ha^{-1} $year^{-1}$ respectively). The model was used to predict potential productivity in a number of operational areas. The results are being used to guide fertiliser applications and evaluate management limitations.

A spatial version of the model running in a Geographic Information System (GIS) is being used to estimate productivity in terms of forest volume in current production areas and on new lands, and to quantify the effects of environmental factors and management actions on forest productivity. This use allows quantification of the risks associated with production, and increases the quality of the decision-making process. Current research is focused on the question of soil fertility rating, as well as tree physiological characteristics and differences among clones at several sites. A total of 520 permanent sample plots (check plots) distributed in the planted areas was installed. These are allowing comparisons of model performance and actual productivity and will provide the information required for model improvement. The progress made in applying 3-PG reported here demonstrates the valuable role that process-based models can play as practical and applied tools in commercial forest management, especially in fast-growing *Eucalyptus* plantations with short-rotation times (5-7 years), and for testing hypotheses about the way trees function and respond to environmental changes.

Keywords: Process-based model, *Eucalyptus grandis* plantations, 3-PG model, Forest management, Forest productivity, Stand volume, Mean annual increment, Biomass production, Leaf area index.

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LIST OF ABBREVIATIONS OR ACRONYMS

Abbreviation	Meaning
3-PG	Physiological Principles in Predicting Growth
$3\text{-}PG_{PJS}$	Version of 3-PG developed by Dr. Peter Sands (August 2002)
3-PGS	Spatial version of 3-PG developed in Arc/Info™ under a collaboration between Aracruz and CSIRO - Forestry and Forest Products
Age_{MAIx}	Age at which maximum MAI is achieved
ANU	The Australian National University
ANUDEM	Digital elevation modelling software developed and marketed by Centre for Resource and Environmental Studies (CRES), The Australian National University
ANUSPLIN	Software for fitting surfaces to noisy data. Developed and marketed by Centre for Resource and Environmental Studies (CRES), The Australian National University
APAR	Absorbed photosynthetically active radiation
APARU	Utilisable absorbed photosynthetically active radiation
AR	Aracruz region
ARC/INFO	Industry Standard Geographic Information Systems Software developed by Environmental Systems Research Institute (ESRI).
ARCEL	Aracruz Celulose S.A.
AWS	Automatic weather station
BA	Basal area
CAI	Current annual increment
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CNPS	Centro Nacional de Pesquisa de Solos
CVI	Current volume increment
DBH	Diameter at breast height (1.3 metres)
DEM	Digital Elevation Model
DM	Dry (bio) mass
E	Spodosol (soil type)
EGROW ARCEL	Empirical forest model used at Aracruz.

Abbreviation	Meaning
Embrapa	Empresa Brasileira de Pesquisa Agropecuária
ET	Evapotranspiration
FOREST-BGC	FOREST-Bio-Geo-Chemical simulation model
FR	Fertility rating
G	Gleysol (soil type)
GIS	Geographic Information System
GPP	Gross primary production
LA	Latosol (soil type)
LAI	Leaf area index
LAI-2000	Plant canopy analyser, Li-Cor, Lincoln, NE
Lat	Site latitude
LCA-4	Gas analyser, Li-Cor, Lincoln, NE
LI1600	Porometer, Li-Cor, Lincoln, NE
LI3100	Area meter, Li-Cor, Lincoln, NE
LI-190SA	Photosynthetically active radiation sensor, Li-Cor, Lincoln, NE
MAI	Mean annual increment
MAI_x	Peak mean annual increment
MBE	Experimental catchment
N	Nitrogen
NPP	Net primary production
P-M	Penman-Monteith equation
PA	Agrisol (soil type)
PAR	Photosynthetically active radiation
PBM	Process-based model
PBMs	Process-based models
PSP	Permanent sample plot
PSPs	Permanent sample plots
RCA	Residual correction analysis
RH	Air relative humidity
RQ	Quartzose Neosol (soil type)
RUE	Radiation use efficiency
S	Stem number
SB	South Bahia region

Abbreviation	Meaning
SBS	Brazilian Silvicultural Society
SC	Soil class
SE	Standard error
SLA	Specific leaf area
SM	São Mateus region
Stdev	Standard deviation
SV	Stand volume
SX	Planosol (soil type)
SW	Available soil water
TP	Temporary plots
UAPE	Water balance model "Uso de água em plantações de eucalipto"
VPD	Vapour pressure deficit
VPD_{24h}	Daytime average value of vapour pressure deficit
VPD_{day}	VPD during daylight hours
$VPD_{del.T}$	VPD calculated using daily T_{max} and T_{min}
WUE	Water use efficiency

LIST OF SYMBOLS AND DEFINITIONS

Symbol	Name	Unit
a_f	Coefficient in foliage allometric relationship with DBH	-
a_s	Coefficient in stem allometric relationship with DBH	-
B	Stem diameter	cm
c_θ	Relative water deficit for 50% of reduction of available soil water	-
D	Vapour pressure deficit	mbar or kPa
D_d	Daylight vapour pressure deficit	mbar or kPa
D_q	Specific saturation deficit	mbar or kPa
D_t	Vapour pressure deficit calculated from maximum and minimum temperature	mbar or kPa
D_{24}	Average daily (24 h) vapour pressure deficit	mbar or kPa
e_a	Vapour pressure of unsaturated air	-
e_s	Saturated water vapour pressure	mbar or kPa
F_a	Relative age	-
f_{age}	Stand age modifier	-
f_D	Vapour pressure deficit modifier	-
f_F	Days of frost modifier	-
f_N	Soil nutrition modifier	-
f_{Nn}	Power of (1-FR) in f_N	-
f_{N0}	Value of f_N when $FR = 0$	-
FR	Site fertility rating	-
FR_{0p}	Fertility rating in re-establishment stands at age from zero to four years	-
FR_{4p}	Fertility rating in re-establishment stands at age higher than four years	-
FR_{0c}	Fertility rating in coppice stands at age from zero to four years	-

Symbol	Name	Unit
FR_{4c}	Fertility rating in coppice stands at age higher than four years	-
f_T	Temperature modifier	-
f_θ	Soil water modifier	-
g_B	Canopy boundary layer conductance	m s^{-1}
g_C	Canopy conductance	m s^{-1}
g_{Cx}	Maximum canopy conductance	m s^{-1}
g_s	Stomatal conductance	m s^{-1} or mmol m^{-2} s^{-1}
g_{sx}	Maximum stomatal conductance	m s^{-1} or mmol m^{-2} s^{-1}
I	Precipitation interception	mm
I_x	Maximum proportion of rainfall evaporated from canopy	mm
k	Extinction coefficient for absorption of PAR by canopy	-
k_D	Response of canopy to vapour pressure deficit	$mbar^{-1}$
k_y	Power of litterfall function	-
L^*	Leaf area index	m^2 leaf m^{-2} ground
L_{Cx}	L^* for maximum canopy conductance	-
L_{Ix}	Leaf area index for maximum rainfall interception	-
m	Fertility dependent variable	-
m_0	Value of m for poorest soils	-
N	Stem population	tree ha^{-1}
N_i	Stem population in the model initialisation	tree ha^{-1}
n_{age}	Power of relative age in function for f_{age}	-
n_f	Power coefficient in foliage allometric relationship with DBH	-
n_{fN}	Power coefficient fertility modifier	-
n_m	Exponent in the self-thinning law	-
n_s	Power coefficient in stem allometric relationship with DBH	-
n_θ	Power of moisture ratio deficit	-
p_{BB0}	Branch and bark fraction at age 0	-
p_{BB1}	Branch and bark fraction for mature stands	-

Symbol	Name	Unit
p_{FS}	Ratio of foliage biomass partitioning to stem biomass partitioning	-
p_{FS2}	Ratio of biomass allocation to foliage and stem at DBH = 2 cm	-
p_{FS20}	Ratio of biomass allocation to foliage and stem at DBH = 20 cm	-
P_G	Gross primary production	t DM ha^{-1}
P_N	Net primary production	t DM ha^{-1}
R	Total monthly precipitation	mm
r_{age}	Relative age to give $f_{AGE} = 0.5$	-
RH	Air relative humidity	%
r_θ	Monthly moisture ratio	-
s_*	Rate of change of saturated vapour pressure	-
V	Stand volume	m^3 ha^{-1}
t	Stand age	years
T_a	Monthly mean daily air temperature	ºC
t_{BB}	Age at which bark and branch rate have median value	year
T_{max}	Maximum air temperature for growth	ºC
T_{min}	Minimum air temperature for growth	ºC
T_{opt}	Optimum temperature for growth	ºC
$t_{\gamma F}$	Age at which litterfall rate has median value	month
t_σ	Stand age at which $\sigma = (\sigma_0+\sigma_1)/2$	years
Y	Ratio P_N/P_G	-
w_{Sx}	Maximum stem mass per tree	kg $tree^{-1}$
w_{Sx1000}	Maximum stem mass per tree @ 1000 trees/hectare	kg $tree^{-1}$
w_f	Single-tree foliage mass	kg $tree^{-1}$
w_s	Single-tree stem mass	kg $tree^{-1}$
W_F	Foliage biomass	t ha^{-1}
W_R	Root biomass	t ha^{-1}

Symbol	Name	Unit
W_S	Stem biomass	t ha^{-1}
α_C	Canopy quantum efficiency	mol C mol PAR^{-1}
α	Maximum canopy quantum efficiency	mol C mol PAR^{-1}
ΔNa	Degree of soil limitation - fertility index for natural fertility	-
ΔNp	Degree of soil limitation - fertility index for potentiall fertility	-
ΔH	Degree of soil limitation - fertility index for water	-
ΔO	Degree of soil limitation - fertility index for oxigen	-
ΔM	Management impediment	-
ε	Radiation use efficiency	g DM MJ^{-1}
ϕ_n	Net radiation	MJ m^{-2} day^{-1} or W m^{-2}
ϕ_p	Photosynthetically active radiation	MJ m^{-2} day^{-1} or μmol m^{-2} s^{-1}
ϕ_{pa}	Absorbed photosynthetically active radiation	MJ m^{-2} day^{-1} or μmol m^{-2} s^{-1}
ϕ_s	Short-wave solar radiation	MJ m^{-2} year^{-1} or MJ m^{-2} day^{-1} or W m^{-2}
γ	Litterfall	t DM ha^{-1}
γ_F	Litterfall rate	1/month
γ_{Fx}	Maximum litterfall rate	1/month
γ_{F0}	Litterfall rate at t = 0	1/month
γ_R	Average monthly root turnover rate	1/month
η_F	Partitioning coefficient for foliage	-
η_R	Partitioning coefficient for roots	-
η_S	Partitioning coefficient for stem	-
η_{Rx}	Maximum fraction of P_N to roots	-
η_{Rn}	Minimum fraction of P_N to roots	-
φ	Physmod	-
λ	Latent heat of vaporisation of water	J kg^{-1}
λE	Canopy transpiration	mm month^{-1}

Symbol	Name	Unit
θ	Current available soil water	mm
θ_i	Initialisation available soil water	mm
θ_m	Minimum available soil water	mm
θ_x	Maximum available soil water	mm
ρ	Wood basic density	t m^{-3}
ρ_a	Air density	kg m^{-3}
ρ_m	Minimum basic density - for young trees	t m^{-3}
ρ_x	Maximum basic density - for old trees	t m^{-3}
σ	Specific leaf area	m^2 kg^{-1}
σ_0	Specific leaf area at age zero	m^2 kg^{-1}
σ_1	Specific leaf area at maturity,	m^2 kg^{-1}

Chapter 1

1. INTRODUCTION

1.1. Background

Global demand for wood products is increasing, but the forest resources of the world are decreasing (FAO, 1999). Wood for different purposes, including furniture, paper, civil construction, building and energy, comes from native forests and/or forest plantations. A recent study by FAO (1999) shows that the total world demand for wood is projected to increase from 1996 to 2010 at an annual rate of about 1.7 percent, from 1490 million to 1870 million cubic metres. According to this report, the demand for fuel-wood should increase at about 1.1% per year until 2010. To guarantee the supply to meet this demand will require an increase in the area of forest plantations and the application of modern technology in wood processing industries. The FAO report estimates that there are more than 60 million hectares of forest plantation in the developed world and more than 55 million hectares in developing countries.

In recent years, forest plantations have been established for several purposes, including wood production and carbon sequestration, for which finance may become available as a result of the Kyoto protocol. The potential of forests for carbon sequestration may provide a strong incentive for increasing the area of forest plantations in the future.

Species selection for forest plantations depends of local conditions, environmental restrictions and final management purposes. Major areas of softwood plantations around the world include large areas of Sitka spruce (*Picea sitchensis*) in Britain, loblolly and slash pine (*Pinus taeda* and *Pinus elliottii* respectively) in the southern United States, Douglas fir (*Pseudotsuga menziessi*) in the Pacific north western United States and Canada, and *Pinus radiata* as the major softwood plantation species in Australia, New Zealand, Chile and South Africa (Landsberg & Gower, 1997). With respect to hardwoods, different species of *Eucalyptus* were introduced into a number of countries with different ecosystems; in many cases they are well adapted and have high growth rates. *Eucalyptus* plantations have been widely established in countries like Brazil, India, Portugal and South Africa during the last 30 years and their area is still increasing. Large pulp and paper industry complexes in these countries are being supplied by different species and hybrids of *Eucalyptus*. In Brazil, there are 4.8 million hectares of forest plantations, of which 1.8 million are *Pinus* and 3.0 million are *Eucalyptus* (SBS, 2001). Most of these plantations are used to supply the pulp and paper industry, while sawmills and farmers using the wood as an energy source, represent other users of plantation-grown wood.

Fast growing forest plantations can be considered as crops, and their management equivalent to crop cultivation, in terms of practices such as soil preparation, spacing, weed control, fertilization and harvest. Obtaining successful results from forest plantation projects, regardless of their intended purpose, requires a broad knowledge of natural, economic and social resources and their inter-relationships. There are many questions and uncertainties regarding the sustainability of repeated rotations of intensive forest plantations in different environments. These questions are focussed mainly on water use, nutrient conservation, impacts on biodiversity and the capacity of the environment to sustain production for a continuous series of rotations. Finding useful answers to these questions requires long-term studies and monitoring of different ecosystems and management systems.

The growth rates attainable by forest plantations, and their potential productivity, depend on interactions between climate, soil physical and chemical properties, water availability, tree species and silvicultural practices including soil preparation, fertilization and weed control. Seasonal and annual variations in climate have a direct and strong influence on the volume and quality of wood produced. For example, long drought periods can reduce tree growth drastically (White *et al.*, 1996; Tschaplinski *et al.*, 1998); this is observed more easily in fast growing forests.

Optimum forest management practices must be based on site characteristics. To determine these characteristics requires the identification of limiting factors critical for sustained growth: erosion susceptibility, fertility level, soil physical characteristics, rainfall distribution and the availability of water resources, slope and biodiversity. Mathematical models and geographic information systems (GIS) are the most appropriate tools to integrate this information and to assist in management decision-making (Pokharel, 1998). While our understanding of forest production and forest growth is incomplete (Andersson *et al.*, 2000a), it is good enough to allow the development and testing of process-based models (PBMs) which, when well adjusted and parameterised, should provide powerful analytical tools for analysing the relationships between climate and soils and provide valuable information that will help optimise our management of natural resources.

Forest resource management requires decisions to be made on strategic, tactical and operational aspects. At all these levels, decision-making may be supported by mathematical models (Hinssen, 1994). Growth and yield models have been used mainly to provide decision support information that meets basic operational needs for evaluating various forest management scenarios (Mohren & Burkhart, 1994), but the development of process-based models of forest growth has been increasing in recent years. These models focus on the representation and explanation of the processes that take place in forest ecosystems and highlight state variables that are closely associated with processes (Larocque, 1999). Despite the logical concepts of process-based models, most of them are used only as research tools; they are not being used as operational tools in forest management. Some of the reasons for this are the complexity of ecosystems, the large number of specific parameters required and the difficulty of obtaining data to test and validate tree growth models (Mohren & Burkhart, 1994; Korzukhin *et al.*, 1996; Battaglia & Sands, 1998b; Sands *et al.*, 2000).

Although process-based models have not yet been implemented in operational management systems, many such systems are under development (Mäkelä, 1997).The research reported in this thesis investigates the applicability of a process-based model (PBM) to the management of *Eucalyptus* forest plantations at an operational scale. It provides a unique opportunity to parameterise and validate a PBM in detail because of the large amount of relevant data collected for this purpose. This research provides the most important test of forest growth PBMs to date and will provide invaluable guidance to forest managers as to the possible benefits of investing in expensive data collection to parameterise these types of models.

The study also represents the first case where a process-based model has been tested and applied as a practical tool in large-scale *Eucalyptus grandis* Hill ex.Maiden hybrids plantations in Brazil. It is expected that the outcomes will be generally relevant to tropical *Eucalyptus* plantations and will provide a reference for the application in other regions. The results should help forest planners and decision-makers to optimise environmental, human and economic resources. They should also help provide answers to questions about forest ecosystem management and the best options to guarantee sustainability of intensive tree production on a large scale.

1.2. Approach to the study

The two main questions that lie behind this study are:

- Is it possible to adapt and use a process-based forest model to describe the main features of tree growth, and can the model be used as a reliable prediction tool for forest plantation management?

- What are the main limitations associated with the approach and how can they be addressed?

1.3. Objectives

The objectives of this thesis are:

- To identify a PBM suitable for analysing the performance of *Eucalyptus* forest plantations.

- Parameterise, adjust and test the selected model for applications in *Eucalyptus grandis* plantations in Brazil.

- To use the model to identify and analyse environmental factors limiting the growth of *Eucalyptus grandis* plantations in Brazil.

- Identify limitations and uncertainties in the use and performance of the model.

- Analyse the feasibility of using the model as an analytical tool at an operational scale.

1.4. Thesis structure

This thesis is divided into nine chapters. An overview of the concepts involved in both empirical and process-based forest models, and examples of available PBMs along with their application, is presented in Chapter 2. It describes the advantages and disadvantages of different kinds of models and the reasons for using them. The reasons for selecting the 3-PG model are considered.

A complete description of the 3-PG model is presented in Chapter 3, including the model concepts, assumptions and sub-models.

The data collected for model parameterisation and testing, and the methods for collecting it are presented in Chapter 4, while an analysis of the data is presented in Chapter 5. The procedure and the results of model parameterisation are shown in Chapter 6. Comparisons between observed data and predicted outputs from the model demonstrate the value of the model as a tool for predicting forest growth. Sensitivity analyses of the main factors that affect *Eucalyptus grandis* plantations are also presented in this chapter.

The results obtained from this research are intended for application at an operational scale and to contribute to decision -making processes in the forestry industry. The model has been applied in different regions of eastern Brazil and the results allow validation and an assessment of the limitations of the model.

Chapter 7 presents a discussion of the needs and opportunities for applying a process-based model in *Eucalyptus* plantations in Brazil and other regions.

Chapter 8 presents an integrated discussion about the research and the results obtained. An overall perspective is provided and the concepts and the results are evaluated. Finally, Chapter 9 presents the main conclusions of the study and a list of recommendations for further research.

The Appendices present complete tables of the data, figures, maps that have been used in the research and shows pictures that illustrate the research area.

Chapter 2

2. REVIEW OF FOREST MODELS

2.1. Forest models

Mathematical models have been used in forest industries to estimate forest growth and wood volume, and to predict future volume, for many years. The main reasons for using models are economic, to support forest planning and as aids to practical decisions in forest operations. They also provide information about production potential and the basis for decision making for land management. Models are essential as frameworks for research projects; they help to formulate and clarify hypotheses for research programs (Landsberg *et al.*, 1991). More recently, forest models are being used to quantify carbon sequestration by natural and forest plantations and to quantify net ecosystem exchange (Law *et al.*, 2000). Appropriate models can be important tools in the management of forest parks and public forest lands in ways consistent with conservation and sustainability concepts and they are becoming an important factor in forest industries through simulation of various scenarios for land use and landscape management amalgamating ecological and economic interests (Nelson, 2003).

Considerable progress has been made in forest modelling, in the last 20 years, as a result of increasing knowledge of tree growth, and improvements in computer technology. The most significant progress has been in the evolution of process-based models. For reviews see: Landsberg *et al* (1991); Ågren & Wikström (1993), Tiktak & Grisven (1995), Landsberg & Gower (1997), Battaglia and Sands (1998b), Kirschbaum(1999), Kirschbaum & Mueller (2001). There is a wide range of users of forest growth models, representing a variety of objectives and spatial scales. They include wood industrialists, foresters, forest managers, ecologists, students, economists and financial advisers (Battaglia & Sands, 1998b). Landsberg (2003) discussed the need for forest models in terms of different groups in society, including forest industries, 'the broader community' and the academic and scientific communities. According to Battaglia and Sands (1998b), no one model can satisfy all people and predictive requirements;

consequently a diversity of modelling approaches is required and the needs of the users are among the most important aspects to be considered in developing models. Regardless of whether it is necessary to understand the processes and their interactions within the system, or whether only the output of the system – e.g. predicted wood volume – is desired, the model must be developed at the appropriate level of detail and spatial and temporal scale for the problem to be addressed. To be used as management tools forest models must be useful in predicting growth and yield with the required level of accuracy and also aid in identifying potential productivity and the factors that might constrain growth in new areas. Practical models should also be useful for simulating possible risks involved in wood production, predicting the effects of different management practices, and evaluating environmental resources (water, fertility, climate) and the sustainability of production. If the management practices used in an area are poor, intensive wood production, particularly in fast growing forest plantations, can cause impoverishment of the soil (Fox, 2000). A calibrated process-based model can help in predicting that risk, allow the simulation of scenarios, and the evaluation of the consequences of silvicultural practices (Battaglia & Sands, 1998b).

The general increase in environmental awareness in society is resulting in calls for guarantees of sustainability and effective social participation in decisions about forests and their uses. Forest producers or management agencies are expected to provide reasonable answers to questions about environmental impacts, forest diseases, water use, nutrient cycling and mineralization. In all these areas, appropriate process-based models can help provide the information required to enhance decision-making processes (Landsberg, 2003).

Korzukhin *et al.*(1996) compared process and empirical models. They challenged the view that the two types are essentially different, and claimed that a continuum exists between them: most models use elements of both empirical and process-based approaches. Korzukhin *et al.* (1996) concluded that "process models offer significant advantages over empirical models for increasing our understanding of and predicting forest behaviour".

2.2. Traditional forest mensuration models

Forestry has a long tradition of using quantitative methods and models, especially for growth and yield analysis based on forest inventory (Scolforo, 1998). In traditional growth and yield research, the emphasis has been on the development of yield tables, or the more versatile equivalent (growth and yield models), with the aim of providing decision support for practical forest management (Mohren & Burkhart, 1994). Empirical growth and yield models, that rely on fitting functions to measurement data from a sample of the forest population of interest (Burkhart, 1999), are the tools that have been mainly used to provide decision support information that meets basic operational needs for evaluating various forest management scenarios (Mohren & Burkhart, 1994). Growth and yield predictions are used to assess profitability, determine harvesting schedules, estimate site potential and risks involved and evaluate silvicultural practices (Dye, 2001).

Empirical models are usually developed by examining correlative relationships from sample data and then applying statistical procedures to estimate the model parameters (Amateis, 1994). Growth and yield curves, generated from measurements made in at least two periods, provide information about the increment in volume in a particular location or region, often in relation to the "site index", which provides a measure of the productivity of the site, usually expressed in terms of average dominant tree height at one specific age (Scolforo, 1998). The curves may be periodically adjusted based on statistical analyses of new inventory data. Measurements commonly used to develop and validate these models include stand density, tree dominant height, stem diameter and stem taper function. Site index, particularly in short rotation forests, can be significantly affected by the nature of weather that occurs during growth periods, e.g. a long drought period reducing growth rates. To generate a site index it is necessary to have data from the specific area. This reflects the results of interactions between the species and local soil, climate and the management practices applied (Scolforo, 1998). The concept of site index therefore limits the applicability of models based on it to the areas where the measurements were made.

Empirical growth models may be at different levels of detail (Maestri *et al.*, 1995). While useful and widely used, empirical models have well-recognized limitations (Korzukhin *et al.*, 1996). They often are not transportable to other data sets, and the problems of extrapolation beyond the available data are well known (Amateis, 1994). One of the main problems is the incapacity to detect the effects of fluctuations in growing conditions without repetitive and frequent measurements.

This category of models is used by most forestry companies for planning, for estimating timber volumes, organizing harvest scheduling and optimising timber supplies to mills. They may be size class models, singletree models, or apply to a whole stand, depending on the detail required. These models are derived from tree size data from stands in a range of ages, site indices, stand densities and management conditions (Almeida *et al.*, 2003). These models are powerful tools to estimate timber diameter distribution and volumes; they are often used to optimise the final product.

2.3. Process-based forest models (PBMs)

Different definitions of process-based forest models can be found in the literature. Landsberg & Gower (1997) defined PBMs as - "models that are based on the processes, or mechanisms, underlying the responses to change (stimuli) of the system under study". Mäkelä *et al.* (2000) defined a PBM as - " a procedure by which the behaviour of a system is derived from a set of functional components and their interactions with each other and the system environment through physical and mechanistic processes occurring over time".

In this study, a PBM is defined as "a mathematical model used as a tool to predict forest growth and study the interaction between the forest and its dynamic environment". This definition is presented to adapt the PBM concepts to the objectives of the research as practical application in forest plantations. PBMs should have the ability to predict the effects of changes in key environmental variables such as climate, soil nutrition and water availability.

The application of PBMs in natural forests is even more complex than in forest plantations, because of forest heterogeneity and differences in species behaviour. These problems are minimized in fast growing, homogenous forest plantations where detailed information is available for each genotype and stand, silvicultural practices such as soil preparation, weed control and fertilization are uniform, and there is detailed knowledge of soil characteristics. Short rotation forests grown for pulp, with rotation lengths varying between 5 to 7 years, in countries such as Brazil and South Africa, present ideal systems to test and validate forest PBMs (Almeida *et al.*, 2004a).

According to Battaglia and Sands (1998b) only a few PBMs have been applied as tools in forest management, whereas in agriculture various process and semi-empirical models are being used as part of crop decision-making. Generally, process-based forest models are considered as academic tools, used only for research purposes by those interested in translating causal relationships into mathematical equations (Larocque, 1999). Some of the reasons for this lack of application are the complexity and difficulty of modelling the effects of environmental changes affecting plants over long periods, and the requirements for complex data to calibrate and validate these models. Another important reason for lack of adoption and application is that - perhaps particularly in Brazil - education in the biophysical concepts that underlie PBMs is separate from training in forest. Consequently, forests and forests managers have difficulty understanding the relevance and validity of these models. Nevertheless, there are evidences of increasing interest in PBMs.

The interest of forest industries in PBMs in recent years is driven by the need to answer questions that cannot be answered using empirical models, such as: What is the effect of long drought periods on wood volume and quality? What is the potential productivity of a site where plantations have not previously been grown and for which there is no inventory data? What are the limitations and constraints to obtaining high productivity and how is it possible to control these? How much carbon can be sequestered by a forest? The use of PBMs is also being proposed to answer controversial questions about forest sustainability, use of water and soil fertility (Sands, 1995; Almeida, 2000). The freedom to adapt models for operational needs in terms of accuracy is an important factor in the adoption of PBMs for practical use.

As noted earlier, PBMs are likely to include both causal and empirical components and different levels of detail. Relatively simple, climate-driven models can be used to estimate potential plantation productivity, provide a basis for comparison between regions and evaluate their limitations for different land uses. More detailed, mechanistic models are more appropriate for understanding the way systems function, and are more likely to provide information about local constraints and the factors that limit productivity (Landsberg, 2003). Currently available process-based models can provide good estimates of growth and biomass productivity at various scales; combined with conventional models they can provide information of the type required by managers and planners (Landsberg, 2003; Almeida *et al.*, 2003). PBMs therefore provide powerful tools to aid decision-making in commercial forestry (Landsberg, 2003).

The adoption of a PBM by forest managers is more likely if the model is developed with the direct involvement of the final users, clearly identifying their objectives, needs and applications. The model should have a simple and transparent structure, be simple to operate and appropriately documented, use only readily available data as input, and be supported by expert advice and services (Sands *et al.*, 2000). Almeida *et al.* (2003) presented an example of linking process-based and empirical models, and the practical application of both categories, emphasising the possibilities and benefits that each model can provide. In their example, forest growth, in terms of mean annual increment (MAI) was estimated by the PBM and the empirical model was applied to estimate stem diameter distribution, which is important for product type definition.

For practical applications of PBM and empirical models, managers and forest planners should consider the potential of each one and be able to use it according to specific needs, taking into account (Almeida *et al.*, 2004b) the accuracy and resolution needed, the availability of inputs, and the specific output required (Battaglia & Sands, 1998b). Future forest growth models should be simple, able to simulate processes using a spatial approach, integrated with Geographical Information System (GIS) and remote sensing techniques to obtain the accuracy and resolution needed at a range of scales, and be adapted to the needs of different levels of users. Model outputs must be easily updated using real climate and environmental drivers that affect forest growth. Using these techniques, future development should focus on models that are able to reduce forest inventory effort and maintain, or improve, the accuracy of estimates of forest growth over large areas. This will be more critical in fast growing forest plantations where variations in climate have a strong and immediate effect on final productivity.

2.4. Comparison between PBMs

Some comparisons between PBMs can be found in previous studies: for reviews see Tiktak and Grisven (1995), Landsberg and Gower (1997), Battaglia and Sands (1998b), and more recently, Kirschbaum & Mueller (2001), Schwalm and Ek (2001), Johnsen *et al.* (2001) and Landsberg (2003),. These reviews generally reinforce the point that each model has specific characteristics and was developed for different purposes. However, despite different approaches, equations and assumptions, these models may generate similar outputs. The level of complexity, resolution and generality are variable between models and are significant factors in determining the potential use and practical application of the model. Battaglia and Sands (1998b) presented good examples of these variations and their results.

Some of the PBMs most frequently cited in the recent literature have been selected for review here because they can be applied to *Eucalyptus* plantations. This section provides a brief description of these models: 3-PG, CENTURY, CenW, FOREST-BGC, ProMod and Biomass.

3-PG

Process-based models have been, so far, of limited utility for practical forest management because they require many input data and parameter values that are not readily available in all situations. The 3-PG model developed by Landsberg and Waring (1997) is a simple process-based model based on solid physiological concepts, most of which are simple in their nature (see Chapter 3). The development of 3-PG was an attempt to bridge the gap between conventional, mensuration-based growth and yield, and process-based carbon balance models. Most of the parameter values used in the model can be readily determined by calibration against experimental data. The accuracy of the output depends directly on the quality of input data and the parameterisation process. 3-PG produces a range of outputs (Sands, 2002) (see Table 3.2) including output variables of interest to forest managers, land use planners and researchers (Landsberg *et al.*, 2000).

3-PG has been applied and used successfully for different purposes and for various forest types occurring in different regions with a range of climates. Almeida *et al.* (2003) showed that 3-PG can be used to estimate biomass productivity and linked it to an empirical model to disaggregate stand productivity into final wood products. Coops *et al.* (1998), Coops *et al.*(2001a), Coops & Waring (2001e), Coops & Waring (2001f), Tickle *et al.* (2001b) and White *et al.* (2000) have demonstrated the application of 3-PG to large areas using spatial data bases or GIS. Dye (2001) used 3-PG to predict growth and water use of *Pinus patula* in South Africa. Landsberg *et al.* (2000), Landsberg *et al.* (2001) and Landsberg *et al.* (2003) evaluated the model's performance using data from experimental and commercial plantations in Australia and New Zealand, the UK, the United States, South Africa, Sweden and Finland. Landsberg & Waring (2003) used it to bridge the gap between CO_2 flux measurements, physiological observations and inventory data. Similarly, Waring & McDowell (2002) used 3-PG to establish the limits of carbon fluxes for Douglas-fir. Law *et al.* (2000) investigated net ecosystem productivity, net primary productivity and water vapour exchange, and compared predictions by 3-PG and Pnet-II (Aber & Federer, 1992) with traditional measurements of net primary production (NPP, P_N). Finally, Sands & Landsberg (2002) presented a detailed procedure for the parameterisation of 3-PG for *E. globulus* growing in Tasmania and Western Australia and evaluated the performance of the model. The most recent changes to the model are presented by Sands (2002) as a user-friendly version (3-PG_{PJS})

developed as Visual Basic macros using Excel spreadsheets[1]. The analyses and results presented in this study used the 3-PG$_{PJS}$ version 2.3 (August 2002).

The 3-PG model has been selected as the model to test the hypothesis of this study; the reasons for the choice are presented later.

CENTURY

The CENTURY model, developed by Parton *et al.* (1987) is a general agro-system model of plant-soil nutrient cycling. It simulates carbon and nutrient dynamics for different types of ecosystems. CENTURY, currently available as Version 5, is composed of soil organic matter/decomposition, water budget, grassland/crop and forest production sub-models, with management and events scheduling functions. It computes the flow of carbon, nitrogen, phosphorus, and sulphur dynamics through the model's compartments on a monthly time step. CENTURY provides the possibility of simulating plant production for different environments with the flexibility of changing the plant community type during the model runs, e.g. changing land use from pasture to forest.

CENTURY was originally developed for use in grasslands and agricultural system rotations, for analysing the effects of climate change and management practices on productivity and soil sustainability. Later versions of the model include plant production models for forests.

The model requires the following driving variables as inputs:

- Monthly precipitation, average maximum and minimum air temperature
- Soil texture
- Plant nitrogen, phosphorus, and sulphur content
- Lignin content of plant
- Atmospheric and soil nitrogen inputs

[1] The software and supporting technical material are available free from the website www.ffp.csiro.au

- Initial soil carbon, nitrogen (phosphorus and sulphur optional)

The soil organic matter sub-model includes active, slow and passive soil organic matter pools with different potential decomposition rates, above and below-ground litter pools and a surface microbial pool, which is associated with decomposing surface litter. The water budget model calculates monthly evaporation, transpiration, water content of the soil layers, snow water content and saturated flow of water between soil layers. It is used to modify soil organic matter dynamics and plant production. Transpiration is calculated empirically as a function of leaf mass, precipitation and potential evapotranspiration.

CENTURY contains two plant production sub-models; a grassland/crop sub-model and a forest production sub-model. Both plant production models assume that the monthly maximum plant production is controlled by moisture and temperature, and that maximum plant production rates are decreased if there are insufficient nutrient supplies. The forest model simulates the growth of deciduous or evergreen forests in early and mature stages.

The soil organic matter sub-model of CENTURY has been widely used in many of the ecosystem process models that simulate soil organic matter, e.g. CenW (Kirschbaum, 1999), G'DAY (Comins & McMurtrie, 1993), and has been used and tested for a wide variety of terrestrial ecosystems and land management practices (Parton *et al.*, 1983; Parton *et al.*, 1987; Metherall *et al.*, 1993; Gilmanov *et al.*, 1997; Clausnitzer *et al.*, 1999; Peng & Apps, 1999; Peng, 2000; Manies *et al.*, 2000). The model includes several empirical relations and a large number of parameters.

CenW

A full description of CenW (Carbon, Energy, Nutrients and Water) is presented by Kirschbaum (1999). The model simulates fluxes of carbon and water, interception of solar radiation and nutrient dynamics through the plant and organic matter pools. The parameters values can be modified for different species and the model runs on a daily time step. Carbon gain is based on light absorption, temperature, soil water and foliar nitrogen concentration. Respiration is calculated as a constant fraction of photosynthetic carbon gain or as a function of temperature and nutritional status. Some carbon is lost in respiration and the remainder is used for plant growth distributed in stem, roots, branches, bark and foliage. Litter is assumed to be a constant fraction of biomass pools and allocation is determined by nutrient level. CenW uses the Penman-Monteith equation (Monteith, 1965) to calculate the water balance (Kirschbaum, 1999; Kirschbaum *et al.*, 2001). CenW calculates a detailed nutrient cycle, considering nitrogen coming from external sources (e.g. in rainfall) or by decomposition of organic matter. This is an important factor if sustainability aspects in terms of nutrient availability to the trees and site carbon budgets are to be considered.

CenW requires daily meteorological data as inputs, including minimum and maximum temperature and rainfall. One of the most significant limitations to its use as a practical management tool is the detailed soil and physiological parameters required to generate accurate outputs. Landsberg (2003) made the following statement about CenW: "CenW was not designed as a tool for management, but is useful as an attempt to link in one model all the biophysical processes considered important in the growth of trees and timber production. Its parameterisation for other stands will be difficult because of the model's demands for data, but the concepts and formulation must be of value, and provide insights into process interactions and the basis for simplification or further developments in this area".

Forest-BGC

FOREST-Bio-Geo-Chemical simulation model (FOREST-BGC) developed by Running & Coughlan (1988) and updated by Running & Gower (1991), is probably one of the best known and most widely used process-based models (Landsberg, 2003). It calculates carbon, water and nutrient cycling through forest ecosystems. FOREST-BGC runs with a daily step time calculating photosynthesis, maintenance respiration, and water balance. Carbon allocation to roots, stem, foliage, bark and branches, and nutritional status and ecosystem carbon is performed annually. The model is relevant to forest landscapes on medium and large scales and it can be driven by data from remote sensing (Coops *et al.*, 2001a; Chiesi *et al.*, 2002). As with other PBMs, FOREST-BGC involves some simplification to facilitate its application at regional spatial and temporal scales. The most important of these are that the trees are represented as pools cycling carbon, water and nitrogen; the canopy is represented by leaf area index (LAI) (Waring & Running, 1998). The model considers LAI as the main variable for calculating canopy interception, transpiration, respiration, photosynthesis, carbon allocation and litterfall (Running & Coughlan, 1988). Daily meteorological data are required from local sites. In some cases these are obtained using the MT-CLIM climate simulation package (Thornton & Running, 1999).

FOREST-BGC is being applied with success for different purposes in a wide range of environments and forest types, varying from temperate to Mediterranean climates (Hunt *et al.*, 1991; Running & Gower, 1991; Milner *et al.*, 1996; Korol *et al.*, 1996; Hoff *et al.*, 2002; Chiesi *et al.*, 2002).

ProMod

ProMod, developed by Battaglia and Sands (1997), was initially applied to predict growth of *Eucalyptus globulus* in Tasmania. More recently Sands *et al.* (2000) parameterised the model for *Eucalyptus nitens* and *Pinus radiata* also in Tasmania. The main output is peak mean annual increment (MAI). However, other outputs include water use efficiency, evapotranspiration, leaf area index, and stemwood. They are all responsive to climatic conditions and site factors. The model inputs are: site latitude, maximum available soil water capacity, fertility, status, daily maximum and minimum air temperatures, incoming solar radiation, precipitation, vapour pressure deficit (VPD) and open-pan evaporation. It uses empirical relationships to represent biomass partitioning processes but light and water use efficiency are derived from mechanistic sub-models. The heart of ProMod is a model of canopy photosynthesis that uses physiological principles (Kirschbaum *et al.*, 2001). Net canopy production is calculated daily and integrated for annual production. Biomass partitioning is applied on an annual step time (Sands *et al.*, 1999).

ProMod has been used mainly in Australia as shown the references. Mummery & Battaglia (2001) presented a spatial application of ProMod across Tasmania, producing site productivity and suitability maps for *Eucalyptus globulus*. Sands *et al.* (1999) used the model to predict the responses of *Eucalyptus globulus* to irrigation, and the profitability of irrigation. Battaglia *et al* (1999) hybridised ProMod with an empirical growth model (NITGRO) developed for *Eucalyptus nitens* plantations. The peak MAI predicted by ProMod was used to infer site index needed to drive NITGRO. The hybrid model was used to predict height (m), volume growth (m^3 ha^{-1}), stand basal area (m^2 ha^{-1}) and MAI (m^3 ha^{-1} $year^{-1}$) in 16 plantations of *E. globulus*.

BIOMASS

The BIOMASS model was described by McMurtrie *et al.* (1990). It is a detailed process-based model that simulates tree growth and water balance in relation to their nutrition. There are a series of sub-models that describe various physiological process affecting tree growth (McMurtrie, 1993). Carbon gain is based on radiation interception, using canopy structure and foliage photosynthesis characteristics and respiration losses. Carbon partitioning to stems, branches, foliage, roots and litterfall is implemented by partitioning coefficients that vary over the annual cycle and with leaf nitrogen contents. Litterfall is subtracted from each component with rates allowed to vary over an annual cycle (McMurtrie & Landsberg, 1992). The respiration rates are based on surface area for stem, branch and foliage and per unit dry weight for roots. These rates are affected by temperature.

BIOMASS uses the Penman-Monteith equation to calculate water balance. Canopy conductance calculations are carried out for each of threes canopy layers. The hydrologic sub-model calculates rainfall interception, soil evaporation and understorey evaporation and the soil water balance considers two soil layers; the root depth must be supplied as a parameter value.

The model runs on a daily step time and requires meteorological input data and some site data as latitude and longitude, tree density, soil holding capacity, physiological parameters of the trees species and root depth.

BIOMASS has been used in a number of studies in Australia: Hingston and Galbraith (1998) and Hingston *et al.* (1998) applied it yo predict water use and stem growth in *Eucalyptus globulus* and Sheriff *et al.* (1996) used it to assess climatic effects on net annual carbon gain, stem biomass and transpiration for *Pinus radiata*. McMurtrie *et al.* (1994) used BIOMASS to assess climatic factors controlling the productivity of pine stands in Australia, New Zealand, the USA (Wisconsin) and Sweden.

Resume of the PBMs

Table 2.1 synthesises the main aspects of the six PBM described above.

Table 2.1. Main characteristics, references and areas of application the process-based models compared in this study.

Model Name or Acronym	References	Characteristics	Step time	Main Applications
3-PG	(Landsberg & Waring, 1997; Coops, 1999; White *et al.*, 2000; Law *et al.*, 2000; Landsberg *et al.*, 2000; Landsberg *et al.*, 2001; Dye, 2001; Tickle *et al.*, 2001a; Coops *et al.*, 2001a; Coops & Waring, 2001a; Tickle *et al.*, 2001b; Coops *et al.*, 2001b; Coops & Waring, 2001d; Coops & Waring, 2001f; Sands, 2002; Waring & McDowell, 2002; Sands & Landsberg, 2002; Whitehead *et al.*, 2002; Landsberg & Waring, 2003; Landsberg *et al.*, 2003; Almeida *et al.*, 2003; Hirsch *et al.*, 2003; Almeida *et al.*, 2004a; Almeida *et al.*, 2004b)	Stand-level, single species, even-aged, radiation energy conversion	Monthly	✓ Forest industry ✓ Forest management ✓ Research
CENTURY	(Parton *et al.*, 1987; Metherall *et al.*, 1993; Gilmanov *et al.*, 1997; Peng & Apps, 1999; Manies *et al.*, 2000)	Soil-based model	Monthly	✓ Grasslands management ✓ Research
CenW	(Medlyn, 1998; Kirschbaum, 1999; Kirschbaum, 2000; Kirschbaum & Mueller, 2001)	Detailed process-based model with a large number of parameters. Outputs are based on pools carbohydrate concepts	Daily	✓ Forest research ✓ Carbon accounting
Forest BGC	(Running & Coughlan, 1988; Running *et al.*, 1989; Running & Gower, 1991; Korol *et al.*, 1996; Kimball *et al.*, 2000; Hoff *et al.*, 2002; Chiesi *et al.*, 2002)	Considers canopy interception, carbon allocation above and below-ground, litterfall, decomposition and nitrogen mineralization. The model uses LAI to quantify the forest structure and apply in regional scale	Daily /annual	✓ Ecosystem management, ✓ Research
ProMod	(Battaglia & Sands, 1997; Battaglia & Sands, 1998a; Sands *et al.*, 1999; Battaglia *et al.*, 1999; Sands *et al.*, 2000; Mummery & Battaglia, 2001; Pinkard & Battaglia, 2001)	Produce NPP and convert in site productivity based on canopy photosynthesis	Daily /annual	✓ Forest industry ✓ Forest management ✓ Research
Biomass	(McMurtrie & Landsberg, 1991; McMurtrie, 1991; McMurtrie & Landsberg, 1992; McMurtrie *et al.*, 1992a; McMurtrie, 1993; McMurtrie *et al.*, 1994; Sheriff *et al.*, 1995; Sheriff *et al.*, 1996; Hingston *et al.*, 1998; Hingston & Galbraith, 1998; Snowdon *et al.*, 1999)	Detailed model of carbon and water balance	Daily	✓ Research ✓ Process test

Table 2.2 Main advantages and disadvantages observed in the use of PBMs and empirical forest models applied in forest plantations.

	PBM	Empirical model
Advantages	• Integration of the soil, plant, climate factors that drive forest development and growth • Explains the processes and the factors that affect forest growth • Quantifies the climate and management effects on forest growth • Application in lands where forest plantations have not previously been grown, allowing the evaluation of the potential production outside range of available growth measurements • Provide a framework for research and understanding system operations • Wide variety of outputs	• Easy to use and apply • Widely used, accepted and well established • Small variety of data requirement • Diameter distribution and respective wood products outputs
Disadvantages	• Number of parameters and availability of good quality data to calibrate, validate and test the model • Uncertainty of physiological assumptions and constraints on production • Spatial variation of climate and soils properties • Need for expertise and multidisciplinary skills	• Results are not transportable to other locality (Amateis, 1994) • Accuracy is dependent on forest inventory data. Large inventory data sets required to develop specific growth curves • Cannot detect effects of climate variation or management practices on forest growth • Use the concept of site index that is dependent of soil fertility and local climate

2.5. Process-based model selection.

One of the aims of this research was to select and adapt a PBM to become a practical and analytical tool for estimating forest plantation growth rates. It had to be capable of quantifying the effects of the main management practices and climate variability on these rates, and allow comparisons between different genotypes. Ideally, the model should be flexible enough to predict potential productivity in lands with different previous uses.

The number of parameters required can be a limiting factor in some PBMs. Some parameters are extremely difficult to measure, or to obtain reliable values from the literature to apply in different environmental conditions. The models are more susceptible to uncertainty in these values when they are highly sensitive to these parameters. A PBM is not necessarily improved by the addition of more parameters or information if there are uncertainties in our knowledge or information about the mechanisms being considered. Increasing the number of processes included in a model also results in increasing uncertainty (Andersson *et al.*, 2000b). So the requirements for model performance and needs for data must be balanced against the resources that exist to obtain data to run the model.

Lack of knowledge about the differences in soil nutrition and climate (e.g. drought periods) and their effects on forest potential productivity, affect the quality of decision-making processes related to wood production (volume and quality) and ecosystem integrity. Empirical models do not provide answers to some critical questions that arise in the planning and wood production process, particularly in relation to factors that are affected by forest management and climate variation (Mohren & Burkhart, 1994; Constable & Friend, 2000). Process-based models simulate the growth patterns of trees in terms of biophysical mechanisms that define their growth in response to environmental conditions and management practices (Landsberg & Gower, 1997).

The model selected and tested in this thesis was the 3-PG model of Landsberg and Waring (1997). 3-PG can provide accurate estimates of growth rates over short rotations, quantify the influence of climate on productivity and estimate potential productivity in areas where forest plantations have not yet been grown. It can also be used as a tool to quantify the risks associated with external factors, e.g. drought or disease, on forestry production. The selection of the 3-PG model was also influenced by the following practical reasons:

- The model was been tested in different kinds of forests and environments (Landsberg *et al.*, 2003);

- The model is based on the well established principles of energy conversion, modified by factors that constrain it, and carbon allocation based on allometric relationships;

- The model is relatively simple to use and has a low number of parameters when compared with others PBMs;

- The monthly interval for climate inputs allows use the model in areas where daily data are not available.

- The software is available, well documented (Sands, 2002) and easy to use when compared with that of some other PBMs;

- 3-PG can be applied in forest research, operation and planning activities.

- 3-PG can generate 58 different outputs that can be used to understand the processes involved in tree growth and the integration of the outputs demonstrates the robustness of the estimations. Most of these outputs can be tested against observed data to evaluate the model accuracy; and

- The model can be integrated with empirical models (Almeida *et al.*, 2003) and with GIS (Tickle *et al.*, 2001b; Coops & Waring, 2001c; Coops & Waring, 2001f) to provide a hybrid tool for predicting growth and wood products.

Despite these advantages 3-PG has not previously been used in operational scale forest management. Evaluation and successful validation of the model are fundamental in the decision for it to be adopted. Vanclay & Skovsgaard (1997) discussed the importance of model evaluation, which involves several interrelated steps that must be followed. These are the logical and biological principles of the model, statistical properties, characteristics of errors, residuals and sensitivity analyses. Every model should be adapted to the main local characteristics of the situation in which it is to be used, however concepts such as energy conversion and constraints affecting the plants do not change; they are universally applicable.

Chapter 3

3. THE 3-PG MODEL

3.1. Concepts, use and general model description

The model called 3-PG (**P**hysiological **P**rinciples in **P**redicting **G**rowth), developed by Landsberg and Waring, (1997) and modified by Sands and Landsberg (2002) is a simple process-based forest growth model. Relative to other PBMs (cf. Chapter 2.4) it has few parameters. The time step is monthly and the state of the stand is updated each month. The model requires climatic data inputs, a basic knowledge about the local soil water holding capacity, an indication of soil fertility and initial tree numbers per hectare. It also requires initial values for stem (including bark and branches), foliage and root mass per hectare to initialise the model at a selected age (see Table 3.2). This information can be obtained by direct methods, or estimated when experimental values are not available. The climate input data required are values for monthly total short-wave incoming radiation (from which photosynthetically active radiation may be calculated), monthly mean temperature and VPD, and total monthly rainfall. 3-PG can be run with either monthly average weather data or climatic data observed for each month during a particular period.

3-PG is driven by radiation; the efficiency with which radiation is converted to biomass is constrained by environmental modifiers, viz.: temperature, atmospheric vapour pressure deficit (VPD, *D*), frost, available soil water (SW), stand age and site nutritional status. Nutritional status is described by an index called the fertility rating (*FR*) that ranges from one for a site where nutrients are not limiting to growth down to zero for the poorest sites. All modifiers vary from zero (representing total limitation), to one (no limitation). 3-PG essentially consists of five simple sub models: these describe the assimilation of carbohydrates, the distribution of biomass between foliage, roots and stems, the determination of stem number, soil water balance, and the conversion of biomass values into variables of interest to forest managers (Sands & Landsberg, 2002). Biomass partitioning is affected by growing conditions and tree sizes. The model has a function for stem mortality and a water balance sub-model. The stand properties are determined by biomass pools and assumptions about specific leaf area, branch and bark fractions. Wood volume is calculated from stem mass divided by wood density.

3-PG is a generalised stand model (i.e. it is not site or species-specific), but needs to be parameterised for individual species or different genotypes within a species. The model incorporates simplifications of some well-known relations, with the aim of describing complex physiological processes so that they can be applied to plantations or even-aged, relatively homogeneous forests. Waring and McDowell (2002) described these simplifications as: (1) constant ratio of net primary production to gross photosynthesis (gross primary production, GPP, P_G); (2) canopy conductance approaches a maximum above a leaf area index (L^*) of 3.0; (3) the ratio of actual/potential photosynthesis decreases in response to the most restrictive (monthly) environmental limitation; (4) the fraction of production not allocated to roots is partitioned among foliage, stem and branches based on species-specific allometric relationships with tree diameter (DBH); (5) canopy quantum efficiency (α_c) is assumed to increase linearly with soil fertility. Carbon allocation to stems and foliage is on a single-tree basis and relies on the ratio of the derivatives of the allometric equations describing leaf and stem mass in terms of stem DBH. The ratio of foliage to stem allocation declines as DBH increases. The model includes a stem mortality function based on the self-thinning rule, which has been expressed as the 3/2-power law (Drew & Flewelling, 1977).

Figure 3.1 presents a general flow of 3-PG model indicating the relation between environmental factors and their effects in the model.

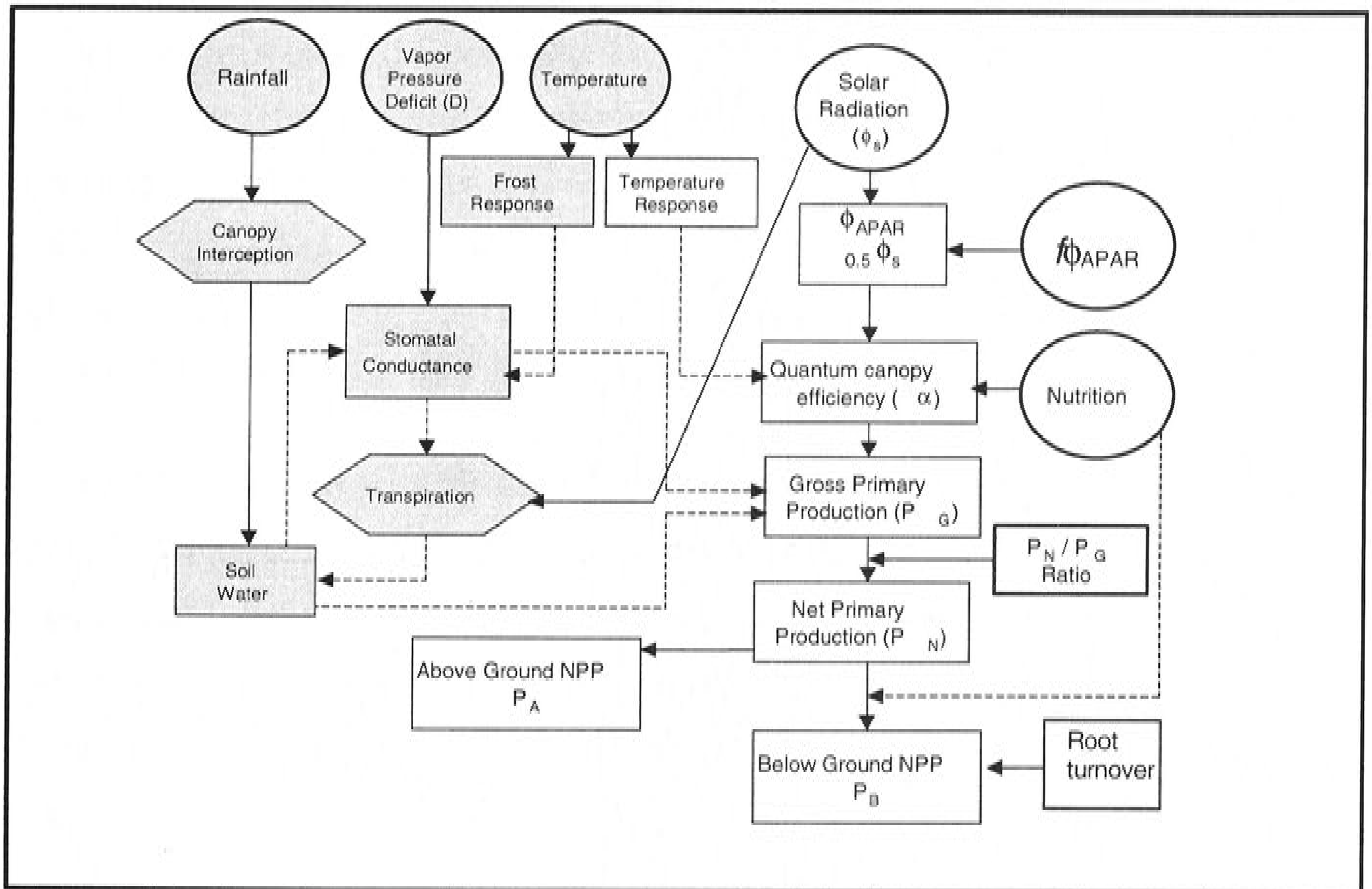


Figure 3.1. Flow diagram of 3-PG. Grey boxes contain the components associated with water balance and the clear boxes contain components associated with radiation conversion and the carbon balance (adapted from Coops & Waring (2001f) and Tickle *et al.* (2001b)).

3.2. 3-PG sub-models and main features

The following section describes the main components of 3-PG and their relationships in the model.

3.2.1. Radiation interception, net and gross primary production

The main principle underlying 3-PG - the absorption of photosynthetically active radiation (PAR[2], ϕ_p, (mol m^{-2})) by tree canopies and conversion to carbohydrates by the process of photosynthesis, leading to the production of biomass - is widely accepted as a basis for modelling the growth of plant communities. (Landsberg, 1986; Russell *et al.*, 1989; Wang *et al.*, 1991; McMurtrie *et al.*, 1994; Landsberg & Hingston, 1996; Landsberg & Gower, 1997; Landsberg *et al.*, 1997; Bartelink *et al.*, 1997; Medlyn, 1998; Ruimy *et al.*, 1999; Brunner & Nigh, 2000; Friday & Fownes, 2001; Wang, 2001). PAR is radiation between the wavelengths 400 - 700nm; i.e. radiation in the visible part of the spectrum.

Calculations of the absorption of PAR and canopy photosynthesis can become highly complex, but Monteith (1977) showed that there is generally a linear relationship between absorbed photosynthetically active radiation (APAR, ϕ_{pa}, mol m^{-2}) and biomass production. The ratio between APAR and the biomass produced is defined as radiation use efficiency (RUE, ε) given by the slope of this linear relationship. The relationship is more reliable when determined over relatively long periods of time (weeks or months) (Landsberg *et al.*, 1997). Although efficiency is technically dimensionless, ε has units of dry mass produced per unit absorbed radiation (g DM MJ^{-1}) (Landsberg *et al.*, 1997). The total biomass produced over any time interval can be expressed by equation 3.1.

$$P_n = \varepsilon \int \phi_{pa} dt \qquad (3.1)$$

where ϕ_{pa} is the photosynthetically active solar radiation absorbed by the canopy and *t* is the time measured in days or months.

Multiplying APAR by radiation use efficiency (ε) to get canopy dry mass production is a simplification of a complex process. Accurate simulation of canopy photosynthesis requires detailed models that divide canopies into multiple

[2] Commonly used variable names are frequently abbreviated and used in the text, the symbols are used in mathematical expressions.

layers with appropriate leaf area and leaf angles in each layer. (Norman & Campbell, 1989; Wang & Jarvis, 1990). Numerical integration of photosynthesis, for each leaf layer yields canopy photosynthesis but requires considerable information about canopy architecture. A more accurate model, which remains mathematically tractable, is provided by McMurtrie *et al.* (1990), who deal with discontinuous canopies, direct and diffuse radiation and the proportion of foliage below photosynthetic light saturation under given conditions. They treat the canopy in three layers and assume a standard leaf photosynthesis curve. dePury & Farquhar (1997) used a single-layer sun-shade model, with direct and diffuse radiation components; this performed as well as a detailed multi-layer model, despite the simplifications.

Photosynthetically active radiation can be estimated as a function of short-wave solar radiation (ϕ_s) where 1MJ of ϕ_s is equivalent to 2.3 mol PAR. The analysis of this relation in the studied sites is presented in Chapter 5 and by Almeida & Landsberg (2003).

It should be noted that ε can be expressed in different units (g MJ^{-1} or mol C (mol photon)$^{-1}$) and does not usually include below-ground biomass, root turnover or litterfall. It also does not incorporate constraints on radiation utilisation by trees. In 3-PG ε is calculated as above-ground P_N produced per unit utilisable ϕ_{pa}. The symbol α_c, called canopy quantum efficiency (molC/mol photons absorbed) [3] is used for GPP (see Landsberg and Waring (1997)). This allows direct comparison with detailed models or measurements of canopy photosynthesis (Wang *et al.*, 1992) and allows estimation of the variation in above-ground productivity caused by differences in below-ground allocation of carbon that result from different growing conditions (Landsberg & Waring, 2003).

[3] "The term 'canopy quantum efficiency' may be slightly misleading: the quantum photosynthetic efficiency of leaves normally refers to the rate of carbon uptake per unit absorbed radiant energy at low photon flux densities. Integrating over time for canopies, the production of carbon per unit APAR is more accurately described as radiation use efficiency of the canopy. However, this is usually applied to dry mass production (see Landsberg *et al.* 1997) and, because the parameter used in 3-PG describes the moles of C produced per mol quanta absorbed. It will retain the term canopy quantum efficiency.

To calculate the light intercepted by the canopy it is necessary to know the leaf area density of the forest canopy. The LAI in 3-PG is determined from foliage mass and the values of specific leaf area (σ, (m^2 kg^{-1})) at different stand ages. The model uses Beer's law (equation 3.2) to calculate APAR, assuming that the long integration time (monthly time step) reduces non-linearities and the consequences of canopy heterogeneity to non-significant levels. The equation is:

$$\phi_{pa} = (1 - e^{-kL^*})\phi_p \qquad (3.2)$$

where ϕ_p is the photosynthetically active radiation and k is the interception coefficient.

To calculate P_G in 3-PG the theoretical maximum canopy quantum efficiency value of α is multiplied by modifiers (f_N, the site nutrition modifier represented by an index - the fertility rating (FR); soil water (f_θ), days of frost (f_F), vapour pressure deficit (f_D), air temperature (f_T) and stand age (f_{age}), which reduce α to an effective value α_C.

$$\alpha_C = f_T f_F f_N \varphi \alpha \qquad (3.3)$$

All the modifiers take values between 0 (poor conditions) and 1 (optimal (non-limiting) conditions); the water modifier (φ) takes the lower of the values of f_D and f_θ. The modifiers f_D and f_θ reduce both canopy conductance (g_c) and α_c through a multiplier φ (called PhysMod in the 3-PG code) defined by:

$$\varphi = f_{age} \min\{f_D, f_\theta\} \qquad (3.4)$$

The temperature (f_T), frost (f_F) and nutrition (f_N) modifiers affect α_c multiplicatively because these are assumed to have independent effects on photosynthesis. Frost effects were not considered in this study because frost does not occur in the studied area, so $f_F = 1$. The age-dependent modifier f_{age} simulates possible decline with age of hydraulic properties or caused by change in stand structure and relative competition between trees (Binkley *et al.*, 2002b), and hence stand productivity. Setting $f_{age} = 1$ the φ factor provides a good index (from 0 to 1) of the effects of climate on forest growth. For full details see Landsberg and Waring (1997) and Sands and Landsberg (2002).

From equations 3.1 - 3.4, GPP (P_G) is calculated from

$$P_G = \alpha_c \phi_{pa} = f_T f_F f_N \alpha \varphi \phi_{pa} \tag{3.5}$$

The ratio of NPP to GPP is taken to be constant at 0.47 ± 0.04 (Arneth *et al.*, 1998; Waring *et al.*, 1998) which eliminates the need for calculation of losses by respiration. This assumption has been challenged (Mäkelä & Valentine, 2001) but it has been shown to be empirically well supported in middle aged stands (Landsberg & Gower, 1997; Malhi *et al.*, 1999; Law *et al.*, 2000; Law *et al.*, 2001a).

The maximum value of the canopy quantum efficiency used in the original version of the model (Landsberg & Waring, 1997) was taken to be 0.03 mol C (mol photons)$^{-1}$, equivalent to 1.68 gm C MJ^{-1} PAR, on the basis of work by Waring *et al.* (1995) at Harvard Forest, a deciduous forest in north-west Massachusetts. Law *et al.* (2000) used 0.04 for *Pinus ponderosa*. An analysis by Landsberg and Hingston (1996) indicated that *Eucalyptus* plantations in Western Australia were producing above-ground biomass at rates that indicated radiation conversion efficiency of up to 0.05 mol C (mol quanta)$^{-1}$ or 2.73 g C MJ^{-1} (APAR) – approaching the value that seems to be about the norm for intensively managed field crops (Landsberg *et al.*, 1997). Correcting for (estimated) below-ground production, converting the biomass to carbon and allowing for litterfall indicated that values of $\alpha_c \geq 0.07$ mol C (mol quanta)$^{-1}$ would not be unrealistic (Landsberg & Waring, 2003). This is taken as the upper allowable limit (α) for calibrating 3-PG (Sands & Landsberg, 2002), although a tuned value of $\alpha = 0.08$ mol C (mol quanta)$^{-1}$ was used by Stape (2002) in hybrids of *Eucalyptus grandis X urophylla* in north-eastern Brazil. Chapter 5 presents the α value obtained in a fertilization-irrigation experiment at Aracruz region.

3.2.2. Temperature modifier

The effects of air temperature on forest growth have been reported in previous studies (Raulier *et al.*, 2000; Morris, 1977; Zhang *et al.*, 1994; Cromer, 1995; Bartelink *et al.*, 1997; Battaglia *et al.*, 1998; Kirschbaum, 1999; Day, 2000; Landsberg *et al.*, 2000; Turnbull *et al.*, 2001; Sands & Landsberg, 2002; Vostral *et al.*, 2002). Most of these effects are attributed to changes in enzymatic systems (Landsberg, 1986). Compared with other factors, such as drought, there is little information about the minimum, optimum and maximum temperatures for different tree species growing over periods as long as a month. The effect of extreme temperatures is directly related to their frequency and duration and is more critical than mean temperatures. However, a reasonable indication of the cardinal temperatures for a species can usually be obtained by examining the average monthly temperatures in the regions where it is well established and to which it is well adapted.

The optimum temperature for photosynthesis varies with species. In general, species from temperate forests have their optimum between 15ºC to 25ºC and tropical trees between 30ºC to 35ºC (Waring & Running, 1998). Based on high growth rates presented by the *Eucalyptus grandis* growing in the study region, the mean annual average temperature in the studied area was considered as an optimum temperature.

The original version of 3-PG did not include a temperature modifier. This was introduced later and the equation used was given in Sands (2002) and by Sands & Landsberg (2002). The modifier $f_T(T_a)$ depends on the monthly average daily temperature T_a, and is defined by:

$$f_T(T_a) = \left(\frac{T_a - T_{min}}{T_{opt} - T_{min}}\right)\left(\frac{T_{max} - T_a}{T_{max} - T_{opt}}\right)^{(T_{max}-T_{opt})/(T_{opt}-T_{min})} \tag{3.7}$$

where $f_T = 0$ if $T_a \leq T_{min}$ or $T_{max} \leq T_a$, and T_{min}, T_{opt} and T_{max} are the minimum, optimum and maximum temperatures for net photosynthetic production.

Figure 3.2 presents how the temperature modifier can restrict the canopy quantum efficiency in 3-PG model.

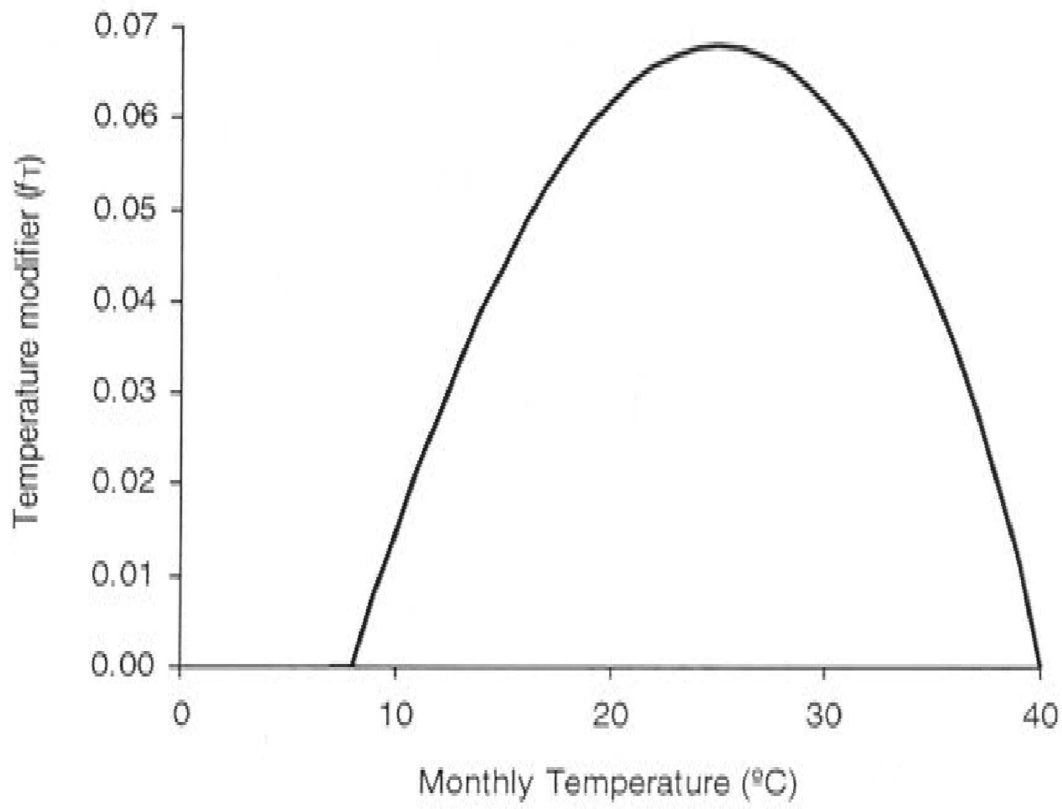


Figure 3.2. Temperature modifier affecting maximum canopy quantum efficiency ($\alpha \approx$ 0.07). The curve assumes that temperatures of 8 °C (T_{min}) and 40 °C (T_{max}) reduce α to zero and that 25 °C is the optimum temperature for growth of *Eucalyptus grandis*.

3.2.3. Vapour pressure deficit modifier

The effect of vapour pressure deficit (VPD, *D*) on forest growth has been reported by several authors (Dye & Olbrich, 1993; Landsberg & Hingston, 1996; Day, 2000; Granier *et al.*, 2000; Almeida & Landsberg, 2003). The constraint caused by VPD is directly related to its effects on stomatal conductance (g_s). Increasing VPD has been observed to cause reduction in g_s in a range of forest species (Dye & Olbrich, 1993; Leuning, 1995; Landsberg & Waring, 1997; Mielke *et al.*, 1999). The effect of VPD in reducing g_s in *Eucalyptus grandis* plantations in Brazil had been reported by Mielke (2000), Stape (2002) and Soares & Almeida (2001). This study primarily concerned with daytime average values of vapour pressure deficit (VPD_{day}, D_d), since this is the driving variable for transpiration and high daytime values cause stomatal closure and reduce growth.

Average daily (24 hr) (VPD_{24h}, D_{24}) VPD can be calculated from hourly temperature and relative humidity values, using the equations given by Landsberg (1986). Because transpiration from trees is affected primarily by day time VPD (stomata are normally closed at night) it is important to calculate, for comparison with VPD_{24h}, a value for VPD during daylight hours (VPD_{day}). This can be derived from measured hourly temperature and humidity values during the period when short-wave incoming radiation is at least greater than 1 W m^{-2}. A detailed analysis and justification of the use of VPD_{day} in 3-PG is shown in Chapter 5.The calculation of VPD was based on hourly relative humidity and temperature. Mean monthly D for daylight time can be calculated assuming that vapour pressure at the minimum temperature is equivalent to the saturated vapour pressure of the atmosphere. The saturated water vapour pressure (e_s) depends on temperature and following Landsberg (1986), can be calculated from:

$$e_s = 0.61078\exp(17.269T/(T+237.3)) \quad (3.8)$$

where T is the average temperature. The vapour pressure of unsaturated air (e_a) is defined as:

$$e_a = RHe_s/100 \quad (3.9)$$

where RH is the air relative humidity. The atmospheric relative humidity measured in the automatic weather stations was used to calculate the hourly and daily values that were integrated to monthly values of e_a, so hourly VPD (D) was calculated as

$$D = e_s - e_a \quad (3.10)$$

The daily D can be defined as the average of daylight hourly values. The monthly values used in 3-PG in this study were derived from daily (daylight) D values.

The calculation of monthly average values of VPD from average maximum and minimum air temperatures can be undertaken within the 3-PG program, but this procedure tends to underestimate the true value of monthly VPD. Chapter 5 illustrates the different ways of obtaining VPD used in 3-PG and the effect on the results of the model estimations.

The VPD modifier in 3-PG is given by:

$$f_D = e^{-k_D D} \qquad (3.11)$$

where k_D is the strength of VPD response and D is the current VPD. The Figure 3.3 shows how increasing VPD affects the VPD modifier.

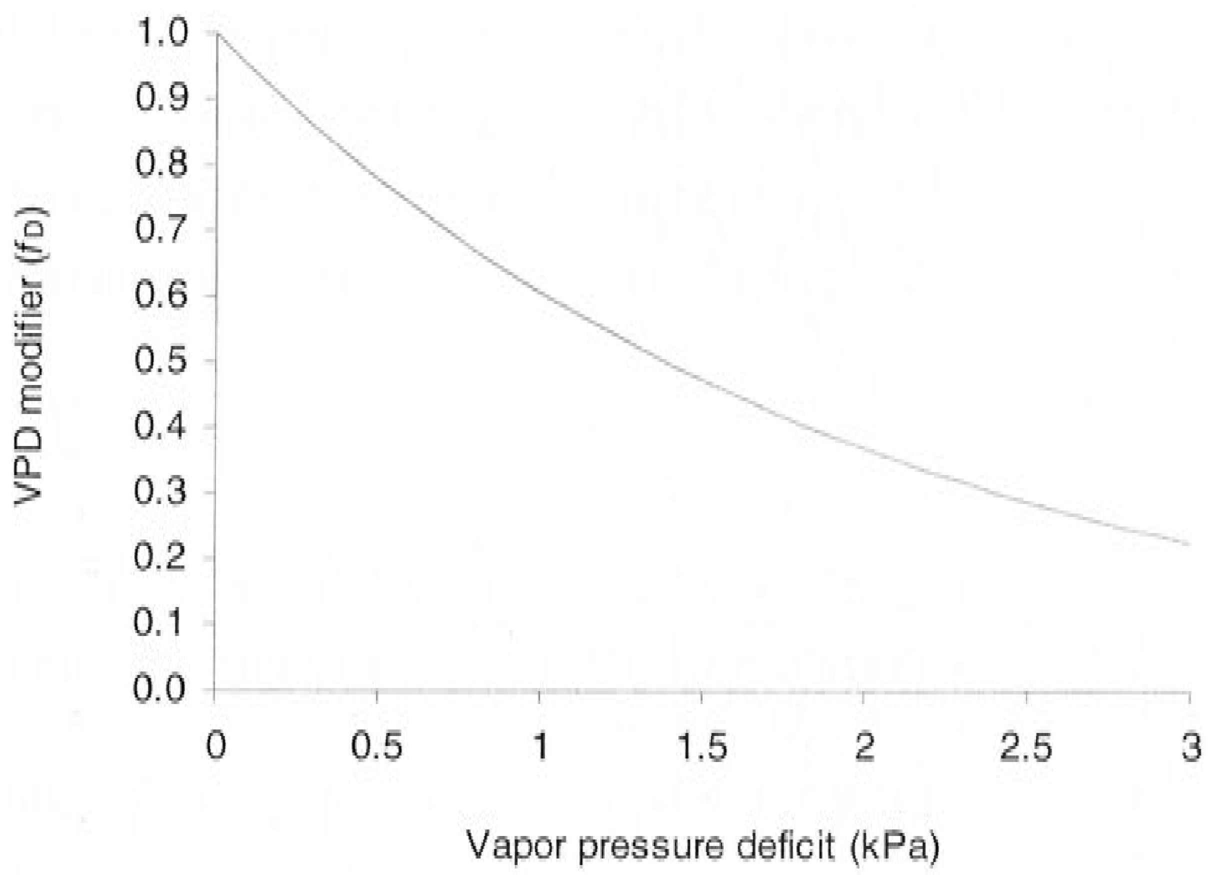


Figure 3.3. The relationship between VPD and the growth-constraining VPD modifier (f_D) used in 3-PG.

3.2.4. Stomatal and canopy conductance

The 3-PG model requires estimates of stomatal conductance (g_s) and canopy conductance (g_c) to be applied in the calculation of transpiration by the canopy, and the water balance. The response of stomatal conductance to environmental constraints has been studied by many authors (e.g. Jarvis (1976), Beadle *et al.* (1985a), Beadle *et al.* (1985b), Sheriff *et al.* (1995)). The main environmental constraints on stomatal conductance are: incident solar radiation, vapour pressure deficit, CO_2 concentration, air temperature and soil available soil water.

The calculation of canopy conductance in 3-PG was re-parameterised by Sands (2002) from the first version of 3-PG (Landsberg & Waring, 1997) as follows:

$$g_C = g_{Cx}\varphi \min\{1, L^*/L_{Cx}\} \tag{3.12}$$

where g_{Cx} (m s^{-1}) is maximum canopy conductance, φ is the physiological modifier, and L_{Cx} is the canopy LAI at which canopy conductance attains its maximum value. Stomatal conductance is the maximum conductance reduced by the physiological modifier φ (equation 3.4). Canopy conductance is stomatal conductance multiplied by LAI up to a maximum LAI of 3 (equation 3.13). Kelliher *et al.*(1995) analysed different vegetation types and showed that forests with LAI >3.0 have a relative stable g_{Cx} values that are close to three times g_s, this can be explained with the decrease of maximum g_s of individual leaves with increasing LAI (Whitehead *et al.*, 1996; Waring & Running, 1998).

$$g_C = \sum g_s L^* \tag{3.13}$$

Figure 3.4 shows the canopy conductance function in 3-PG assuming $\varphi = 1$, a maximum canopy conductance of 0.02 m s^{-1} and at a LAI of 3.

Equation 3.13 simplifies more complex and accurate models of stomatal conductance behaviour that can be obtained by dividing the canopy into different levels (Roberts *et al.*, 1992; Leuning *et al.*, 1995) The g_s values obtained are used in the calculation of canopy transpiration using the "big-leaf" version of the Penmam-Monteith equation.

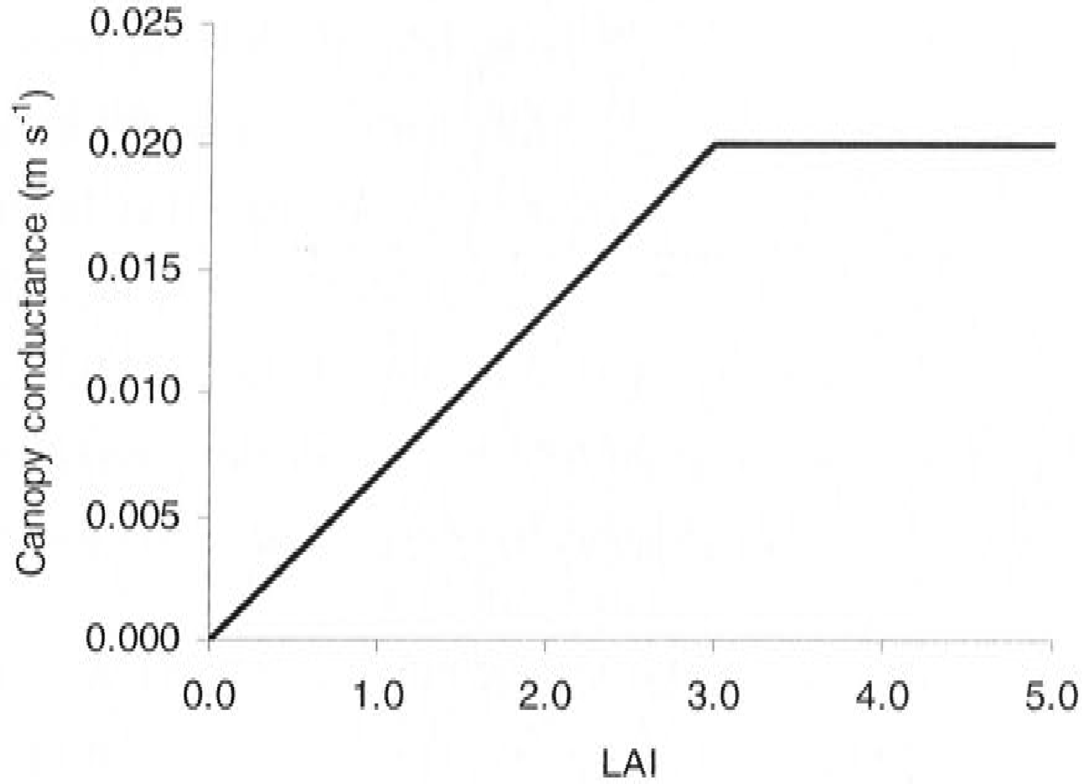


Figure 3.4. Relationship between canopy conductance (g_C) and leaf area index (LAI) used in 3-PG.

There is a considerable literature about stomatal and canopy conductance behaviour in conifers (Running, 1976; Whitehead *et al.*, 1984; McMurtrie *et al.*, 1990; McMurtrie *et al.*, 1992b; Dang *et al.*, 1998; Irvine *et al.*, 1998; Perks *et al.*, 2002) and in *Eucalyptus* species (Dye, 1987; Hatton *et al.*, 1992; Roberts *et al.*, 1992; Dye & Olbrich, 1993; Morris *et al.*, 1998; Mielke *et al.*, 1999; Zubrinich *et al.*, 2000; Mielke *et al.*, 2000; James & Bell, 2000; White *et al.*, 2000). Some studies show significant differences in stomatal conductance between species (Hinckley *et al.*, 1978; Wullschleger *et al.*, 1998), but the variation observed in the measurements tends to be large because of the difficulty of making enough good measurements of stomatal conductance in the field (Landsberg, 1999). The values obtained from the field measurements must be analysed as part of an integrated process involving the specific atmospheric, soil moisture and soil texture conditions as well as the species. This reinforces the need for local measurements covering the most extreme conditions (temperature, VPD and soil moisture) that occur in the study region.

3.2.5. Water balance

The water balance sub-model in 3-PG is calculated using a single-layer soil water balance sub-model. The monthly time step can generate some imprecision when the model is applied in regions that experience rapid soil moisture changes during a month interval. The input is precipitation (*R*) (and irrigation where applicable). Part of the rainfall is intercepted (*I*) by the canopy and re- evaporates at rates determined by atmospheric conditions. The precipitation interception in 3-PG is assumed as a fixed function that depends on LAI. The difference (*R-I*) reaches the soil surface and infiltrates the root zone until its maximum water holding capacity is reached; any further infiltration percolates beyond the rooting zone under gravitational potential and becomes runoff.

Several studies of rainfall interception by the canopy for different species can be found in the literature; some present very detailed and complex models to estimate the throughfall and stemflow. For reviews see (George & Varghese, 1985; Bruijnzeel & Wiersum, 1987; Almeida & Riekerk, 1990; Crockford & Richardson, 1990; Hall *et al.*, 1992; Calder, 1996; van Dijk & Bruijnzeel, 2001). Those studies show that a large variation of rainfall interception can be expected, depending on the intensity and interval of the rainfall. However, a good relationship can be observed between *I* and LAI (Hatton *et al.*, 1992; Vertessy *et al.*, 1996). These authors estimated a leaf storage coefficient of 0.3 mm LAI^{-1} for *E. maculata*.

3-PG assumes that the proportion of rainfall intercepted by the canopy depends on the leaf area index (L^*) of the canopy

$$I(L) = I_x \min\{1, L^* / L_{Ix}\} \tag{3.14}$$

where I_x is the maximum canopy interception, and L_{Ix} is the canopy leaf area index at which interception is maximised.

Figure 3.5 is a schematic presentation of the water balance used in 3-PG, as applied in the study region.

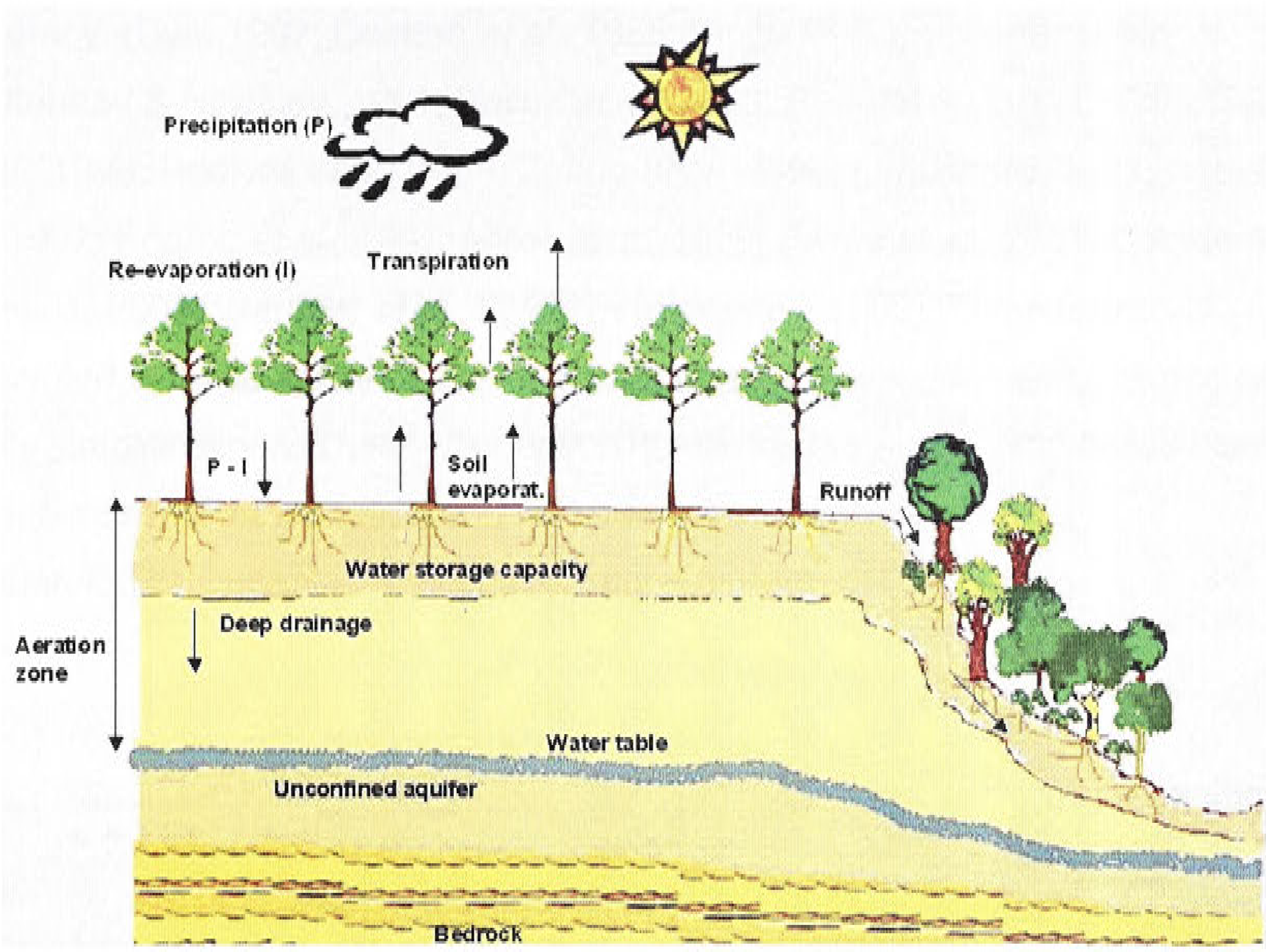


Figure 3.5. General framework of water balance in the study region where *Eucalyptus grandis* is planted in the flat areas and the slopes are occupied by preserved native forest.

It is well established that the main mechanism of water removal from plants and plant stands is through transpiration, a process driven by physical forces acting on the leaves, causing evaporation of vapour through the stomata. This results in water movement through the xylem and absorption of moisture from the soil. Transpiration from canopies is dependent on atmospheric conditions, on foliage area and mean stomatal conductance, and on the water flow properties of the pathway as determined by the cross-sectional area of sapwood and its conductivity (Whitehead, 1998; Soares & Almeida, 2001). Transpiration in 3-PG is calculated using the well-established Penman-Monteith (P-M) equation (Monteith, 1965) assuming the canopy behaves as a large single leaf with an effective area equal to LAI (Leuning *et al.*, 1991b).

The P-M equation has been tested and used successfully in different vegetation types and ecosystems around the world to predict canopy transpiration with good accuracy. (Dye, 1987; Dolman *et al.*, 1988; Monteith & Unsworth, 1990; Whitehead & Hinckley, 1991; Bailey *et al.*, 1993; Roberts & Cabral, 1993; Caspari *et al.*, 1993; Hodnett *et al.*, 1996; Zhang *et al.*, 1996; Landsberg, 1997; David *et al.*, 1997; Soares *et al.*, 1997; Miller *et al.*, 1998; Ewers *et al.*, 2001; Soares & Almeida, 2001; Sommer *et al.*, 2002; Bernier *et al.*, 2002). The equation is presented in those studies with various algebraic formulations and in some cases many simplifications. The P-M equation combines the energy and aerodynamic contributions to transpiration and requires measurements of driving meteorological variables at one level only. The form of the P-M equation used in 3-PG is:

$$\lambda E = \left[\frac{s_* \phi_n + \lambda \rho_a g_B D_q}{s_* + 1 + g_B / g_c} \right] \qquad (3.15)$$

where λE is canopy transpiration (mm month^{-1}), s_* is the rate of change of saturated vapour pressure with T at 20ºC (s_* = 2.2 at 20 ºC), ϕ_n is the net radiation (W m^{-2}), λ is the latent heat of vaporization of water (≈2.46*10^6 J kg^{-1}), ρ_a is the air density (≈1.2 kg m^{-3}) at 20 ºC, D_q is the specific saturation deficit at reference level (≈6.22*10^{-4} *D) (mbar), g_B is the boundary layer conductance (m s^{-1}) and g_c is the canopy conductance (m s^{-1}).

Boundary layer conductance is a function of wind speed, canopy density and structure (see Landsberg, 1986; p.57), it does not vary greatly and changes in its value have little effect on monthly transpiration, so it was taken as a constant with a value of 0.2 m s^{-1} making wind speed measurements un-necessary. This value is substantially higher than stomatal conductance values. Canopy transpiration is used to calculate the water balance for each month of the estimation.

The amount of water available in the soil to the trees (water balance) is obtained as a difference between total monthly transpiration (mm) from P-M equation and monthly precipitation. If the transpiration is larger than rainfall, the water balance is negative. If the precipitation is larger than maximum available soil water, the excess water becomes runoff or drainage. To reduce the possibility of cumulative errors during the first months of the simulation, it is recommended that the model is initialised in periods when the modelled soil moisture is at field capacity (maximum available soil water at root depth, θ_x). The monthly moisture ratio (r_θ) is calculated as a ratio between the actual available soil water and the maximum available soil water in the rooting depth.

$$f_\theta = \frac{1}{1+[(1-\theta/\theta_x)/c_\theta]^{n_\theta}} \qquad (3.16)$$

where θ is the current available soil water, θ_x is the maximum available soil water, c_θ is the relative water deficit for 50% reduction of available soil water and n_θ is the power determining the shape of the soil water response. Table 3.1 shows the c_θ and n_θ values for four soil types in terms of texture. These values were obtained from Dunin *et al.* (1985) and published by Landsberg & Waring (1997).

Table 3.1. Values of c_θ and n_θ according the soil type used to calculate the water balance in 3-PG

Profile texture class	**c_θ values**	**n_θ values**
Clay	0.4	3
Clay loam	0.5	5
Sandy loam	0.6	7
Sand	0.7	9

Landsberg & Waring (1997) presented the curves of soil water modifier based on soil moisture ratio for four soil texture types as shown in Figure 3.6.

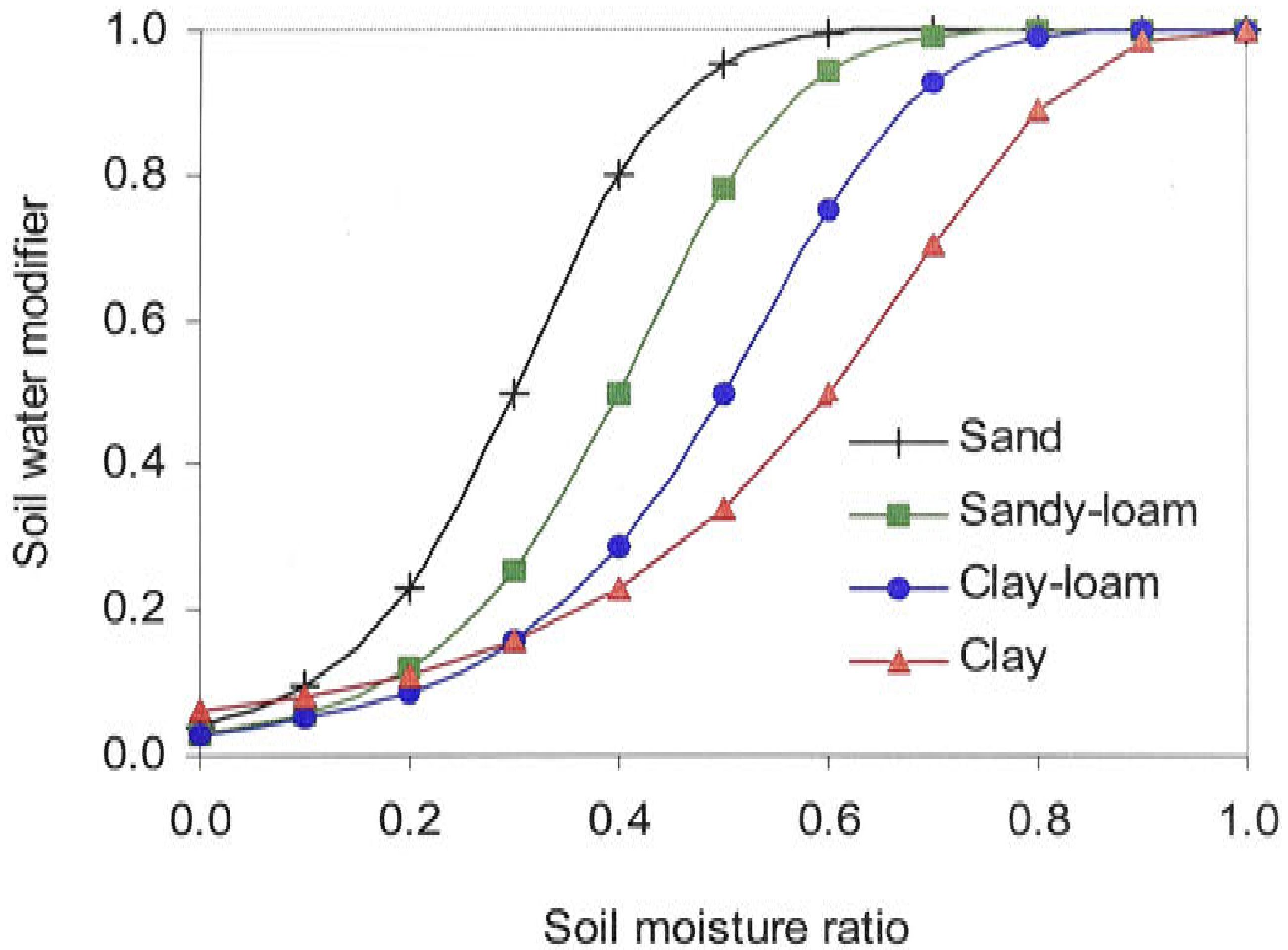


Figure 3.6. Relationship between the soil water modifier (f_θ) and the moisture ratio for four soil types.

3.2.6. Carbon allocation

Estimates of carbon allocation have been made on the basis of allometric relationships for different tree species in a number of models used to predict growth; for example by Bassow *et al.* (1990), Running & Gower (1991), Ågren & Wikström (1993), Cannel & Dewar (1994), Korol *et al.* (1996), Beets & Whitehead (1996), Landsberg & Gower (1997), Mäkelä (1997), Hawkins *et al.* (1998), Bartelink (1998), Droppelmann & Berliner (2000), Barton (2001) Law *et al.* (2001b), Porte *et al.*, (2002). Clonal technology is becoming more important for intensive plantations, and differences between clones may be the result of different allocation patterns (Osório *et al.*, 1998); For modelling purposes, it is essential that the differences in allocation patterns between clones be identified and quantified.

Biomass partitioning in 3-PG was fully described by Landsberg & Waring (1997). There have been no changes in the formulation of the partitioning process, but Sands and Landsberg (2002) and Landsberg *et al.*(2003) described differences in the way the algebra is presented. Carbon allocation to stems and foliage is on a single-tree basis and relies on the principle of conservation of mass: all the biomass (NPP) must be accounted for. Since allocation is to three components of the trees - roots, stem and foliage the partitioning coefficients (η_i, where *i* denotes any coefficient) must sum to unity i.e.

$$\eta_R + \eta_S + \eta_F = 1 \tag{3.17}$$

After each calculation cycle 3-PG allocates a fraction of the biomass increment to roots. The proportion of NPP allocated to roots is influenced by soil nutrition and available soil water (Beets & Whitehead, 1996; Landsberg & Gower, 1997). When conditions for water and nutritional uptake are good, the amount of carbohydrate allocated to roots is relatively small. The fraction increases as growing conditions deteriorate. The partitioning of biomass to roots is determined by the coefficient (η_R), which is parameterised by the maximum (η_{Rx}) and minimum (η_{Rn}) fraction of NPP that can be allocated to roots. The equation for η_R is:

$$\eta_R = \frac{\eta_{Rx}\eta_{Rn}}{\eta_{Rn} + (\eta_{Rx} - \eta_{Rn})m\varphi} \tag{3.18}$$

where *m* is a fertility-dependent variable (see equation 3.19) and φ is the physiological modifier defined in Equation 3.4.

The parameter *m* in Equation (3.18), describes the dependence of biomass allocation to root biomass allocation on soil fertility. The value of *m* is given by

$$m = m_0 + (1 - m_0)FR \tag{3.19}$$

where m_0 is the value of *m* for poorest soils. In extreme cases, *FR* can be zero.

Figure 3.7 shows the curve produced by application of equation 3.18 with the parameter values obtained for *E. grandis* (see Chapter 6) $\eta_{Rx} = 0.6$, $\eta_{Rn} = 0.10$ and $FR = 0.8$.

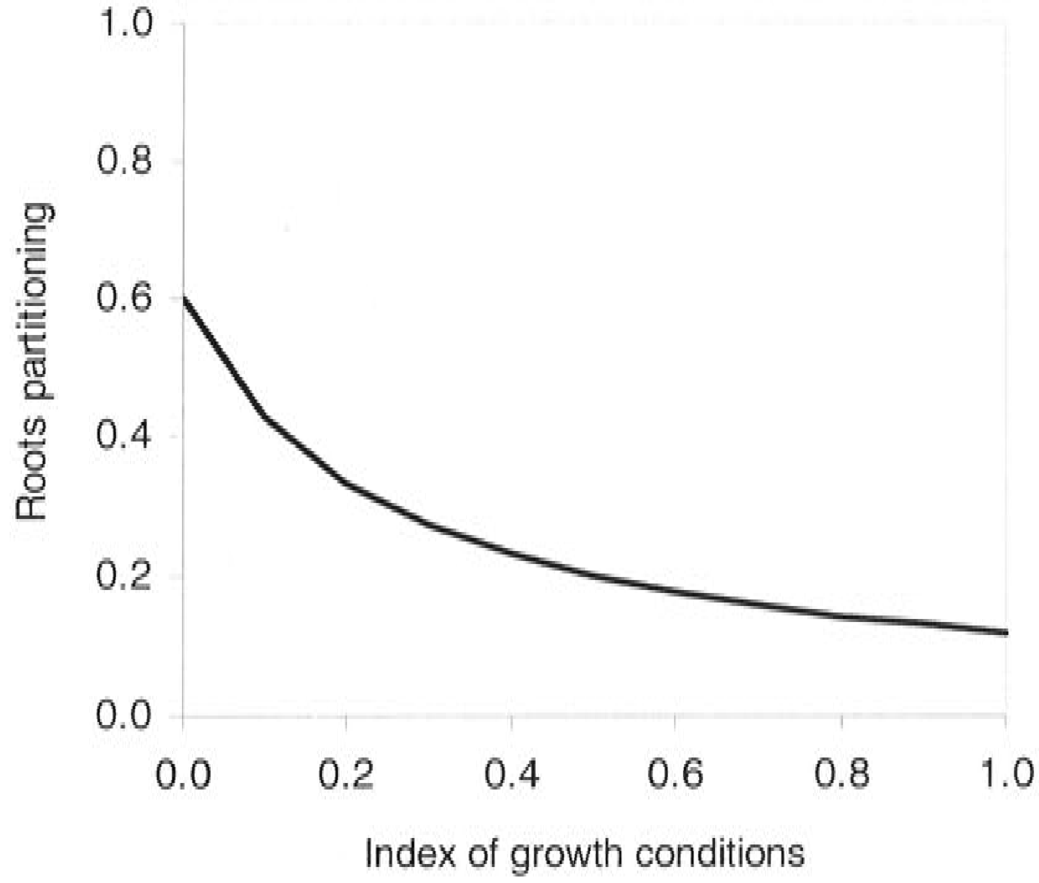


Figure 3.7. Fraction of biomass allocated to roots in *Eucalyptus grandis* in relation to growth conditions (bad condition assumes value zero and good condition assumes value of one) determined by a physiological modifier and the soil fertility rating (*FR*).

Partitioning of biomass between foliage and stem is based on the ratio of the derivatives of the allometric functions describing stem and foliage mass in terms of stem diameter (Landsberg & Waring, 1997; Sands & Landsberg, 2002). The relationships between single-tree woody biomass (w_s) and stem diameter (B) and between single-tree foliage mass (w_f), including accumulated litterfall, and B, are described by equations of the form:

$$w_s = a_s B^{n_s} \qquad (3.20a)$$

$$w_f = a_f B^{n_f} \qquad (3.20b)$$

The ratio of the derivatives of equations 3.20 is

$$dw_f / dw_s = a_f n_f B_f^{\,n-1} / a_s n_s B_s^{\,n-1} \qquad (3.21)$$

from which can be obtained:

$$p_{FS}(B) = a_p B^{n_p} \qquad (3.22)$$

where $a_p = a_f n_f / a_s n_s$ and $n_p = n_f - n_s$ (Sands & Landsberg, 2002). Given n_R, invoking conservation and substituing in equation 3.17, gives

$$\eta_S = \frac{1-\eta_R}{1+p_{FS}}, \qquad \eta_F = p_{FS}\eta_S \qquad (3.23)$$

For ease of calibration, a_p and n_p are expressed in terms of p_{FS2} and p_{FS20}, which are the values of p_{FS} for 2 cm and 20 cm stems, respectively (Chapter 6).

The nature of the partitioning calculations means that biomass allocation to stems (n_S) and to foliage (n_F) varies with growing conditions and also with tree size (Sands & Landsberg, 2002).

Figure 3.8a shows changes in biomass partitioning to stem and foliage with increasing DBH (cm) and Figure 3.8b shows variation in the ratio of foliage to shoot partitioning with increasing DBH. To calculate the values for these figures I used $p_{FS2} = 0.7$, $p_{FS20} = 0.1$ and $n_R = 0.1$. These values were obtained from destructive tree sampling discussed in Chapters 4 and 5.

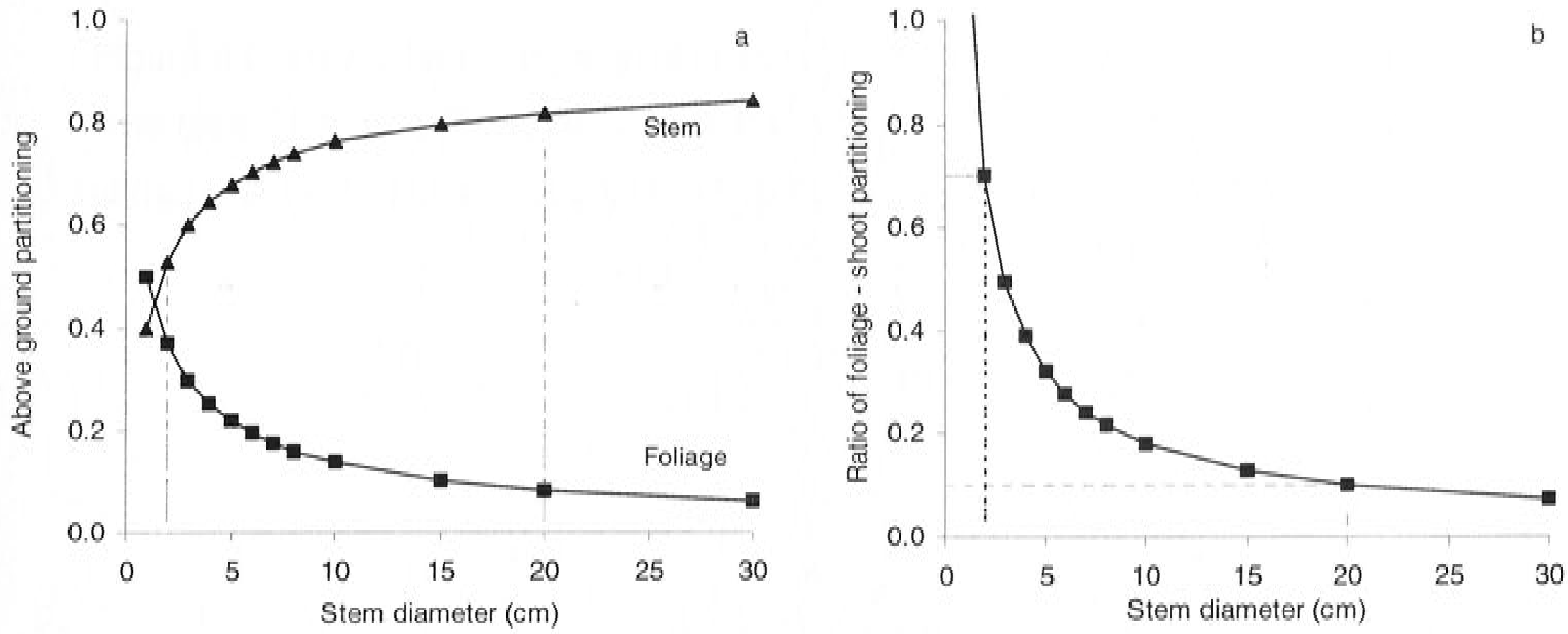


Figure 3.8. a) Variation of biomass partitioning to stem (▲) and foliage (■) with increase of stem diameter and b) ratio of foliage partitioning ($p_{FS} = a_p B^{np}$).

3.2.7. Litterfall and root turnover

Constant values for litterfall, as a fraction of foliage mass of the tree, and root turnover, as fraction of root mass, were included in the first version of 3-PG (Landsberg & Waring, 1997). Litterfall was modified by Sands and Landsberg (2002) to vary with tree age - it is likely to be very low when trees are young, increasing with age, presumably to some asymptotic value. The 3-PG$_{PJS}$ version of the model (August 2002) parameterised litterfall in terms of the rate at age 0 (γ_{F0}), the maximum rate of litterfall (γ_{Fx}) and the age ($t_{\gamma F}$) at which litterfall rate is $1/2(\gamma_{F0} + \gamma_{Fx})$.

$$\gamma_F(t) = \frac{\gamma_{Fx}\gamma_{F0}}{\gamma_{F0} + (\gamma_{Fx} - \gamma_{F0})e^{-k_\gamma t}} \tag{3.24}$$

$$k_\gamma = \frac{1}{t_{\gamma F}} \ln\left(1 + \frac{\gamma_{Fx}}{\gamma_{F0}}\right) \tag{3.25}$$

where t is stand age in months.

Figure 3.9 shows the changes in litterfall rate with stand age. Analysis of litterfall data (see Chapter 5.7) indicated that litterfall rate in the plantations studied also varied with time of year, but this was not incorporated into the model.

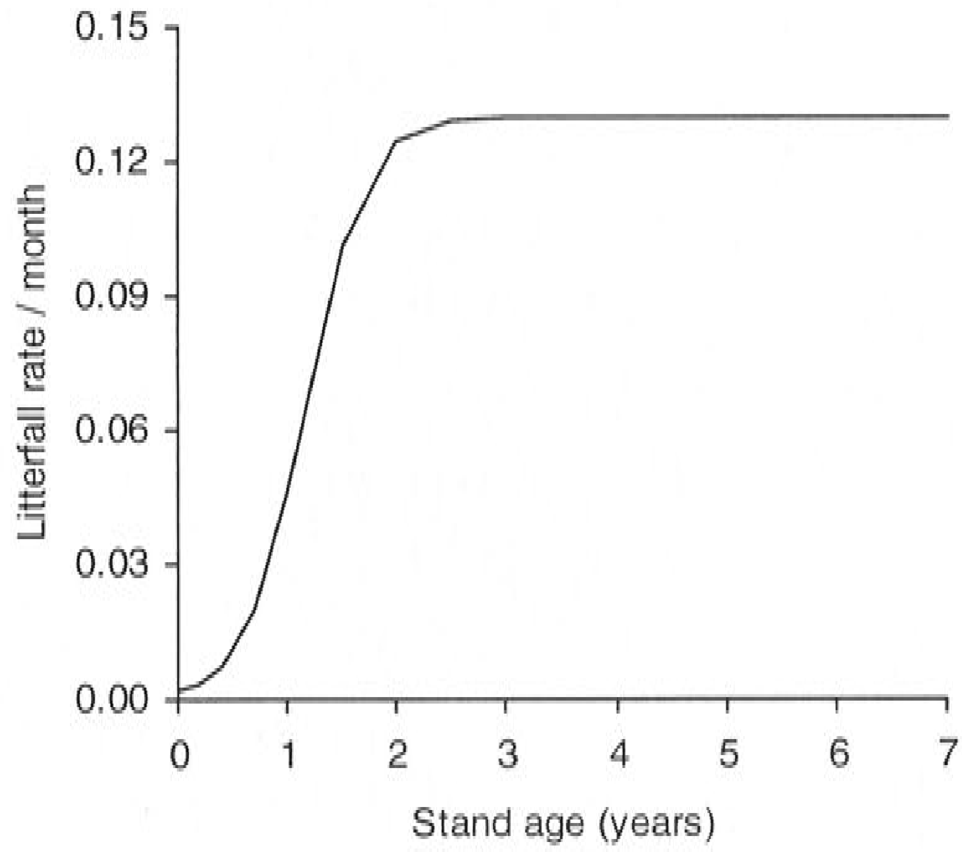


Figure 3.9. Change in litterfall rates with stand age, γ_{F0} = 0.00169 γ_{Fx} = 0.13 $t_{\gamma F}$ = 14.

Fine root biomass is normally affected by soil moisture and can vary drastically between species and season (Vogt *et al.*, 1997). However, accurate measures of root turnover are very difficult to obtain and in 3-PG it is taken to be a constant ratio of root biomass. This can be varied; Kätterer *et al.*(1995) reported a mean lifespan of individual fine roots of 5 months. A value of γ_R = 0.025 month^{-1} is used as the default in the studies on *E. grandis* reported in this thesis.

3.2.8. Fertility

Soil fertility is a key factor in forest production and one of the most difficult to determine since there are many interactions involving the processes that transform the mineral nutrients contained in the soil into forms available to trees (Landsberg & Gower, 1997). The maintenance of high growth rates, especially in short rotation *Eucalyptus* plantations, requires adequate inputs of nutrients as fertilizers (Fölster & Khanna, 1997). Landsberg and Waring (1997) elected to:

"deal with nutrition through the mechanism of carbon allocation rather than attempt to calculate a nutritional modifier that would require information on nutrient availability, and uptake by trees, which would be extremely difficult to simulate". This means that 3-PG externalises the problem of soil fertility rather than internalises it.

As shown in equation 3.19, Sands and Landsberg (2002) changed the original 3-PG formulation in terms of how the root allocation coefficient (now called the root biomass partitioning ratio – η_R) was calculated, which also affected the calculation of the fertility factor *m*. This formulation standardised the calculation of *m* and f_N and related both to the soil fertility rating. The soil fertility regime in 3-PG is represented by an index - the fertility rating (FR) - which takes values between zero (poor fertility site) and one (high fertility site). FR affects both biomass allocation to roots and the canopy quantum efficiency. When conditions are good and the soil is fertile, new photosynthate is allocated more to above-ground biomass. Conversely, when the soil is infertile, proportionally more biomass is allocated below-ground to roots, but the proportion allocated to roots decreases as general growing conditions deteriorate.

A new parameter $f_N(FR)$, depending non-linearly on the site fertility rating *FR*, was introduced by Sands (2002):

$$f_N(FR) = 1 - (1 - f_{N0})(1 - FR)^{n_{fN}} \quad , \qquad (3.26)$$

where f_{N0} is the value of f_N when $FR = 0$ and n_{fN} is a power. If $n_{fN} = 0$, then f_N is set equal to 1.

Landsberg *et al.* (2003) made the following statement about soil fertility:

"Nutrition is obviously an important variable but unfortunately, despite many years of research effort all over the world, our ability to describe soil parent nutrient status in terms usable in quantitative models of plant growth is extremely limited. The question of the appropriate FR is difficult for several reasons: first, because there are few plantations and forested areas for which good quality information about soil physical and chemical properties is available, and second, because there is unlikely to be a simple relationship between some 'state' measure of soil fertility and tree growth. Nutrient availability depends on biogeochemical cycling particularly in relation to nitrogen, so although chemical analyses may provide a guide to FR, a degree of expert knowledge will often be useful. The use of FR therefore remains a somewhat problematical and unsatisfactory - albeit pragmatic- approach." (p.202).

3.2.9. Mortality

Stem mortality in 3-PG was fully described in Landsberg and Waring (1997) and modified by Sands and Landsberg (2002). It uses the self-thinning rule, based on the 3/2 power law (Drew & Flewelling, 1977), that describes the relation between the number of stems and the maximum mean single-tree above-ground woody biomass w_{Sx} (kg tree^{-1}) that can be achieved at any particular stem population N (trees ha^{-1}). This is now expressed, in the model, as follows:

$$w_{Sx} = w_{Sx1000}(1000/N)^{n_m} \qquad (3.27)$$

where n_m is the exponent in the self-thinning law (nominally 3/2), and w_{Sx1000} (kg tree^{-1}) is the value of w_{Sx} when the stocking $N = 1000$ trees ha^{-1}. Tree mortality occurs when $w_S \geq w_{Sx}$. When a tree dies, it is assumed that its biomass is equal to the mean biomass of all trees in the stand.

3.2.10. Age modifier

A widely-observed pattern of forest growth is the decline of current annual increment (CAI) with stand age (Ryan *et al.*, 1997; Battaglia, 2001), but although this effect of age is well documented the reasons for the decline are still controversial. Suggestions for the reason for decline include: wood respiration, nutrient limitation or decline in hydraulic conductivity and changes in biomass allocation (Murty *et al.*, 1996; Ryan *et al.*, 1997; Hunt *et al.*, 1999; Murty & McMurtrie, 2000; Battaglia, 2001; Sands & Landsberg, 2002; Binkley *et al.*, 2002b).

Murty & McMurtrie (2000) have shown that the G' DAY model, which does not include specific mechanisms, cannot reproduce the observed changes in NPP as stands age. The main reasons for the CAI decline with age and how some PBMs deal with it were discussed by Battaglia (2001), who concluded that no existing model is consistent with all the possible reasons for age-related productivity decline. Most of the studies on the phenomenon were undertaken on softwood trees with long growing cycles, but some recent experiments in fast growing Eucalyptus plantations (Binkley *et al.*, 2002a; Binkley *et al.*, 2002b) have shown the same pattern, although a convincing explanation for the mechanism has not been provided yet.

The incorporation of the age effect into forest process-based models is essential if growth patterns towards the end of the cycle are to be reproduced accurately. Its omission can cause an NPP overestimation depending of the reasons that cause the decline.

The 3-PG model includes "an empirical expression in terms of relative age, to account explicitly for the reduction in maximum stomatal conductance as stand age" (Landsberg & Waring, 1997). The age modifier is determined by

$$f_{age} = \frac{1}{1+(F_a / r_{age})^{n_{age}}} \qquad (3.28)$$

where F_a is the relative age calculated as the ratio of actual age (to maximum age of the forest at the end of the cycle), r_{age} is a constant (default value = 0.95) and n_{age} controls the rate of change (default value = 4).

Figure 3.10 shows the behaviour of the age modifier for short rotation *Eucalyptus* plantation.

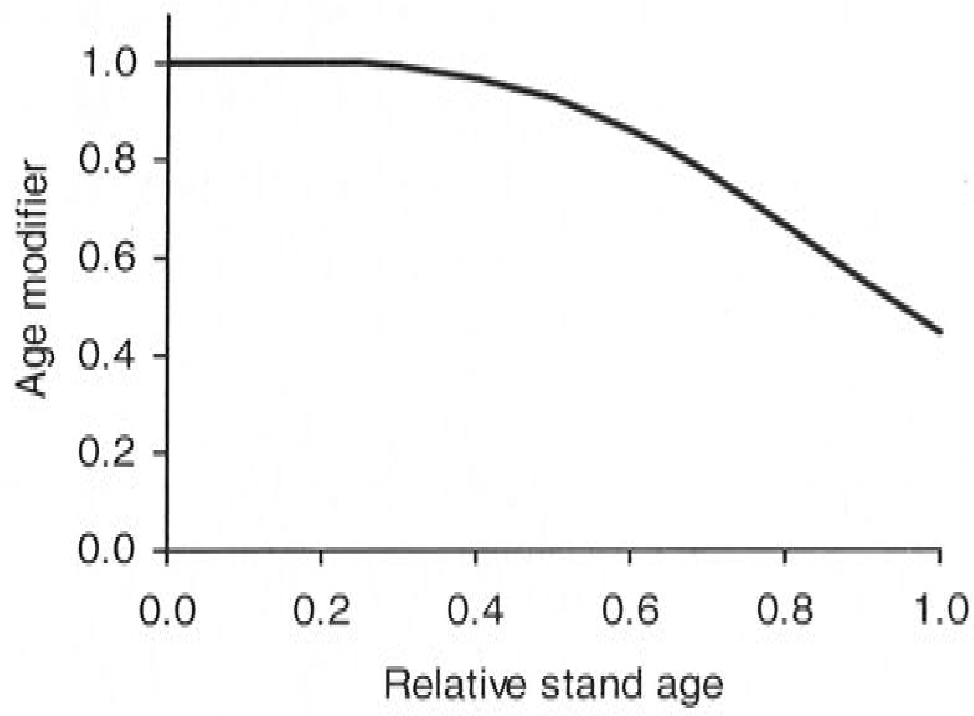


Figure 3.10. 3-PG age modifier curve for an *Eucalyptus* plantation assuming rotation of 10 years, r_{age} = 0.95 and n_{age}= 4 (Equation 3.28).

3.2.11. Stand volume

Forest stand volume is one of the most important pieces of information used by planners and managers in commercial forest companies, although in recent years there has been more interest in the mass of the final product, i.e. mass of pulp per hectare.

Stand volume V (m^3 ha^{-1}) in 3-PG is calculated from above ground woody biomass W_S (t ha^{-1}) and basic density ρ (t m^{-3}), and is discounted for the fraction p_{BB} of W_S as branch and bark at a determined age:

$$V = (1 - p_{BB})W_S / \rho \quad (3.29)$$

The model considers a variation of p_{BB} declining with stand age:

$$p_{BB} = p_{BB1} + (p_{BB0} - p_{BB1})e^{-(\ln 2)t/t_{BB}} \quad (3.30)$$

where p_{BB0} and p_{BB1} are branch and bark fractions at age 0 and for mature stands, respectively, and t_{BB} (years) is the stand age at which p_{BB} = ½(p_{BB0}+ p_{BB1}).

Despite the variation in ρ that can be observed in the same species of *Eucalyptus*, and which is caused by environmental conditions during the trees growth, measurements suggest that, in general, ρ increases with stand age from a low value ρ_0 for young stands to a maximum value ρ_x for older trees:

$$\rho = \rho_x + (\rho_0 - \rho_x)e^{-(\ln 2)t/t_\rho} \qquad (3.31)$$

where t_ρ (years) is the stand age at which $\rho = ½(\rho_0 + \rho_x)$. However, the same observations show a large variation of ρ for a given clone for older trees, often encompassing its value for younger trees (Sands, 2002).

3.2.12. Model calculations, variables, initialisation and outputs

Figure 3.11 shows a flow diagram of the sequence of calculations used in 3-PG.

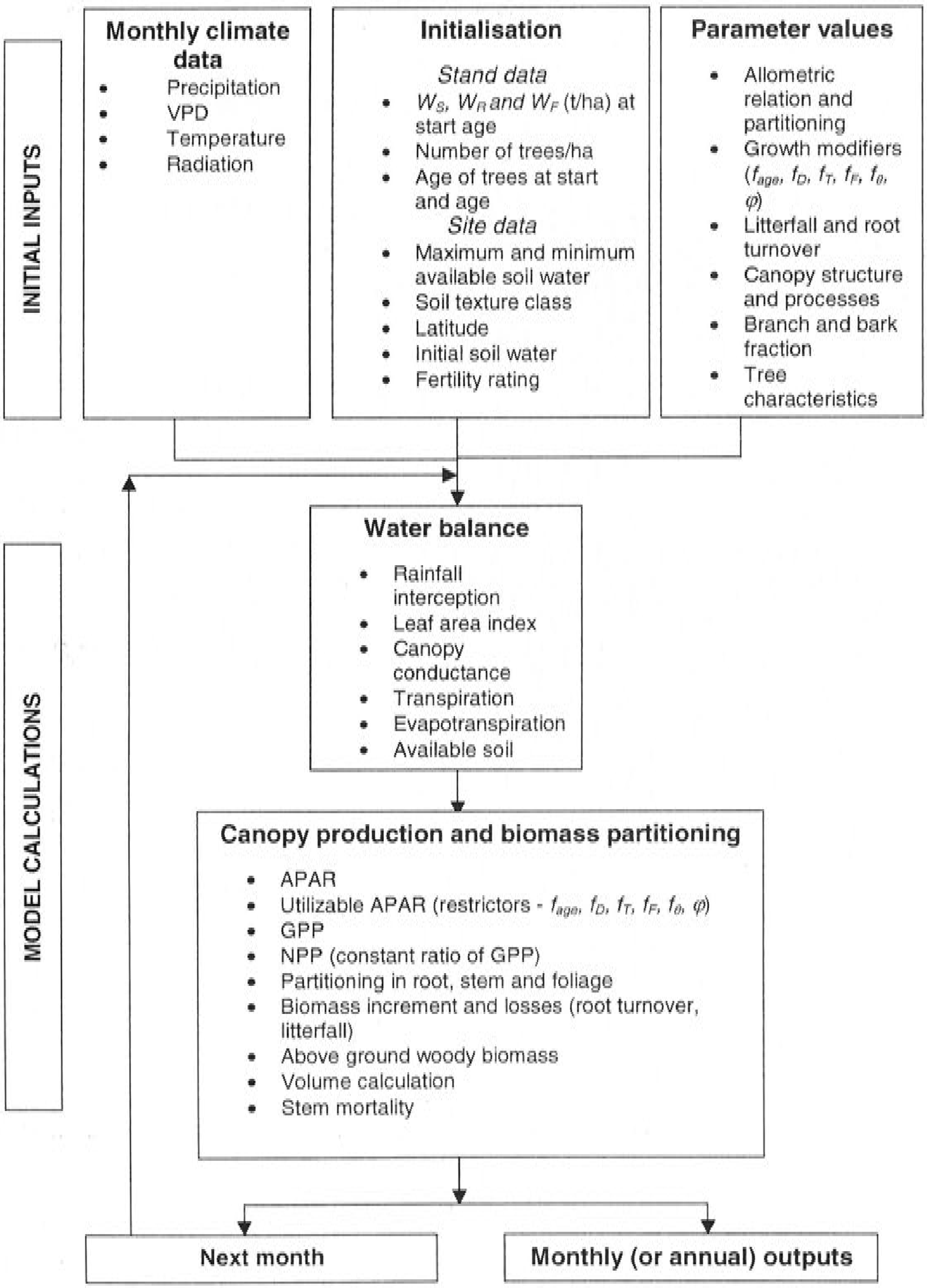


Figure 3.11. Flow diagram of 3-PG showing the inputs and the main calculation.

Table 3.2 shows the main input variables, initialisation conditions, and the most common outputs used in 3-PG.

Table 3.2. Inputs, variables to initialise and main outputs of 3-PG.

Input		
State variables	**Unit**	**Symbol or Abbreviation**
Total monthly precipitation	mm	R
Monthly daily means of temperature	°C	T
Solar radiation	MJ m^{-2} day^{-1}	ϕ_s
Monthly daylight means of VPD	mb	D_d
Site latitude	°	Lat
Maximum and minimum available soil water	mm	θ_x θ_m
Site fertility rating	-	FR
Initialisation		
Starting and ending age	year	
Available soil water	mm	θ_i
Initial stem number	trees ha^{-1}	N_i
Soil class (C, CL, SL, S)	-	SC
Foliage, root and stem biomass at starting age	t ha^{-1}	W_f, W_r, W_s
Main Outputs (monthly)		
Stand basal area	m^2 ha^{-1}	BA
Stand volume	m^3 ha^{-1}	SV
Mean annual increment	m^3 ha^{-1} $year^{-1}$	MAI
Stem numbers	trees ha^{-1}	N
Leaf area index	-	L^*
Foliage biomass	t DM ha^{-1}	W_F
Root biomass	t DM ha^{-1}	W_R
Stem biomass	t DM ha^{-1}	W_S
Litterfall	t DM ha^{-1}	γ
Growth modifiers (age, VPD, temperature, frost, soil water, nutrition, physiological of canopy conductance)	-	f_{age}, f_D, f_T, f_F, f_{sw}, φ
GPP	t DM ha^{-1}	P_G
NPP	t DM ha^{-1}	P_N
Light use efficiency	g DM MJ^{-1}	ε
Water use efficiency	g DM mm^{-1}	WUE
Evapotranspiration	mm	ET
Available soil water	mm	SW
Wood density	t m^{-3}	ρ

Chapter 4

4. METHODOLOGY, EXPERIMENTAL SITES AND DATA COLLECTION

4.1. Methodology of the research

This research involves the parameterisation of the 3-PG model based on detailed data from an experimental catchment (Microbacia) and a fertilised and irrigated site both in Aracruz, ES, Brazil. To test and validate the model performance, data from other areas, representing different climate and soil characteristics, or areas in the catchment area or close to it, were used. Comparisons between different genotypes have been undertaken and analyses developed to determine the accuracy of the model outputs in terms of plantation growth (stem volume and stem mass), available soil water, basal area, diameter at breast height, LAI and biomass partitioning. The results of these analyses and tests in different regions will determine the applicability and limitations of using the model at an operational scale.

Some of the experimental measurements were used to calibrate the model and estimate parameter values, while others were reserved for model validation. The measurements used to calibrate 3-PG were:

- biomass in foliage, stems and roots and determination of respective allometric equations;
- stomatal conductance, specific leaf area, litterfall rates,
- wood density,
- soil water holding capacity and soil texture.

Measurements of available soil water, stand volume, DBH, basal area and LAI were used in the validation process, which involved comparing observed and estimated values. In some cases only the stand volume and stand DBH from permanent sample plots (PSP) were used (see Chapter 6).

Fast-growing *Eucalyptus grandis* hybrid plantations owned and managed by Aracruz Celulose S.A. (ARCEL) in Eastern Brazil provide an ideal system to apply and test forest growth PBMs like 3-PG. The growth rates of these plantations are high (40 - 45 m^3 ha^{-1} y^{-1}), the stands are relatively homogenous and rotations are short (5 - 7 years). Detailed information on silvicultural practices such as soil preparation, weed control and fertilisation, and detailed knowledge of soil characteristics, are available for individual stands with different genotypes. The optimum stocking density in short rotation plantations is determined from experiments and mortality can be expected to be low in clonal plantations. The observed current annual increments obtained from inventory in permanent sample plots show that these plantations are very responsive to water availability and different growth rates can be obtained depending on climate conditions.

4.2. General characterization

The experimental data were collected in lands owned and managed by ARCEL on the eastern coast of Brazil at two different spatial scales. One, a more generic data set, was collected in three different regions called Aracruz, São Mateus in Espírito Santo State and South Bahia in Bahia State. These areas cover a total of 305,363 hectares with 185,894 hectares of plantations of *E. grandis, Eucalyptus urophylla* and hybrids of these species, and 102,143 hectares of preserved native rainforests. These plantations supply about 8,000,000 m^3 per year of wood to pulp production (2 million tons of pulp in 2003) and 48,000 m^3 per year of logs to a sawmill. From these areas, data concerning climate, forest growth from permanent growth plots and soil physical and chemical characteristics were used. The other data source was an experimental catchment and an irrigated and fertilized experiment located in Aracruz region. Table 4.1 presents a summary of major site characteristics.

ARCEL first started planting hybrids of *Eucalyptus grandis* and *Eucalyptus urophylla* in the southern part of the region, called Aracruz (AR), in 1967. Planting started in the São Mateus (SM) region in 1976 and in the south of Bahia (SB) State in 1989. Parts of these regions are now in the fourth 7-year rotation. All plantation and silvicultural operations are recorded and controlled. The resulting data provide good information about past productivity and historical management practices, such as soil preparation and amounts of fertilizer applied, in each of the 11,200 planted blocks of the plantation estate. Tree improvement, breeding and clonal techniques were developed through major research efforts and, over a number of years, resulted in increases in forest productivity. Specific forest management techniques such as definition of the areas to be coppiced - depending on previous yield and also, to some extent, on the clone - soil preparation and fertilisation techniques, which differed for soil types, and insect and weed control practices were developed for this region.

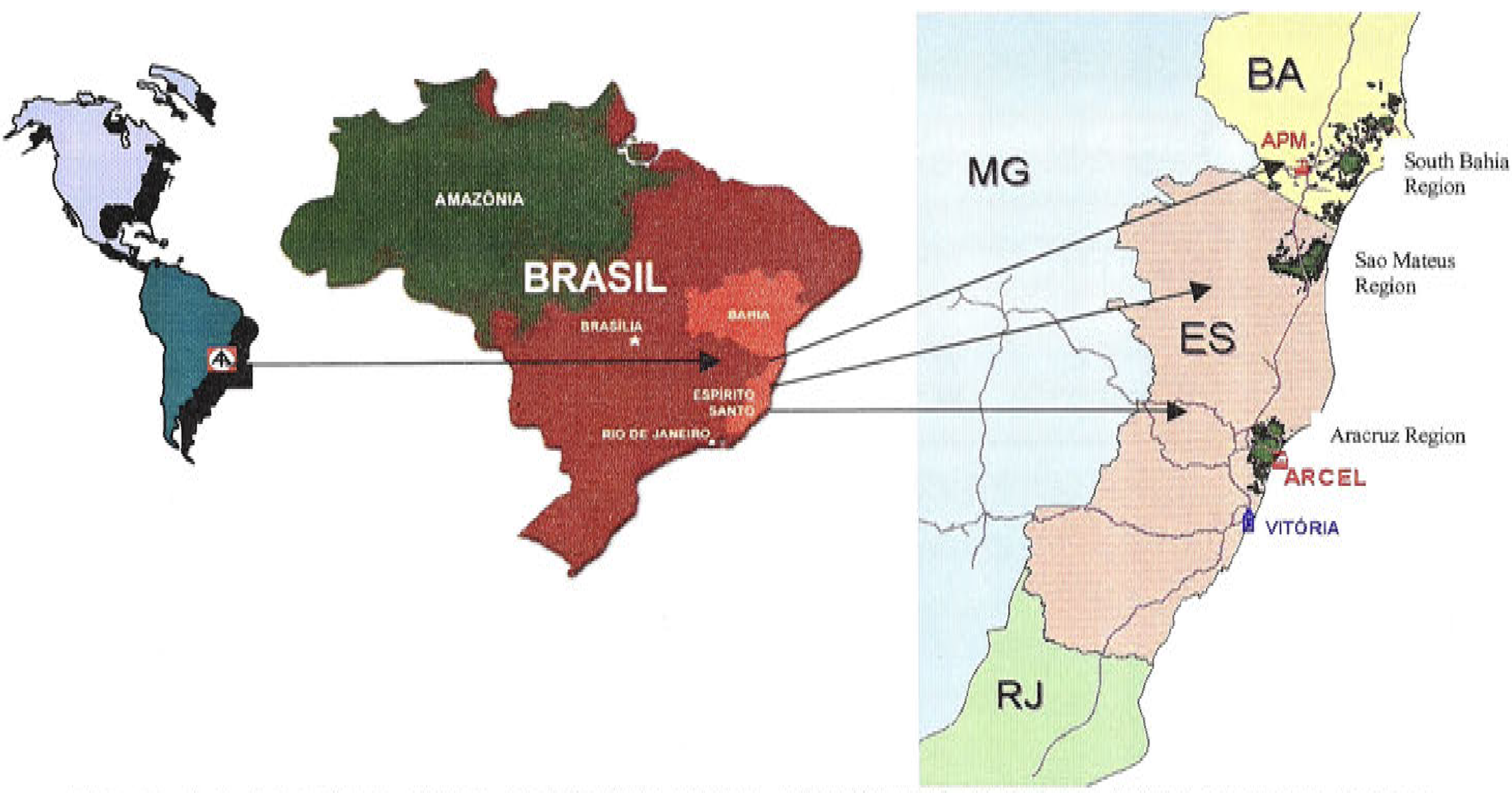


Figure 4.1. Location of the plantation areas, distributed mainly in three regions called Aracruz, São Mateus and South Bahia, Brazil.

4.3. Location of study areas

The study areas are located on the eastern coast of Brazil as shown in Figure 4.1. Table 4.1 shows the main areas used in this study.

The areas occupied by *Eucalyptus* plantations in the three regions are flat and most of the slopes are covered by native and Atlantic rainforest. Figure 4.2 shows the general landscape of the region and the distribution of *Eucalyptus* plantation and native forest.

Table 4.1. Experimental sites location and size (Microbacia and fertilised-irrigated sites are in Aracruz region)

Region	Scale	Area (ha)	Longitude	Latitude	Altitude (m)
Aracruz	Regional	69,510	40º 23' 12" W 39º 55' 39" W	20º 08' 24" S 19º 27' 10" S	0 to 144
Microbacia	Local	286	40º 13' 15" W 40º 11' 44" W	19º 51' 16" S 19º 52' 18" S	10 to 52
Fertilised-irrigated	Local	3.5	40º 04' 53" W	19º 47' 37" S	15
São Mateus	Regional	71,230	40º 23' 53" W 39º 41' 59" W	19º 13' 15" S 18º 11' 01" S	1 to 104
South Bahia	Regional	164,623	40º 08' 30" W 39º 12' 39" W	18º 17' 24" S 17º 13' 50" S	1 to 142

Figure 4.2. Landscape of the study areas, showing the *Eucalyptus* plantations and preserved native rainforest.

4.3.1. Regional scale database

The land use of the three studied regions (Aracruz, São Mateus and South Bahia) is presented in Table 4.2. Regional scale data were used to validate 3-PG at different sites.

Table 4.2. Aracruz land use area (ha) in December 2002 .

Region	Eucalyptus Plantation	Native Forest	Others	Total
Aracruz	39,720	25,315	4,475	69,510
São Mateus	51,020	16,283	3,927	71,230
Bahia	95,154	60,545	8,924	164,623
Total	185,894	102,143	17,326	305,363

The three operational production regions have plantations, intended for pulp production, which range in age from zero to eight years. Older thinned blocks provide saw logs. The land use planning activities define the plantation blocks distribution, road networks and location of natural reserves. The criteria used to establish the plantation sites are based on State and Federal laws, which require the establishment of a buffer protection zone of 30 m on each side of streams, and protection of water resources and biodiversity. Susceptibility of soils to erosion must be considered and operations may be restricted by this.

4.3.2. Catchment experiment

The experimental catchment (MBE) (for "Microbacia Experimental") is at 19º 51' S, 40º 14' W on Brazil's Atlantic coast, Espirito Santo State. The catchment is 286 ha, of which 188.69 ha are covered by *Eucalyptus grandis* hybrid plantations, currently in the fourth rotation, and 86 ha of native tropical rainforest (Mata Atlântica). The topography of the planted area in the catchment is flat, with native forest covering the hilly drainage areas of the system (Figure 4.3). Land use in the catchment is shown in Table 4.3. The site of the experimental catchment was chosen for its balance between planted areas (66%) and native preserved forest (30%), dominant soil types, topography, planted genotype, location, size of the catchment (2.8 km^2 with two drainage channels) and logistics. It was also considered its location, soils, cover and drainage system, representing the main eucalypt production area (40,000 ha) in the Aracruz region (Aracruz Celulose S.A., 2002).

A hydro-geological sounding using geophysical techniques was done to ensure that the basin was closed, and to evaluate the surface and underground water coincidence (Albuquerque *et al.*, 1997; Blanco *et al.*, 1997). These studies concluded that the catchment is a closed system and that the topographic and underground surface boundaries are similar, the difference in the area of the topographically determined (above-ground) catchment and the below-ground extent of the basin is estimated at only 4%.

Table 4.3. Catchment land use based on topographic surface boundary.

Land Use	Area (ha)	Percentage of total
Eucalyptus plantation	188.69	66.0
Native rainforest	85.45	30.0
Roads and others	11.98	4.0
TOTAL	286.12	100.0

The MBE was established and operated by Aracruz Celulose from the end of 1993. The project is part of a program aimed at addressing sustainable wood production, hydrologic and biodiversity issues.

The MBE area was planted with *Eucalyptus* for the first time in 1968. It is now in its fourth rotation of 7 - 9 years. The *Eucalyptus grandis* plantation was last harvested between September and November 1996, 27.37 ha were maintained as coppice and 161.34 ha were re-established with new clonal seedlings from January 1997. The MBE boundary involves 25 blocks as shown in Table 4.4.

The experiments conducted in this catchment were aimed at integrating the main environmental factors such as climate, soil, water, and the development of flora, fauna, and the plantation attributes. A network of hydrological and meteorological measurements complements intensive ecophysiology campaigns run under different conditions of water availability (Mielke *et al.*, 2000). Large amount of data on stomatal conductance, soil moisture and biomass have been collected (Soares & Almeida, 2001).

To allow a comparison between genotypes, measurements were made in six blocks of 1 ha with 1111 trees each (see Figure 4.3). These blocks included 5 different *E. grandis* clones and one coppiced area.

Most of the data used in this study that came from the catchment experiment were collected from 1996 onwards. Biomass, litterfall, precipitation interception, and stomatal conductance measurements made at the end of the previous rotation, from 1995 to 1996 (Mielke *et al.*, 1999; Neves, 2000; Soares & Almeida, 2001) were made on a single clone (no. 1248); they are not presented in this thesis (except for rainfall interception data; see Figure 5.22) but the results were generally consistent with those I obtained from the clones in the catchment over the period of this study.

Table 4.4. Catchment areas, compartments, land use, management, genotype and plantation establishment date.

Area Identification	Block Identification	Eucalyptus Plantation (ha)	Native Forest (ha)	Road (ha)	Management	Genotype	Establishment Date
004	01	19.11	12.10	0.93	Re-establishment	AR4	12-96
004	02	11.55	8.76	0.84	Re-establishment	1825	10-97
004	03	11.25	6.50	0.74	Re-establishment	AR4	12-96
004	04	0.90	0.00	0.19	Re-establishment	1825	12-96
004	05	0.08	0.00	0.04	Coppice	1225	09-96
004	06	3.47	0.00	0.35	Re-establishment	AR4	01-97
006	05	0.04	0.00	0.19	Re-establishment	AR4	12-96
006	06	0.26	0.00	0.11	Re-establishment	847	01-97
006	08	8.00	3.17	0.59	Re-establishment	4619	12-96
006	09	11.65	7.07	1.00	Re-establishment	2225	12-96
007	03	1.77	0.00	0.21	Re-establishment	847	01-97
007	04	5.43	0.00	0.27	Re-establishment	2225	02-97
007	05	10.06	7.57	0.72	Re-establishment	AR4	01-97
007	06	23.25	14.40	1.37	Re-establishment	15	10-97
007	07	10.65	7.25	0.83	Coppice	1248	09-96
007	08	16.64	3.04	0.95	Coppice	1248	10-96
007	08 - 2	0.98			Re-establishment	1248	02-97
007	08 - 3	1.00			Re-establishment	847	02-97
007	08 - 4	0.91			Re-establishment	AR4	02-97
007	08 - 5	0.99			Re-establishment	22	02-97
007	08 - 6	1.01			Re-establishment	15	02-97
007	09	21.59	2.11	0.70	Coppice	9999	10-96
008	01	20.90	13.40	1.19	Re-establishment	AR6	10-97
008	02	4.43	0.06	0.55	Re-establishment	4619	04-97
008	03	2.79	0.00	0.25	Re-establishment	AR4	02-97

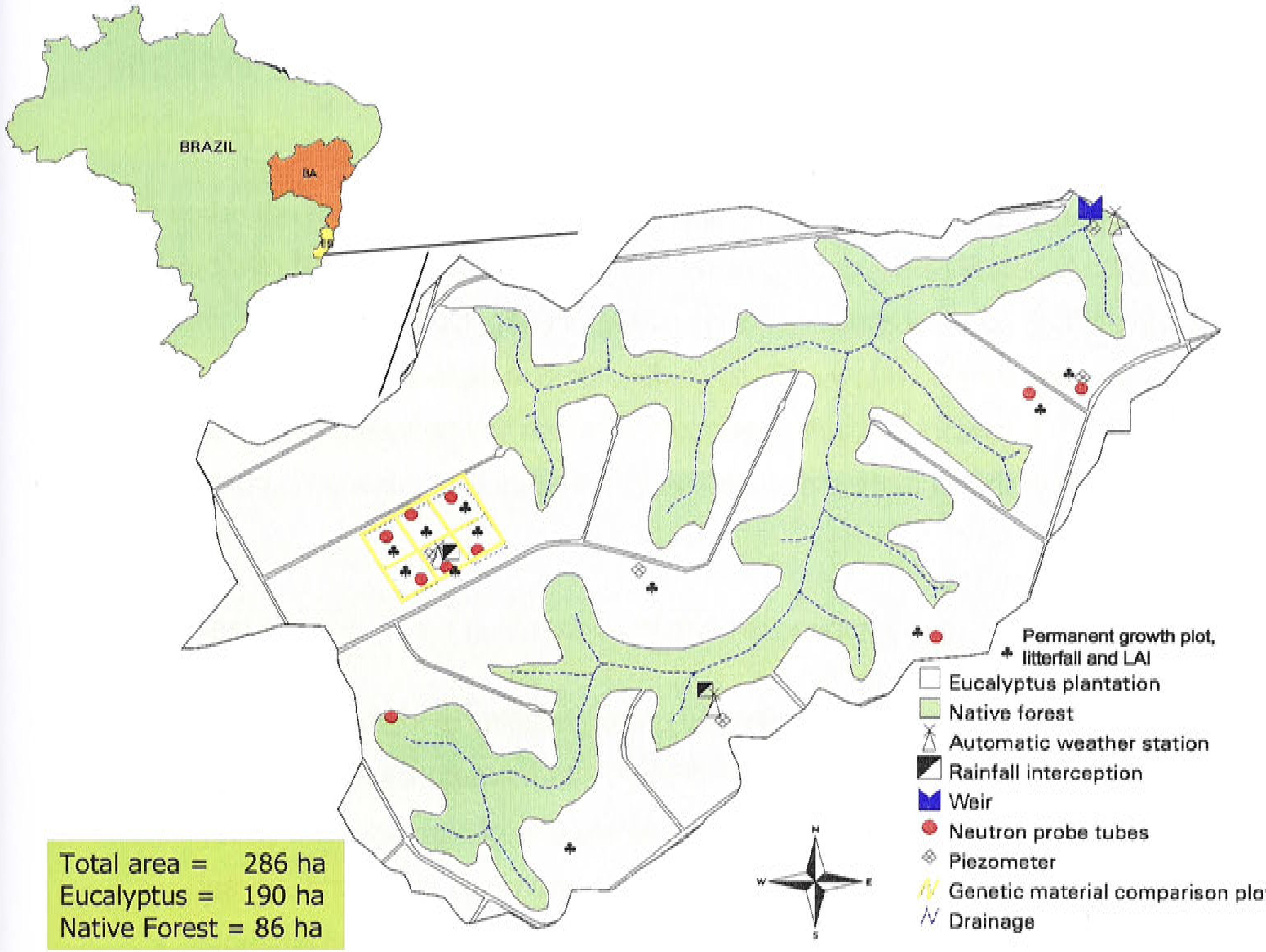


Figure 4.3. Catchment experiment area.

4.3.3. Fertilization and irrigation experiments

A fertilization and irrigation experiment was established by the Aracruz research group to evaluate the economic and environmental feasibility of this practice at an operational scale[4]. One experiment was established in August 1998 covering an area of 2 ha in the Aracruz region. It tested 18 treatments, including three different types of genotypes and six spacing treatments, (1 x 1 m, 1 x 2 m, 1 x 3

[4] I was not responsible for the establishment of this experiment or for the collection of data from it. Data were made available to me and I used them to determine the value of maximum canopy quantum efficiency (α), see Chapter 5, Figure 5.27.

m, 2 x 2 m, 2 x 3 m and 3 x 3 m) which were submitted to irrigated and fertilized conditions.

The soil in the experimental area (see Tables 5.7 and 5.8) was ripped and fertilized with NPK at operational levels when *Eucalyptus* was planted. Additional fertilization was applied using the irrigation system. Weeds were controlled by application of herbicide at an early growth stage. The water balance was calculated daily, based on soil moisture measurements and incoming precipitation. The water was supplied by an irrigation system when water deficit occurred.

The measurements in the fertilization-irrigation experiment were:

- DBH, tree height to calculate stand volume, mean annual increment and current annual increment at 3 monthly intervals;
- yearly biomass data from 3 plants in each treatment, used to quantify leaves, branches, barks and stems mass;
- stomatal conductance and leaf water potential during daytime for different treatments;
- leaf area and specific leaf area.

4.4. Forest plantation characteristics

The species of *Eucalyptus* used in this study are *Eucalyptus grandis* and *Eucalyptus urophylla* hybrids, planted at a density of 1111 trees per hectare (3 x 3 m). As mentioned earlier, the rotation length of these plantations is 6 to 7 years for pulp production and 14 to 17 years for solid wood products. Before planting, the soil is ripped to 60 cm depth and herbicide is applied to control weeds. NPK fertiliser is applied when the seedlings are planted. Additional nutrients are applied during the first 2 years after planting.

4.5. Data collection

4.5.1. Weather data

Meteorological data have been continuously recorded by three fully automatic weather stations in the experimental catchment since 1995. These provided daily measurements of precipitation (mm), air temperature (ºC), relative air humidity (%), global solar radiation (W m^{-2}), net radiation (W m^{-2}), PAR (μmol m^{-2} s^{-1}) and wind speed and direction (m s^{-1} and degree). The stations are installed in towers above the tree canopy. The instruments are scanned each minute and the data integrated to give hourly, daily and monthly means, and total monthly rainfall and radiation. The data are stored in a CR10X datalogger (Campbell Sci.) and transmitted daily by radio to the central office. The monthly meteorological data from the catchment site used in 3-PG simulation is presented in Appendix II.

A network of 19 automatic weather stations (AWS) was established in the three main planted areas (AR, SM and SB) (Figure 4.4). These stations provide continuous measurements of precipitation, air temperature and humidity, global solar radiation, net radiation, phosynthetically active radiation, and wind speed and direction. Seventeen conventional weather stations are used to complement measurements of precipitation across these regions. The AWS network established by ARCEL ensures good spatial coverage of its entire plantation area. The network was used to determine the relationship between global and net radiation used in water balance calculations. It also allowed us to establish the best method of calculating daylight VPD to apply in the model (Almeida & Landsberg, 2003) (see Chapter 5).

4.5.2. Rainfall interception

The amount of precipitation intercepted by a canopy affects soil moisture. A precipitation interception experiment was conducted in the catchment from September 1995 to July 1996 and restarted at the end of 1997 until the middle of 2000. Rainfall was collected above the canopy by two automatic raingauges (CS-700 L, Hydrological Service, Sydney, Australia). Throughfall was measured by 2 automatic rain gauges plus 25 conventional rain gauges installed in one of the permanent growth plots of 625 m^2. Throughfall and stemflow were measured after rainfall events and the rainfall interception by the foliage was calculated. The volume of water reaching the soils by stemflow was insignificant over a 2 year period. The results of the precipitation interception study were reported in Soares and Almeida (2001), Almeida & Soares (2003) and are given in Chapter 5. The concept of rainfall interception as a function of LAI was incorporated in the 3-PG code by Sands (Sands, 2002).

4.5.3. Soil texture

A relatively detailed soil survey of 133,000 ha of ARCEL lands was carried out by the Centro Nacional de Pesquisa de Solos (CNPS) of the Empresa Brasileira de Pesquisa Agropecuária (Embrapa) in 1988. Embrapa (2000) produced maps at scale 1:10,000 of the main soil types. Embrapa classified the local soils to 16 map units in Aracruz, 19 in São Mateus, and 28 in Bahia, all classified using the old Brazilian Soil Classification System. The dominant soil types across all regions were Yellow Podzolics with smaller areas of Planosols, Podzols and Quartzose Sands. In the Aracruz Region, the subdominant soil types were Yellow Latosols while in South Bahia Region there were small areas of Gley soils.

Detailed chemical and physical laboratory analyses were conducted by soil horizon from the 32 soil profiles. Selected examples of these analyses were presented in Embrapa (2000).

A revision of the Embrapa (2000) map legends after the release of the new Brazilian Soil Classification System reduced the 65 map units down to 22 (Curi, 2001). The dominant soil types are now called Yellow Agrisols (Yellow Podzolics), the Podzols are now Spodosols, and the Quartzose Sands are now called Quartzose Neosols.

The predominant texture of the study areas is a sand/loam texture in the top layer and clay texture in the deeper horizons.

The texture class by soil map unit is presented in Chapter 5.

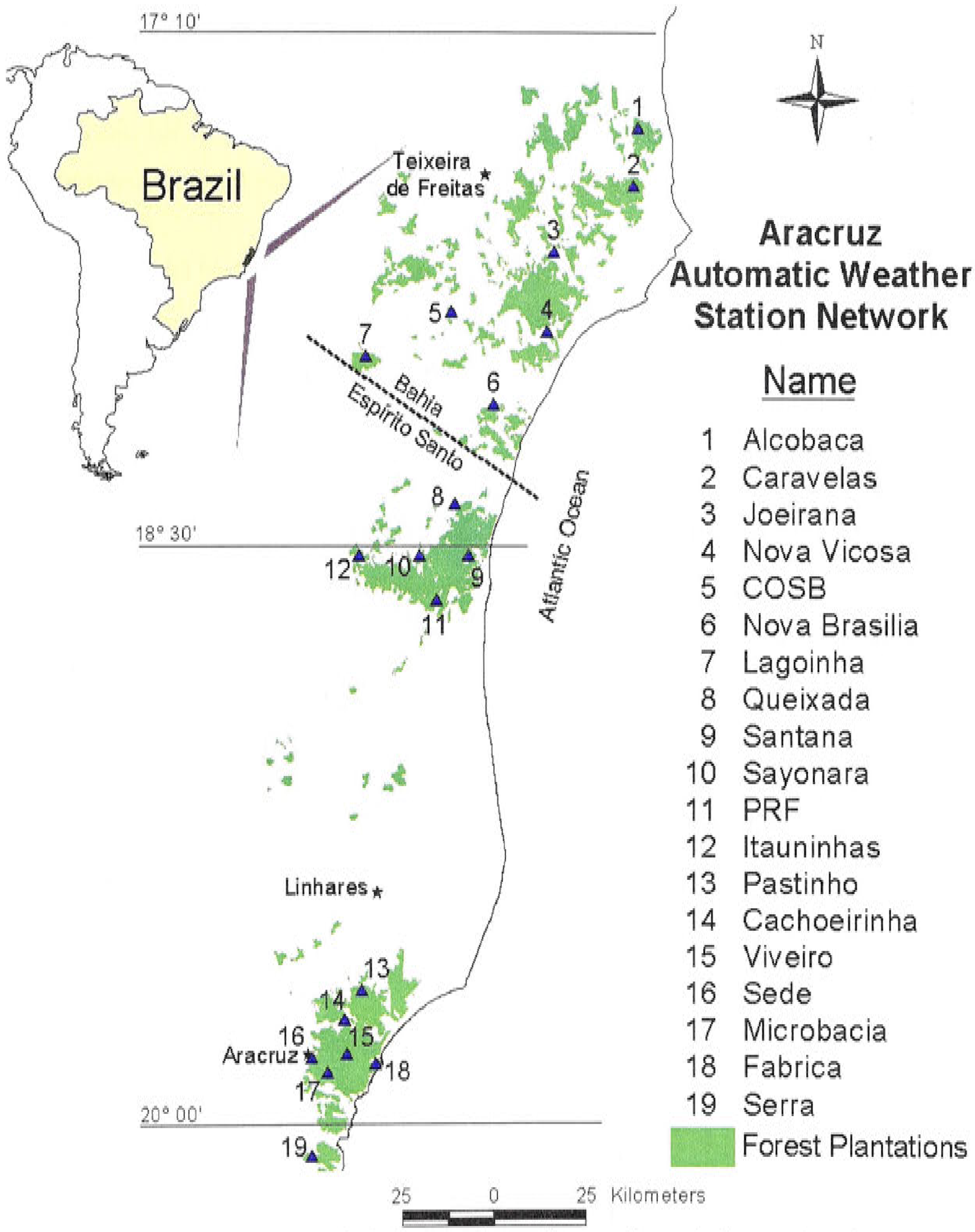


Figure 4.4. Location of Aracruz Celulose automatic weather station network.

4.5.4. Soil water holding capacity

The Embrapa soil survey (Embrapa, 2000) produced water retention curves up to 2.5 m depth for the main soil types. Comparisons with measured soil moisture using a neutron probe provided an indication of the available soil water to 2 m depth.

4.5.5. Soil fertility

Natural soil fertility is low; the soil is poor in primary minerals, with high bulk density. An intensive soil survey that produced one composite sample per planted block, for 0 - 20 cm and 20 - 40 cm every 2 ha provides the main soil information in terms of physical and chemical aspects at the end of each rotation.

Samples from soil fertility trials in the catchment area indicated the total amounts of the principal nutrients, determined by standard laboratory techniques, in the areas occupied by different genotypes. The values given in Table 4.5 are for the top 20 cm of the soil, where most of the fine roots occur.

Table 4.5. Total average amounts of the soil nutrients in the top layer, in the MBE area occupied by five genotypes.

Genotype	**P** (ppm)	**Ca** ($meq/100cm^3$)	**K** ($meq/100cm^3$)	**Mg** ($meq/100cm^3$)	**Organic matter** (%)
847	5.67	0.35	0.06	0.12	1.90
1248	7.00	0.66	0.07	0.22	1.98
15	4.83	1.07	0.07	0.30	2.28
22	8.00	0.35	0.06	0.11	1.93
AR4	5.33	1.33	0.08	0.35	2.23

4.5.6. Soil moisture

The soil moisture in the catchment was measured in nine neutron probe access tubes in the top 2.8 m (three tubes at up to 5.6 m depth) of the soil. Measurements were taken at vertical intervals of 20 cm in each plot for each genotype (see Figure 4.3 for tubes distribution). The measurements started in 1995 at weekly intervals during the wet season and fortnightly during the dry season. The neutron probe measurements were calibrated against the gravimetric moisture content of soil samples collected at the same depths during different seasons (Appendix III shows calibration curves).

4.5.7. Stomatal conductance

Stomatal conductance (g_s) was measured in MBE hourly at two levels in the canopy of two genotypes on 13 mornings over a period of about two months in 1999. Measurements were taken using the gas analyser (LCA-4) and / or a porometer (LI1600). Results from previous similar campaigns in the same area, conducted in 1995 and 1996, were reported by Mielke *et al.* (1999) and Mielke *et al.* (2000). These campaigns provided data that made it possible to identify differences between genotypes in terms of stomatal conductance and the effect of VPD on canopy conductance (g_c).

4.5.8. Leaf area index

Estimation of the leaf area index (L^*) is particularly important since it regulates the ecophysiological process, evapotranspiration and photosynthesis, and is a key parameter in process-based models (Running & Coughlan, 1988; Cutini *et al.*, 1998; Law *et al.*, 2001c). The leaf area index was estimated monthly in MBE using the LAI-2000 plant canopy analyser (Li-Cor, Lincoln, NE). The LAI-2000 measurements were made using the two-sensor method (Li-Cor, 1992) with a reference sensor collecting data above the canopy and the measuring sensor located below the canopy. LAI-2000 measurements were also made in permanent growth plots. Monthly LAI-2000 records were obtained from 25 readings randomly recorded in each area.

Values of plant area index obtained with the LAI-2000 were calibrated against L^* determined from biomass sampling and destructive leaf area determination in 38 trees of different genotype and age from six stands. The result of the calibration is presented in Appendix II and is consistent with other studies (Hingston *et al.*, 1998; Battaglia *et al.*, 1998; Cutini *et al.*, 1998) which indicated that direct measurements with the LAI-2000 underestimate L^*. This is despite the fact that the LAI-2000 measures plant area index (i.e. it includes the effects of stems and branches) rather than LAI.

4.5.9. Specific leaf area

The differences in specific leaf area (SLA) (σ, $m^2\ kg^{-1}$) between species, clones and stands of different age have been reported in other studies (Will *et al.*, 2001; Pita & Pardos, 2001; Sands & Landsberg, 2002). To establish the local values of SLA and its variation with stand age, 55 sampled trees from 5 genotypes ranging in age from 2.2 to 4.7 years old, in the MBE were used. The leaves of each tree were collected and the fresh mass recorded. A sub-sample of 100 leaves was oven-dried to calculate the total dry mass. The Leaf area was determined for a sub-sample of fresh leaves using the Li-Cor LI 3100 area meter.

4.5.10. Litterfall

Monthly litterfall mass was collected during two years in three 1 m^2 traps for each of the five genotypes in MBE. A wide variation was observed between months and between genotypes in the same month. Litterfall was also measured in the fertilised and irrigated experiment in 3 genotypes. The litterfall measurements allowed estimation of litterfall rates and, associated with LAI measurements, made it possible to determine canopy dynamics and the way these varied with stand age.

4.5.11. Biomass distribution

Annual changes in carbon allocation can be determined through destructive analysis of the trees and quantifying how growth is distributed (Waring & Running, 1998). One of the most important factors that must be determined for process-based models is above and below-ground biomass distribution (Cannell & Dewar, 1994). The measurement of below-ground biomass is one of the most difficult and resource-consuming measurements to make.

Three trees of each of the five genotypes studied were sampled destructively in the experimental catchment every year for four years (1999 - 2002). One of these three trees had the average DBH and height of the stand; one tree was selected at one standard deviation above, and another tree at one standard deviation below the average DBH and height. These samples provided values of DBH (cm) and tree height (m), stem, bark, branch, root and foliage biomass (kg tree^{-1}), and wood density (t m^{-3}).

The stems were harvested, dried and weighed to establish their volume and the wood density. The canopy was divided into three layers, the total foliage mass of each layer was weighed, and a sub-sample of leaves (approximately 100 leaves) from each tree was used to determine the leaf area using the Li-Cor LI-3100. Tree roots were dug up and all live roots collected. These were separated into fine roots (< 2 mm), medium roots (2 - 5 mm) and coarse roots (> 5 mm). The samples were dried and weighed.

4.5.12. Forest growth

Forest growth was measured through intensive inventory based on annual measurements in Permanent Sample Plots (PSP) and temporary plots (TP). The measurements are normally done in pre-harvest temporary plots when the forest is 2 and 4 years old. In this study only data from the PSP from different regions (AR, SM and SB) and years were used.

Table 4.6. Permanent sample plots measured from 1996 to 2002 in AR, SM, SB and in the MBE.

Size and period of measurement	Local	Frequency	Number of measurements / number of plots	Parameters measured
Circular plots - 855 m^2 from 1996 to 2002	AR, SM, SB	Annually from the second year after planted	2482 / 1299	DBH, height of 25% of trees and height of dominant trees and number of trees
Circular plots - 855 m^2 from 1997 to 2002	MBE	Monthly	504 / 12	DBH, height of 25% of trees and height of dominant trees and number of trees

Twelve circular permanent growth plots of 855 m^2 each were established in the catchment. The PSPs were measured monthly for 5 genotypes and one coppiced stand. An additional six plots were measured in different parts of the catchment. Monthly measurements of tree height, DBH and stem numbers in each plot were used to estimate MAI, basal area, stand volume and stand DBH.

The PSPs in the AR, SM and SB regions are well distributed to represent the main growth differences. As in the catchment, the plots are circular with fixed radii giving an area of 855 m^2. They are located randomly in each block. The diameter and height of every tree in the three central lines is measured as well as the nine dominant heights. Using diameter - height measurements the Curtis model was applied (Curtis, 1967): ($\ln (Ht) = a+b_0(1/B)$, where *B* represents stem diameter, to calculate the volume based on a model by Schumacher & Hall (1933) applied to individual trees. The equations were adjusted for each administrative region and for the management applied (i.e, stands coppiced or re-established) and genotype, based on standard company inventory practices. The inventory also registered the number of dead trees. Stand volume and current increment at each measurement were calculated once a year and basal area was obtained from the stem diameter measurements and stem number. Final wood volumes were recorded when the plots were harvested. Parcels with at least 3 consecutive measurements and from representative genotypes that have been broadly planted, were selected for this study.

Chapter 5

5. DATA ANALYSES

This chapter presents the analyses of the dataset collected in the areas studied and used in 3-PG parameterisation and validation. The chapter is divided into topics that have major effects on the model inputs, calibration and outputs.

5.1. Weather [5]

Data from the ARCEL meteorological network provide the opportunity to test relationships used to estimate global radiation and VPD, and to evaluate variations in the parameter values of the well-established linear relationship between global and net radiation. They also allow evaluation of the ratio of PAR to global radiation, and the spatial variation, across relatively short distances, in VPD.

Six stations, providing good coverage of the region, were selected for most of the analyses presented here. Data from others are included in some cases. Figure 5.1 shows the annual variation in precipitation across the region; Figure 5.2 shows the range of rainfall received at the selected stations over a 13-year period; the time course (average monthly) of radiation across the region as a whole (Figure 5.4) and the time course of VPD_{day} at the six selected stations (Figure 5.5). These data provide considerable information about the climate of the area.

5.1.1. Rainfall

Nobre *et al.* (1999), showed that rainfall in this region is produced mainly by the South Atlantic Convergence Zone from the frontal systems interacting with

[5] Part of this chapter has been published in Almeida & Landsberg (2003).

tropical convection, during the hottest months (October to March) generating convective storms.

Figure 5.1 shows that the rainbearing weather systems affect the whole region similarly; there are slight differences in annual mean rainfall at particular locations (Figure 5.2) - the range in total precipitation over a 13-year period varies from about 958 to 1940 mm at Microbacia (mean = 1284 mm) to 780 to 2872 mm at Queixada (mean = 1463 mm). At time of writing there were only eight years data available for Lagoinhas, hence the smaller range at that station. The rainfall in the region varies from 50 to 150 mm per month from January through August / September, with a tendency for higher values (150 mm) in March/April and the lowest values in August/September – commonly around 70 mm/month. October, November and December are the wettest months, with more than 40% of total annual rainfall, (see Appendix II).

5.1.2. Temperature

The annual average temperatures at different locations through the region are similar; maximum temperatures vary from 29 ºC in the Alcobaca and Lagoinhas areas to 27.8 ºC in the Microbacia area. The minimum annual average temperature varies from 20.1 ºC to 20.8 ºC between locations. Monthly maximum average temperatures across the regions vary from 30 to 32 ºC in January and February to 25 to 26 ºC in July. Monthly minimum average varies from 23 ºC in January to 18 ºC in July.

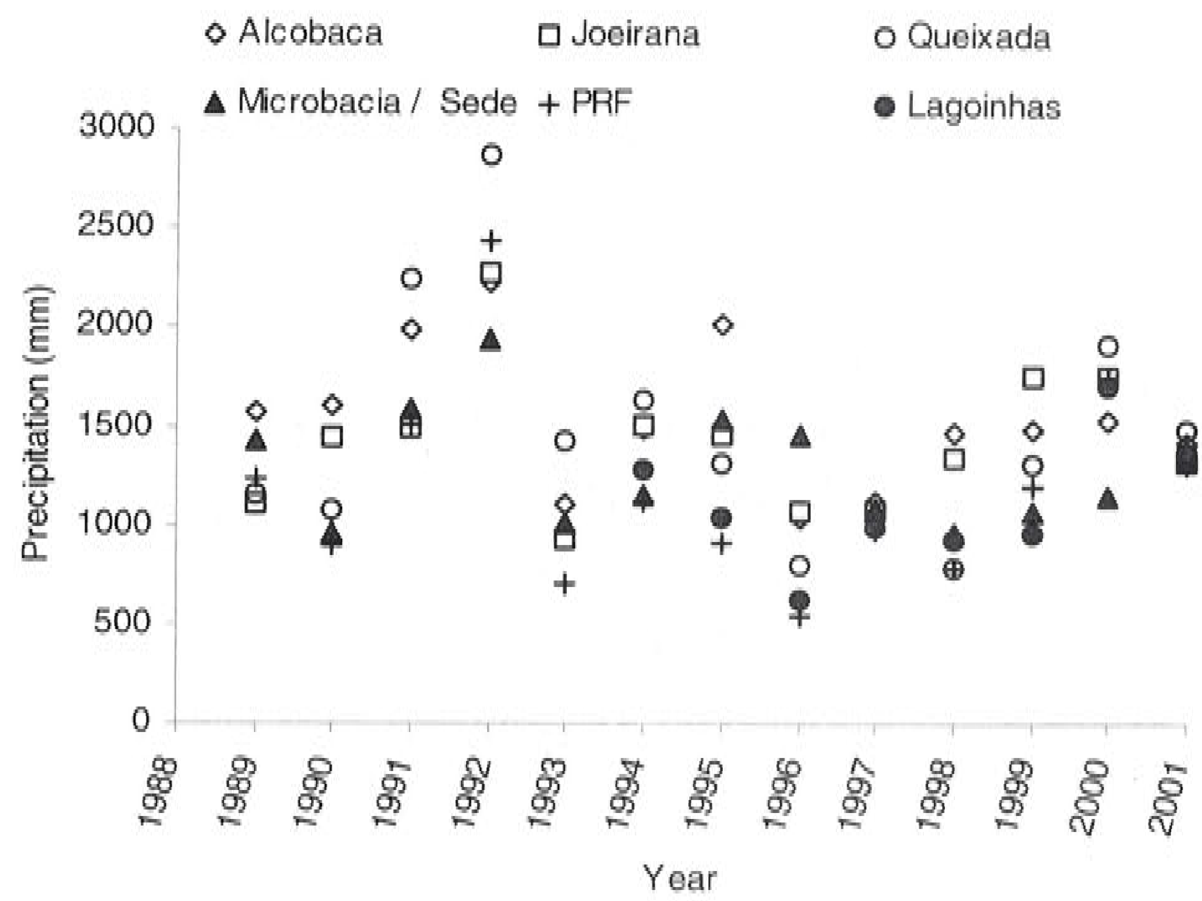


Figure 5.1. Annual precipitation (mm) at six weather stations over a 13-year period. Lagoinhas station has 8-year period only.

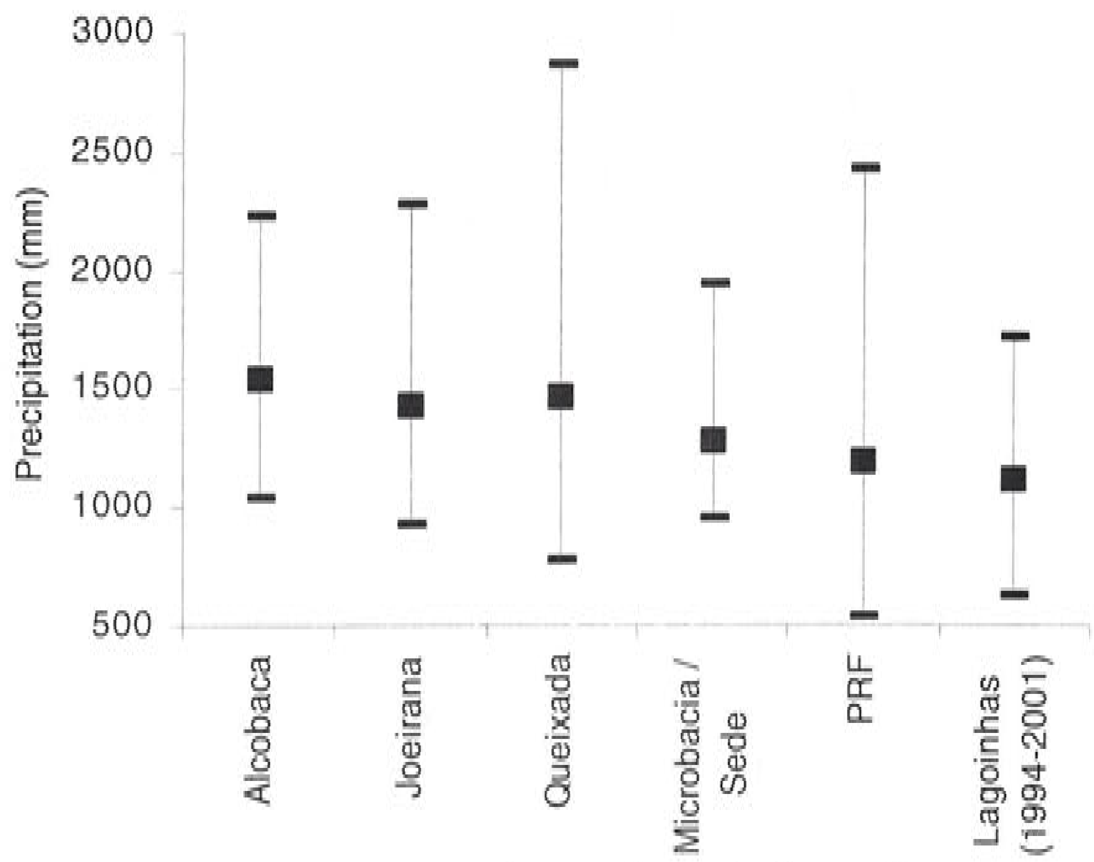


Figure 5.2. Annual rainfall variation at six weather stations. Squares are average values; the lines span the maximum and minimum precipitation from 1988 to 2001 in six weather stations. Data for Lagoinhas station are from 1994 to 2001 only.

5.1.3. Global radiation

Total annual measured global radiation (ϕ_s) is approximately the same at all sites across the region - about 6,250 MJ m^{-2} $year^{-1}$. Alcobaca has the highest value (6,444 MJ m^{-2} $year^{-1}$) and Lagoinhas, the most inland area, the lowest value (5,877 MJ m^{-2} $year^{-1}$). On a seasonal basis, ϕ_s varies from monthly averages of about 20 MJ m^{-2} day^{-1} in January- February to minimum monthly averages of around 10 MJ m^{-2} day^{-1} during mid-winter. There is a significant dip in the amount of energy received in October-November, coincident with the rainfall peak in November.

5.1.4. PAR as a fraction of global radiation

3-PG uses a fixed ratio between PAR and global radiation to calculate the incoming radiation as input. The ratio of PAR to total radiation, in energy units, is often taken as 0.5, although it is known to vary with atmospheric turbidity, solar elevation and the water content of the atmosphere. Ross and Sulev (2000) cite a range of 0.42 to 0.49 for this ratio, which can be expected to vary for clear sky global and diffuse radiation. Li-Cor LI-190SA instruments, which provide a direct measure of PAR, are mounted at eight sites in the Aracruz network and data from them were used to examine the ϕ_p/ϕ_s ratio in the Aracruz region. Figure 5.3a, and 5.3b present data from two stations. Sede is near Microbacia, and PRF is in the central region (see Figure 4.4).

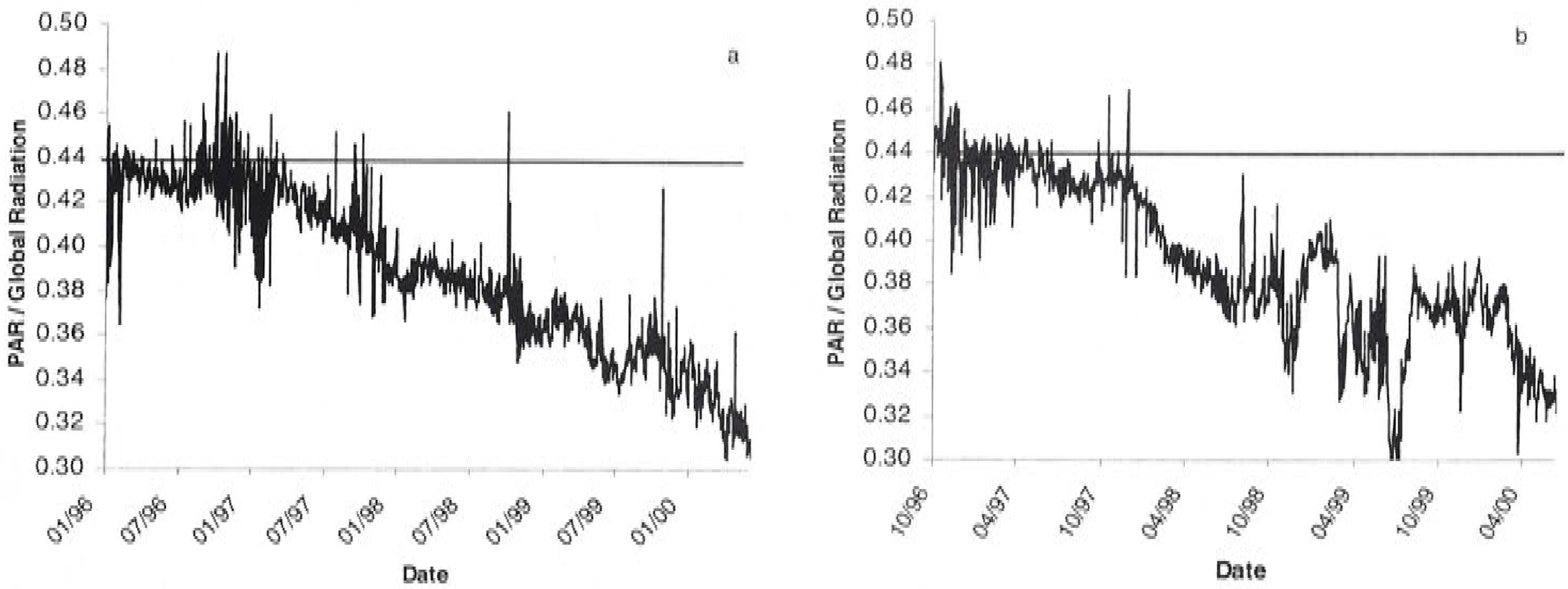


Figure 5.3. The ratio of photosynthetically active radiation (ϕ_p) to global radiation (ϕ_s) for a) Sede station and b) PRF station.

It is immediately apparent from Figure 5.3a and 5.3b that there was drift in the instrumental output after about a year. This occurred at all locations, and in some cases was worse than the trends shown for the Sede and PRF stations in Figure 5.3a and 5.3b. The problem almost certainly lies with the Li-Cor quantum sensor; the average ratio between net and global radiation (Figure 5.4), although variable, showed no trend over a 4-year period, indicating that the average relative output of these sensors remained the same. Subsequent calibration of the original global radiation sensor used at Microbacia station against a new sensor indicated that the average output of the old sensor deviated by less than 2% from the new one after 4 years of use in the field. Therefore the analysis was confined to the ϕ_p/ϕ_s ratios for the first year after installation, when the average relative output of the instruments was, apparently, constant. At both Sede and PRF the ϕ_p/ϕ_s ratio was 0.43 and variance was 0.00022 and 0.00014 respectively, consistent with the values given by Ross and Sulev (2000). This was the value used in 3-PG in the calculations reported in this thesis. The hourly average ratio of ϕ_s (W m^{-2}) to ϕ_p (mmol m^{-2} s^{-1}) for one year was 1 J = 2.12 mmol, which falls within the range (1.92 – 2.15) given by Udo and Aro (1999). Seasonal variations can be expected, as shown by Alados *et al.* (1996) and Udo and Aro.

5.1.5. Net radiation as a fraction of global radiation

Net radiation (ϕ_n) is one of the most important driving variables for calculating transpiration. The Penman-Monteith equation, which is used by 3-PG and several other process-based forest models, requires daily or monthly values of ϕ_n. Net radiation is not widely measured on a routine basis – installation for consistent comparisons of ϕ_n for tall vegetation surfaces is not straightforward and instrumental maintenance can be difficult. There were two stations (Cachoeirinha and Microbacia, both in the Aracruz area) where net radiometers were exposed satisfactorily over the plantation canopies. Net radiation data for the period April 1999 to July 2000 for the Microbacia and Cachoeirinha stations are presented in Figure 5.4.

The ratio ϕ_n/ϕ_s can vary widely on an hourly basis and average values show some seasonal variation (Figs 5.4a and 5.4b), because long-wave fluxes are strongly affected by cloud and atmospheric water vapor. In Figure 5.4 precipitation is also plotted on the x-axis, but it is clear that there is no simple relationship between values of ϕ_n/ϕ_s and rainfall, so the matter was not pursued.

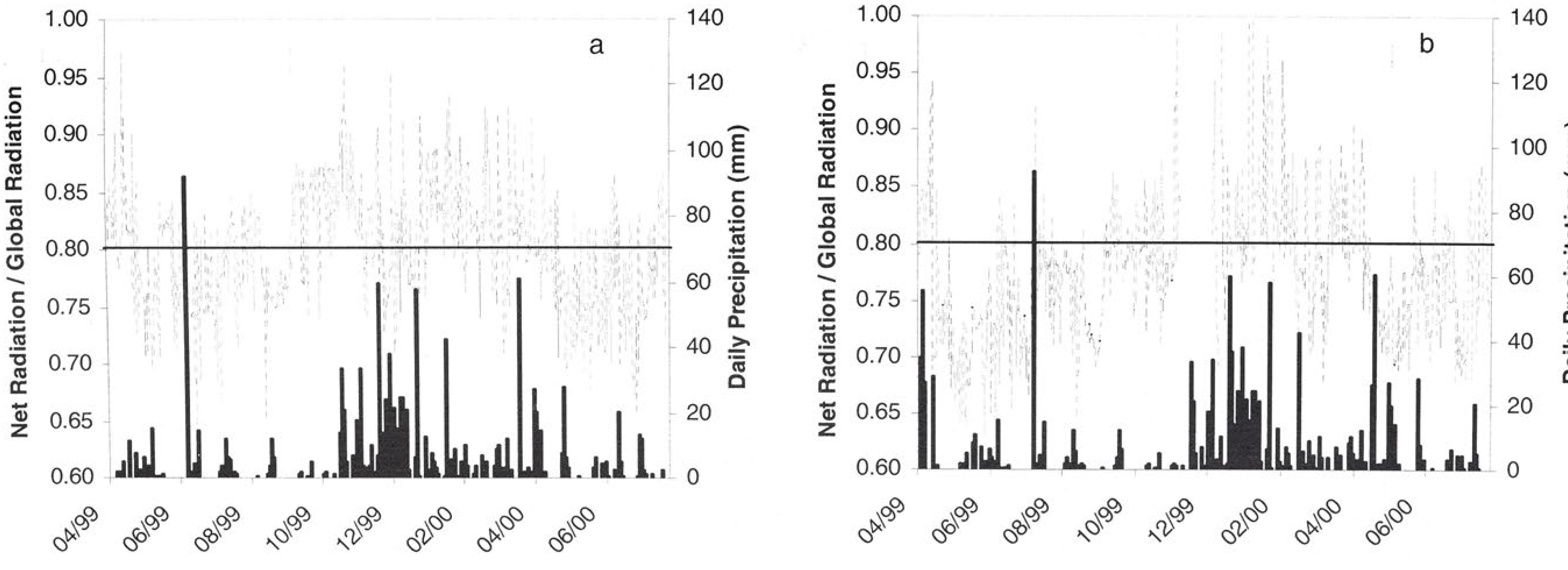


Figure 5.4. Daily values of the ratio of net radiation (ϕ_n) to global radiation (ϕ_s) for a) Microbacia station and b) Cachoeirinha station. Daily precipitation is also plotted (as histograms) There are some indications of seasonal differences in the ratio.

There are a number of studies in the literature, examining the values of the parameters *a* and *b* in the equation, relating ϕ_n and ϕ_s.

$$\phi_n = a + b\,\phi_s \qquad (5.1)$$

Landsberg (1986) reviewed these and suggested a value for *b* of 0.8 for forests. For deciduous forests the best estimate of *a* appeared to be about –90 W m^{-2}. In this study, I obtained, for daily data (average flux densities), from the Microbacia site the relationship obtained was

$\phi_n = -8.85 + 0.82\phi_s$ (W m^{-2}) $r^2 = 0.94$ n = 933

Standard errors: estimate = 24.13 (W m^{-2}), *a* = 2.66 (W m^{-2}) and *b* = 6.6 x 10-3 (W m^{-2})

For Cachoerinha

$\phi_n = -6.78 + 0.81\phi_s$ (W m^{-2}) $r^2 = 0.93$ n = 623

Standard errors: estimate = 24.15 (W m^{-2}), *a* = 3.46 (W m^{-2}) and *b* = 8.8 x 10-3 (W m^{-2}).

The values of *b* (0.82 and 0.81) are similar to those reviewed by Landsberg, but the intercepts are a great deal smaller, so estimates of ϕ_n obtained with these equations will be significantly higher than those obtained assuming *a* = -90 W m^{-2}.

Since, for calculations of daily transpiration, integrated values of ϕ_n were required, the relationships between ϕ_n and ϕ_s in MJ m^{-2} day^{-1} were also calculated giving, for Microbacia

$\phi_n = -0.23 + 0.74\phi_s$ (MJ m^{-2} day^{-1}) $r^2 = 0.95$ n = 933

Standard errors: estimate = 0.99 (MJ m^{-2} day^{-1}), a = 0.13 (MJ m^{-2} day^{-1}) and b = 7.0 x 10^{-3},

and for Cachoerinha

$\phi_n = -1.18 + 0.71\ \phi_s$ (MJ m^{-2} day^{-1}) $r^2 = 0.91$ n = 623

Standard errors: estimate = 1.18 (MJ m^{-2} day^{-1}), a = 0.15 (MJ m^{-2} day^{-1}) and b = 88.0 x 10^{-3}. The reason(s) for the differences between the hourly and daily data is discussed in the section 5.1.7.

5.1.6. Daily VPD as a function of maximum and minimum temperatures

In this study the daytime average values of vapour pressure deficit (VPD_{day}, D_d) were of primary interest, since this is the driving variable for transpiration. VPD also has a significant direct effect on productivity; high daytime values cause stomatal closure and reduce growth. Figure 5.5 shows that there are large differences in VPD_{day} across the study regions, particularly in the early part of the year. During February VPD_{day} at Lagoinhas, the most inland of the study sites (Figure 4.4) is around 1.3 kPa - more than twice as high as at Alcobaca (0.5 kPa), the difference gradually reducing to 0.3 kPa in winter and increasing again as temperatures increase, although the high rainfall in early summer (Appendix II) prevents the maximum differences from developing. VPD_{day} at the other measurement sites is intermediate.

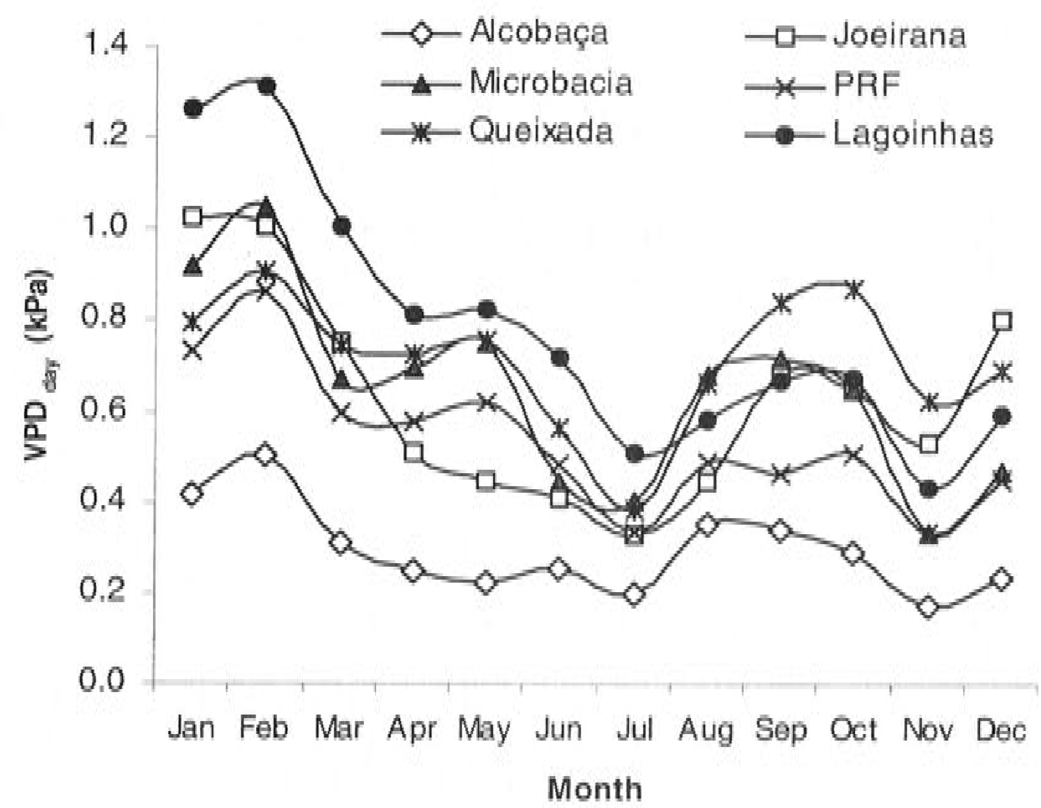


Figure 5.5. Average monthly VPD_{day} (kPa) during years 1997 to 2001 at 6 weather stations.

The original formulation of 3-PG (Landsberg & Waring, 1997) estimates VPD using maximum (T_{max}) and minimum (T_{min}) daily temperature. Average daily (24 hr) vapour pressure deficit (VPD_{24h}, D_{24}) is often estimated as half the difference between saturated vapour pressure at the dewpoint and at daily maximum temperature (T_{max}) (Running & Coughlan, 1988; Kimball *et al.*, 1997; Coops *et al.*, 2000). The values calculated this way are denoted as $VPD_{del.T}$ (D_t). Kimball *et al* (1997) introduced a procedure that improves on this, but it requires daily precipitation and radiation and, since this study is primarily concerned with monthly average values, it is not used. As stated earlier, VPD_{day} was calculated from the automatic weather station data, as the average VPD for the period from the first hour when $\phi_s > 1$ W m^{-2} to the last.

Regression of monthly average VPD_{day} against the estimator value, monthly average $VPD_{del.T}$, for the period January 1995 to July 2000 for Microbacia, September 1996 to July 2000 for PRF and Queixada and January 1997 to July 2000 for Alcobaca, Lagoinhas and Joeirana weather stations, gave the results shown in Table 5.1. The slope of the relationship varies from 1.57 at Joeirana to 1.14 at Microbacia; the intercepts also vary widely – from -0.065 at Queixada to

-0.483 at Lagoinhas. Regressions using daily data gave slightly different results; these are illustrated for Microbacia and Lagoinhas in Figure 5.6. The equations of the lines in Figure 5.6 are:

(a) $D_d = 0.001 + 1.07\ D_t$ ($r^2 = 0.65$).

(b) $D_d = -0.273 + 1.22\ D_t$ ($r^2 = 0.68$)

Table 5.1. Constants and coefficients of linear regressions, for different areas, of average monthly daytime VPD values (D_d, kPa) against VPD calculated from daily maximum and minimum temperatures (D_t), i.e. $D_d = a + m.D_t$.

Weather station	Intercept (a)	Slope (m)	r^2	n (months)
Alcobaca	-0.392	1.370	0.525	37
Joeirana	-0.464	1.568	0.788	41
Lagoinhas	-0.483	1.502	0.688	43
Queixada	-0.065	1.194	0.542	43
PRF	-0.227	1.213	0.647	44
Microbacia	-0.033	1.138	0.653	66

Figure 5.7 shows that the ratio of VPD_{day} to $VPD_{del.T}$ varied from zero to 2.4 at Microbacia Station and from 0.2 to 2.2 at Lagoinhas Station. At Microbacia, near the coast (Figure 4.4) – the values are normally distributed around 1.0, particularly during the wetter months. During the drier months, VPD_{day} is generally higher than $VPD_{del.T}$, as we would expect. The seasonal cycle is clearer at the inland station (Lagoinhas), where the ratio is also more consistent.

From the point of view of biophysical models involving calculations of transpiration, VPD_{day} is more important than the average value of VPD calculated over 24 hours of the day. However, since this is a commonly used variable, the relationship between VPD_{24h} and $VPD_{del.T}$, is presented for two of the weather stations, is presented in Figure 5.8. This shows that $VPD_{del.T}$ overestimates the true average daily value of VPD in both locations.

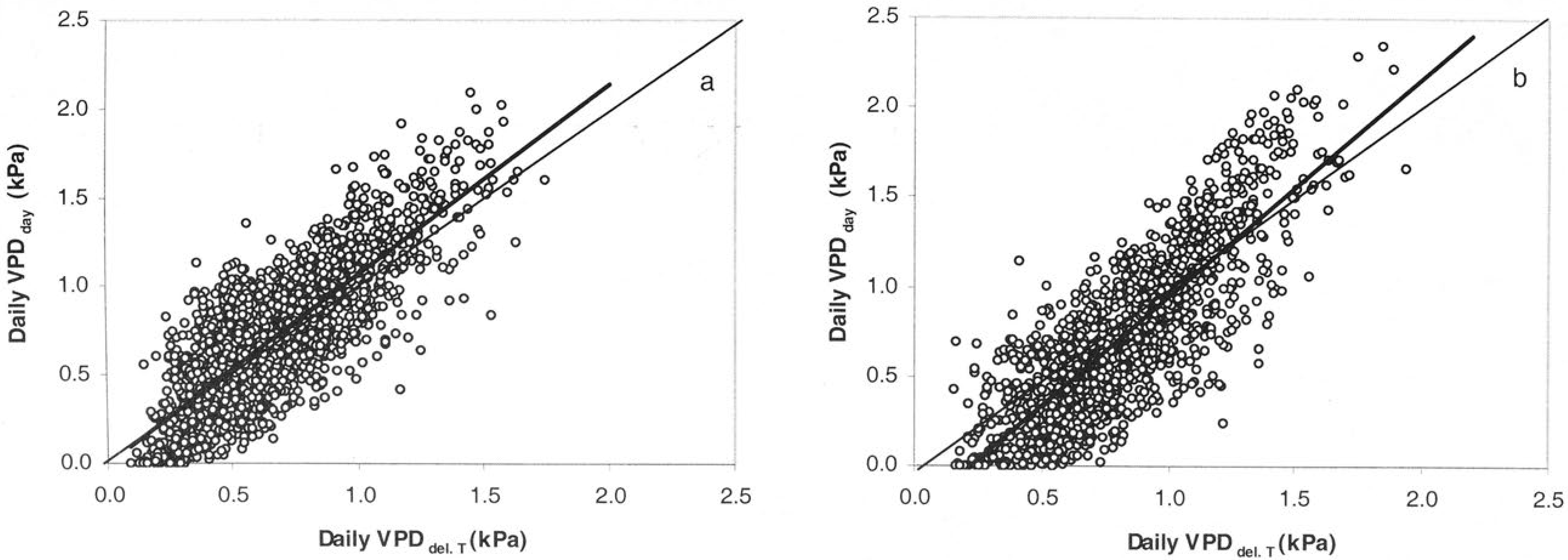
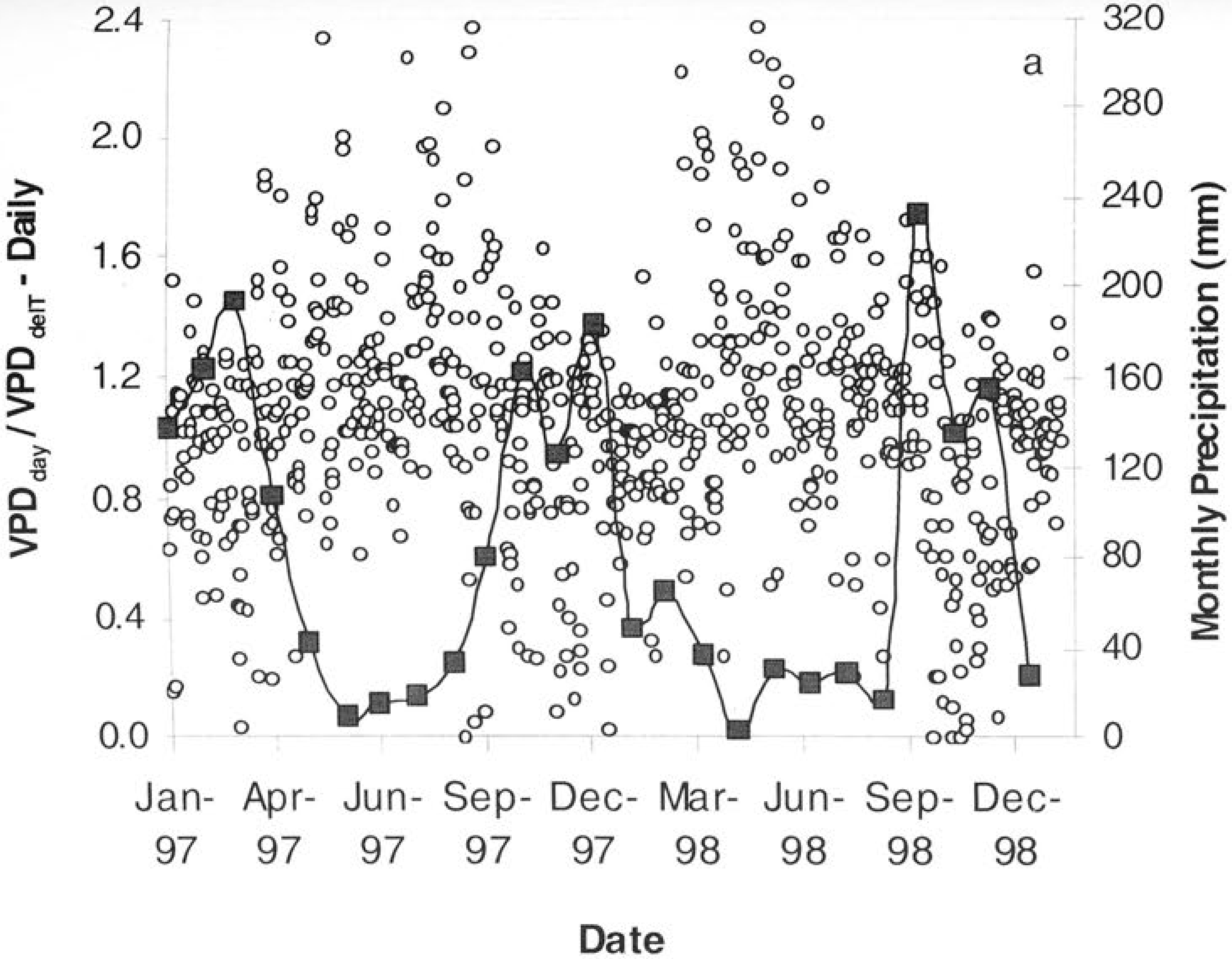


Figure 5.6. Relationships between daily average values of VPD_{day} and $VPD_{del.T}$ at a) Microbacia and b) Lagoinhas. The 1:1 line is shown.



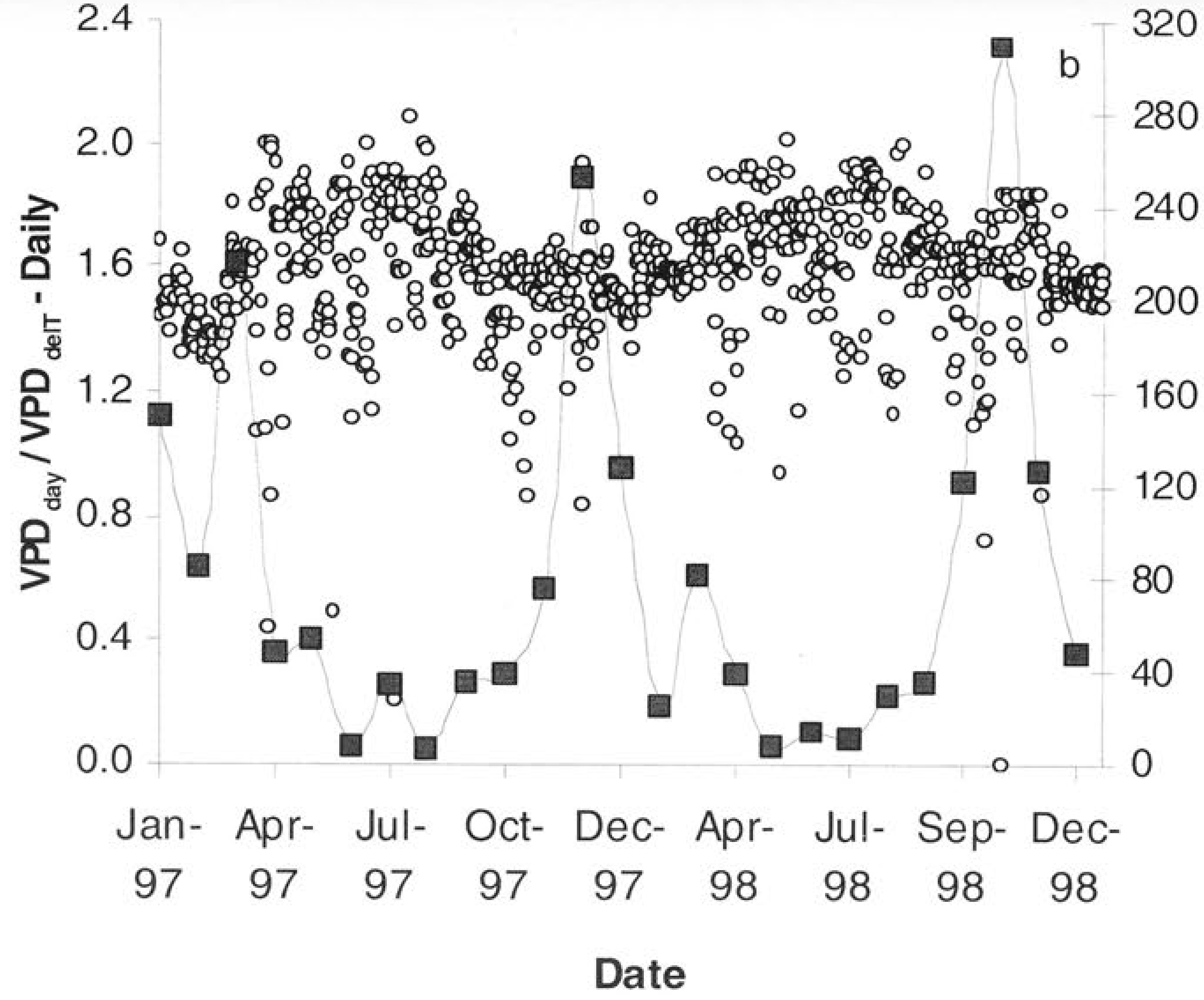


Figure 5.7. Ratios of daily values of VPD_{day} to $VPD_{del.T}$ at a) Microbacia station and b) Lagoinhas station (dots) and respective monthly precipitation (lines).

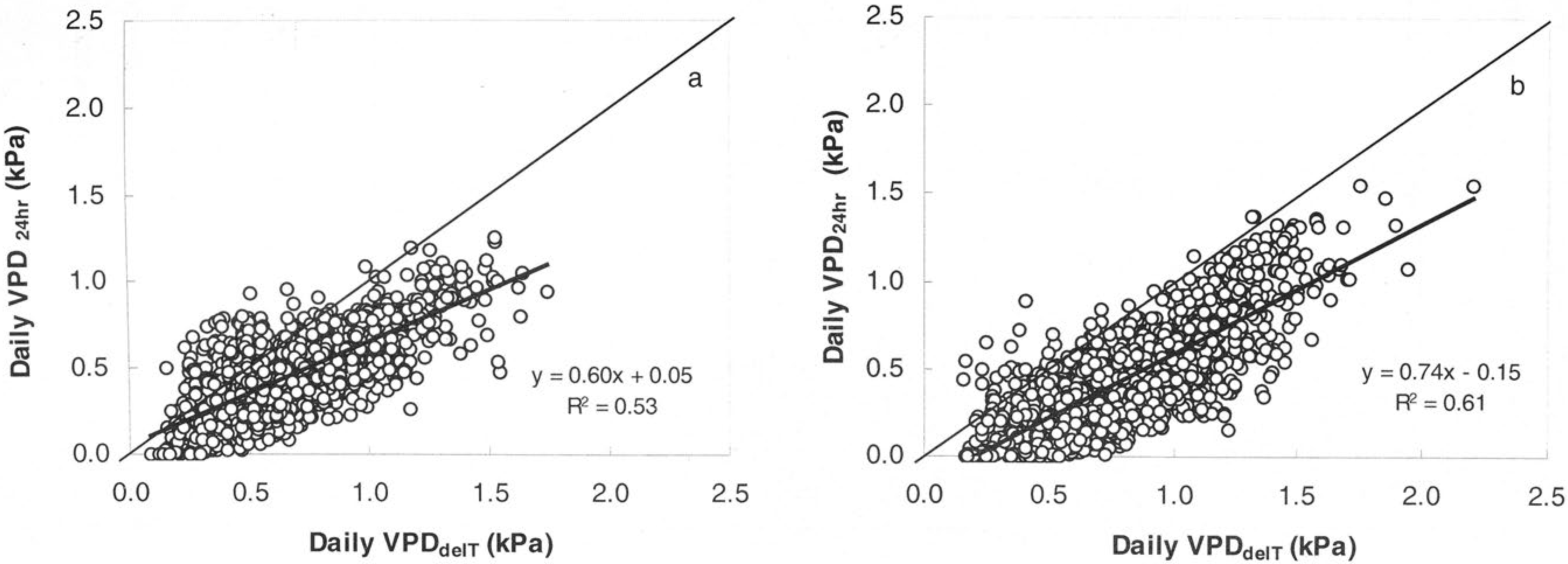


Figure 5.8. Daily values of VPD_{delT} (kPa) plotted against VPD_{24h} at a) Microbacia and b) Lagoinha station.

Average values of atmospheric VPD can be estimated in various ways. The AWS provide the data needed to calculate true 24 hr averages (VPD_{24h}) or average values for daylight hours (VPD_{day}). It was found that $VPD_{del.T}$ underestimated VPD_{day} by amounts varying from about 13% to about 50%; this is to be expected because $VPD_{del.T}$ includes the night-time periods when VPD is low, often approaching zero (the dew point) in the early hours of the morning. VPD_{day} includes the high values that occur when temperatures rise during the day, and does not include the low night-time / early morning values. $VPD_{del.T}$ generally overestimated VPD_{24h}, but the relationship was very different near the coast (Alcobaca) and 50 km inland (Lagoinhas) because of the influence of humid air from the sea; at Alcobaca the values of VPD_{24h} are only about 60% of the estimates made using $VPD_{del.T}$, while inland at Lagoinhas the air is drier and VPD_{24h} is about 74% of the estimates made using $VPD_{del.T}$. This result suggests that the influence of water vapour in the air coming off the sea is localised and has more effect on air humidity than on radiation.

Accurate values for atmospheric VPD are important because of the effects of this variable on stomatal conductance and hence on transpiration rates, affecting stand water use and the soil water balance. VPD_{day} is the best variable to use for calculating transpiration and for modelling growth. It can be reasonably well estimated from linear regression of VPD_{day} on $VPD_{del.T}$, when $VPD_{del.T}$ accounts for between 53% and 79% of the variance in VPD_{day}. However, the slopes of the relationship varied significantly from site to site within the study region, indicating that it could lead to significant errors if used as a predictive relationship in areas where it has not been tested. Because the study region is relatively small, and is strongly influenced by maritime air, it is not possible to say whether variations of this magnitude can be expected between localities in other regions of the world. Although the fact that the predictive power of $VPD_{del.T}$ as an estimator of VPD_{24h} has been quite widely tested (Running & Coughlan, 1988; Coops *et al.*, 2000), the study reported here demonstrated that, in this region, VPD_{24h} was significantly underestimated by $VPD_{del.T}$, with indications that the site to site differences also occur in this relationship.

5.1.7. Weather: synthesis and implications for 3-PG model.

From the point of view of operational use of a forest growth simulation model by ARCEL, the network of automatic weather stations provides the necessary climatic input data.

The relationship between PAR and global radiation, on a daily basis, was similar to that found elsewhere and consistent with the results from the very careful and detailed study by Ross and Sulev (2000). There were indications of seasonal variation in this ratio, but instrumental problems precluded thorough investigation. It was observed that the LI-190SA PAR sensor lost accuracy after about one year's use. A value of 0.43 for the ratio between global radiation and PAR will give better results - at least in eastern Brazil - than the commonly used approximation (e.g. by Landsberg and Waring, 1997) of 0.5.

The linear relationship between net radiation and global radiation, based on hourly data obtained at two sites, appears to be robust and consistent with published relationships, except that the intercept, which reflects net long-wave flux, is very much smaller than many published values. This indicates that the energy retained by the surface – and hence available for transpiration – is relatively higher, per unit ϕ_s, than in other published relationships. This may reflect the generally high water vapour content of the air in this tropical coastal region. Figure 5.4 shows that there are some seasonal variations in the relationship; the slope of the linear regression during September to April (wet season) is about 0.84 and during May to August it is about 0.76. To calculate ϕ_n from ϕ_s, in terms of W m^{-2}, the slope of the relationship is about 0.81 and the intercept –7 W m^{-2}. If ϕ_s is in terms of MJ m^{-2} day^{-1} the slope of the relationship is 0.71 and the intercept is –1 MJ m^{-2} day^{-1}. This latter relationship is probably more useful for the calculation of daily transpiration rates for use in, for example, forest growth simulation models such as 3-PG that run over long periods with time steps of a month. The reason for the differences between the equations obtained by regression analyses of hourly and daily ϕ_n and ϕ_s data lies in the different distribution of the values obtained from hourly flux density measurements and integrated daily total energy income values. Regressions of ϕ_n on ϕ_s using hourly data have higher slopes because of the occurrence of high midday flux density values and low morning and evening values; ϕ_n is occasionally negative in early morning when ϕ_s is positive. Daily values are obtained by multiplying hourly flux density values by time (s), leading to a different distribution and the differences in the relationships indicated by equations.

5.2. Biomass partitioning

The data used to establish carbon partitioning and the growth patterns of *Eucalyptus grandis* were collected yearly over a five year period in the MBE for five genotypes. A complementary data set was obtained from destructive sampling of trees in operational areas. The allometric equations used in the calibration of 3-PG were established using this database. The annual destructive sampling allowed the generation of specific equations for each genotype and one general equation for use in large areas including different clones. The distribution of total biomass produced, to stems, bark, branches, foliage and roots, changes with age as shown in Figure 5.9. The proportion of foliage reduced from 31% of total biomass at age 1.2 years to 2.2% at age 5.4 years; stem biomass varied from 21.4% to 71.6% with the major changes taking place before the third year. The proportion of roots did not change significantly during the rotation.

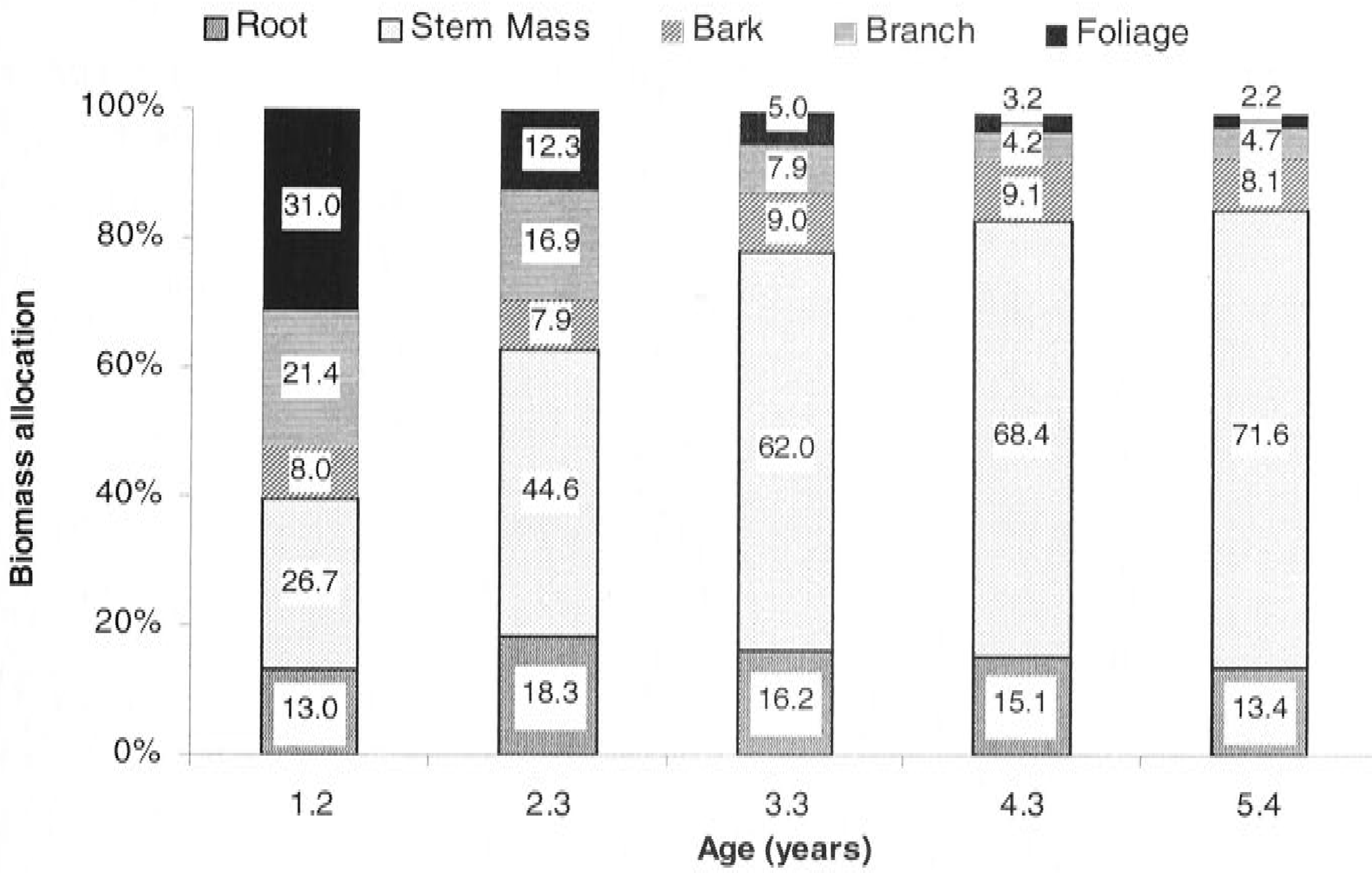


Figure 5.9. Biomass allocation as a function of stand age at the MBE site. Data are averages for five genotypes.

Table 5.2 summarises the average total mass (kg tree^{-1}) in each component of the three trees for each of the five clones from age 1.2 to 5.4 years.

Table 5.2. Variation of DBH and average biomass in the tree components in five ages. Those numbers are the average of five clones and three trees per clone.

Age (years)	DBH (cm)	Stem	Bark	Foliage	Branch	Root	Total biomass
				(kg tree^{-1})			
1.2	-	0.8	0.2	0.9	1.2	0.4	3.5
2.3	8.2	10.9	1.9	3.0	4.5	4.5	24.8
3.3	12.0	33.6	4.9	2.7	6.8	8.8	56.7
4.3	13.5	54.7	7.3	2.5	6.3	12.1	82.9
5.4	15.0	85.1	9.6	2.6	8.3	16.0	121.6

As mentioned in Chapter 3, one of the most important components of 3-PG is the relationship between single tree woody biomass (w_s) and stem diameter (denoted by B in equations). Figure 5.10 illustrates the relationships between DBH (cm) and w_s (kg; stem, branches and bark) for five clones and Table 5.3 shows the coefficients of the non-linear regression of DBH (B, cm) against woody biomass (kg tree^{-1}) (see equation 3.20a).

Table 5.3. Stem constant (a_s) and stem power (n_s) values for five clones in the MBE area.

Genotype	a_s	n_s	r^2
AR4	0.071	2.636	0.957
22	0.033	2.912	0.975
15	0.049	2.822	0.984
1248	0.009	3.481	0.980
847	0.033	2.879	0.981

To analyse the model performance and differences between genotypes, clone 15 and clone 22 were selected because they are the most planted clones and show significant differences in growth.

The significance of the differences in the relationships for these clones was tested by fitting multiple linear regression using *dummy* variables (Draper & Smith, 1981) where biomass was the dependent variable, diameter at breast height and clone (*dummy* variable) were the independent variables. The results indicated that differences between clones 15 and 22 were significant (t-test of the dummy coefficient estimator = -4.158, $p < 0.0001$).

The stand volume calculation in 3-PG includes a fraction of bark and branches (p_{BB}) dependent on stand age (Equation 3.30). Figure 5.9 shows that p_{BB} can be obtained from the average five clones where: age 1.2 years = 29.4% and age 4.4 years = 13.3%. From this relation it was established the bark and branches parameter values for 3-PG: p_{BB0} = 30%, p_{BB1} = 12% and t_{BB} = 2 years.

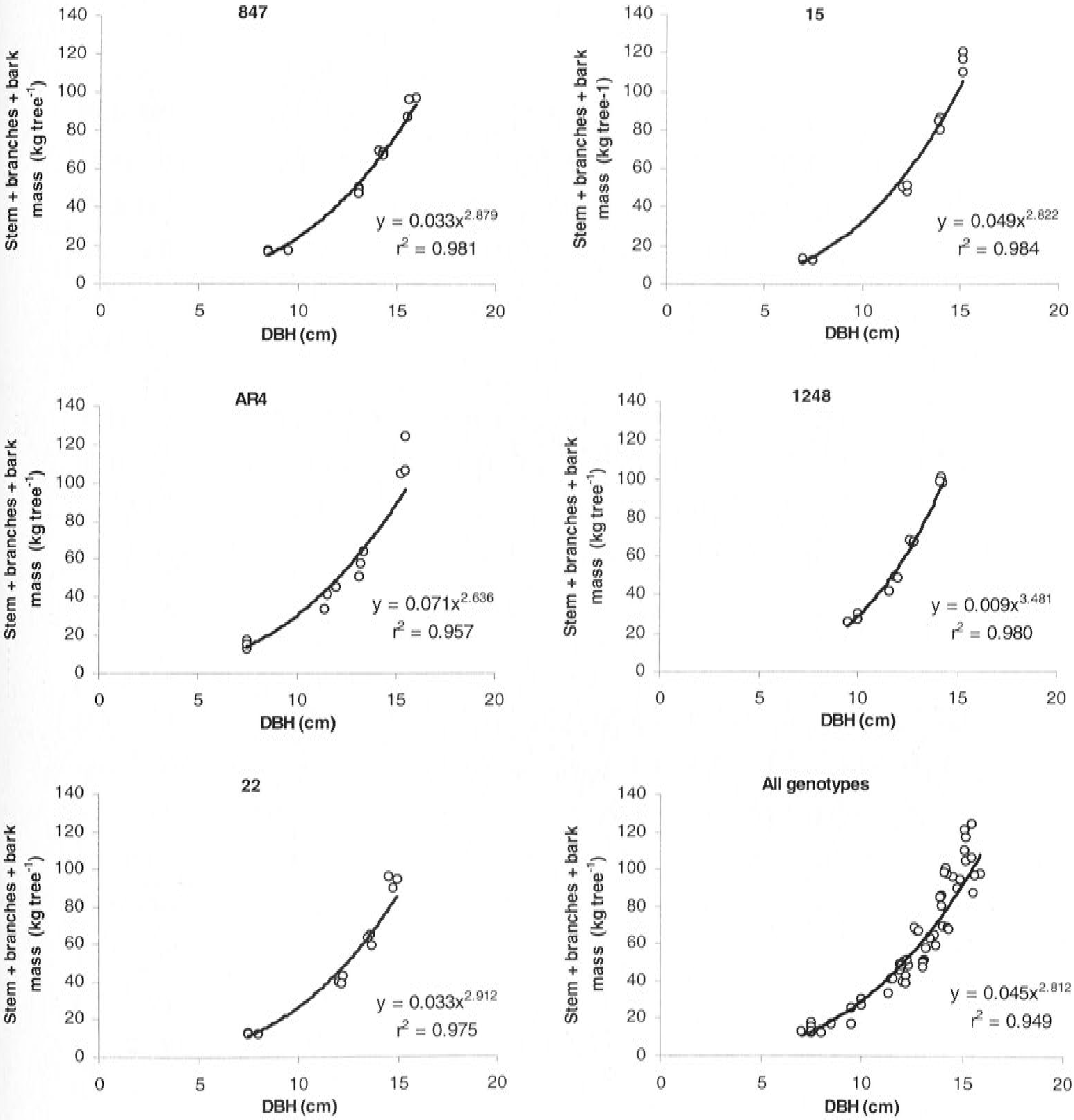


Figure 5.10. Regressions of woody biomass (stem + bark + branches) (kg tree^{-1}) on DBH (cm) for five genotypes and pooled data for all clones.

5.3. Root biomass

Root biomass and turnover are among the most difficult data to obtain to use in forest models. Accurate measurements of roots are hard, and timing consuming, to obtain. In the MBE experiment root biomass was collected in four years in five clones through destructive samples in three trees each clone. The total root biomass was composed of the sum of fine (<2 mm), medium (2-5 mm) and coarse roots (>5 mm).

Table 5.4 shows that clone 15 allocates less biomass to roots than the other clones. The root depth is relatively shallow, about 2 m at 5.4 years, which limits water use to this depth in the soil profile. It appears that clone 1248 allocates much more biomass to roots during the early stage, while AR4 increases its root mass during the final growth stage.

Figure 5.11 shows the relationship between root mass and DBH for clone 15 (Figure 5.11a) and clone 22 (Figure 5.11b), obtained from destructive samples of roots that still excludes carbohydrates required to maintain active mycorrhizae and that in exudates. A non-linear equation was established by regression. To find the best values for the 3-PG parameters defining the maximum fraction of NPP allocated to roots (η_{Rx}), for both clones, and the minimum fraction of NPP allocated to roots (η_{Rn}), the two parameters were tuned so that the root mass predicted by 3-PG corresponded closely to the observed data. The red dotted line in Figure 5.11 was produced by the model after this procedure. The values obtained were $\eta_{Rx} = 0.6$ for both clones and $\eta_{Rn} = 0.07$ for clone 15 and 0.12 for clone 22) (Note that the value assumed by root turnover rate (γ_R), which may affect this result, was not altered in this exercise).

Table 5.4. Root depth and root biomass in five clones at age 2.3 to 5.4 years. The values are averages for three trees of each clone.

Clone	Age (years)	Average root depth (m)	Average fine root biomass (kg tree^{-1})	Average medium root biomass (kg tree^{-1})	Average coarse root biomass (kg tree^{-1})	Average total root biomass (kg tree^{-1})
AR4	2.3	103	0.13	0.18	4.19	4.49
22	2.3	80	0.19	0.14	2.85	3.18
15	2.3	93	0.13	0.14	2.00	2.28
1248	2.3	93	0.13	0.20	7.89	8.23
847	2.3	107	0.25	0.21	3.70	4.15
AR4	3.3	93	0.14	0.22	7.50	7.86
22	3.3	140	0.32	0.28	9.89	10.49
15	3.3	127	0.15	0.19	7.02	7.36
1248	3.3	157	0.16	0.19	8.43	8.78
847	3.3	127	0.27	0.31	10.78	11.36
AR4	4.3	146	0.10	0.20	11.44	11.74
22	4.3	192	0.09	0.14	12.92	13.15
15	4.3	149	0.11	0.16	10.72	11.00
1248	4.3	167	0.06	0.13	10.88	11.07
847	4.3	185	0.10	0.21	13.31	13.62
AR4	5.4	196	0.13	0.52	20.46	21.11
22	5.4	204	0.22	0.79	15.43	16.44
15	5.4	178	0.09	0.29	11.64	12.01
1248	5.4	180	0.14	0.13	13.64	13.91
847	5.4	202	0.16	0.16	15.90	16.22

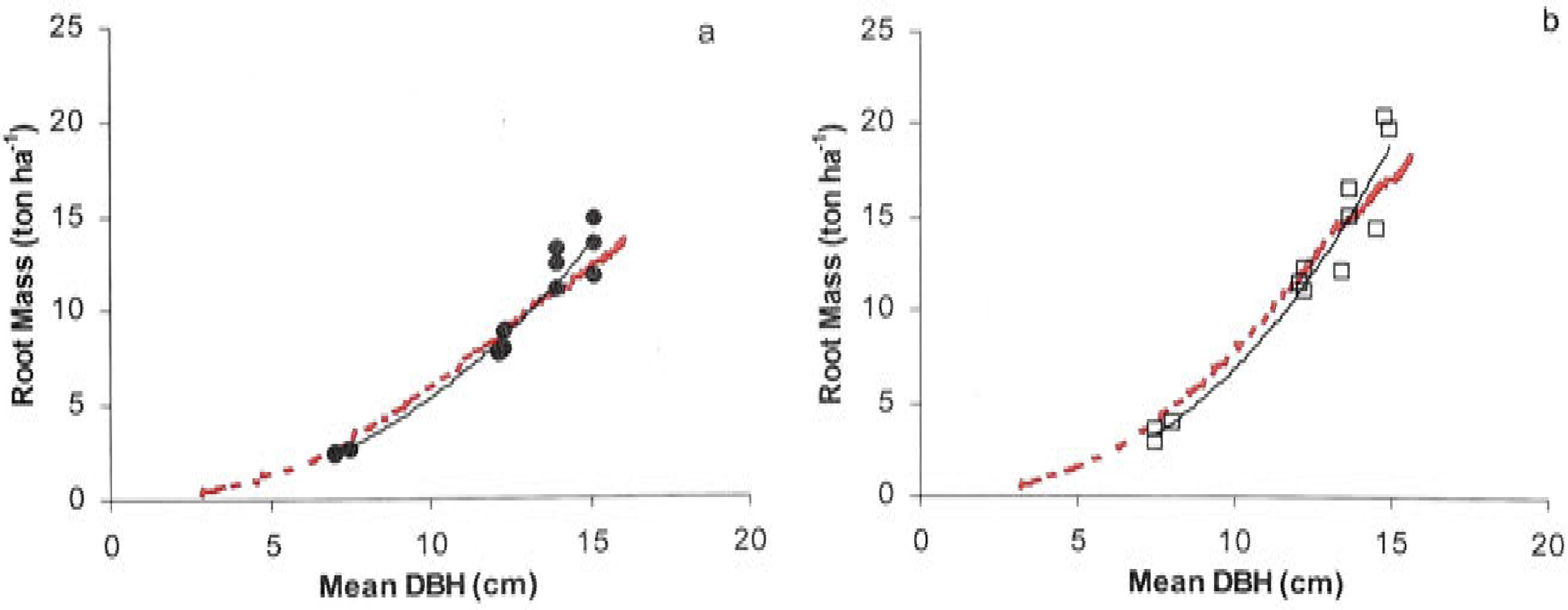


Figure 5.11. Relation between root mass (t ha^{-1}) and DBH (cm) measured in single trees (dots) in a) clone 15 and b) clone 22. The solid lines represent the regression obtained from tree samples and the dashed lines are simulated by 3-PG.

5.4. Wood density

The wood density (ρ) is used to calculate the stand volume. It is age dependent in the same way as p_{BB}. Wood density was measured in operational areas, providing values during the 7-year rotation for clone 15 and clone 22. The results are presented in Figure 5.12.

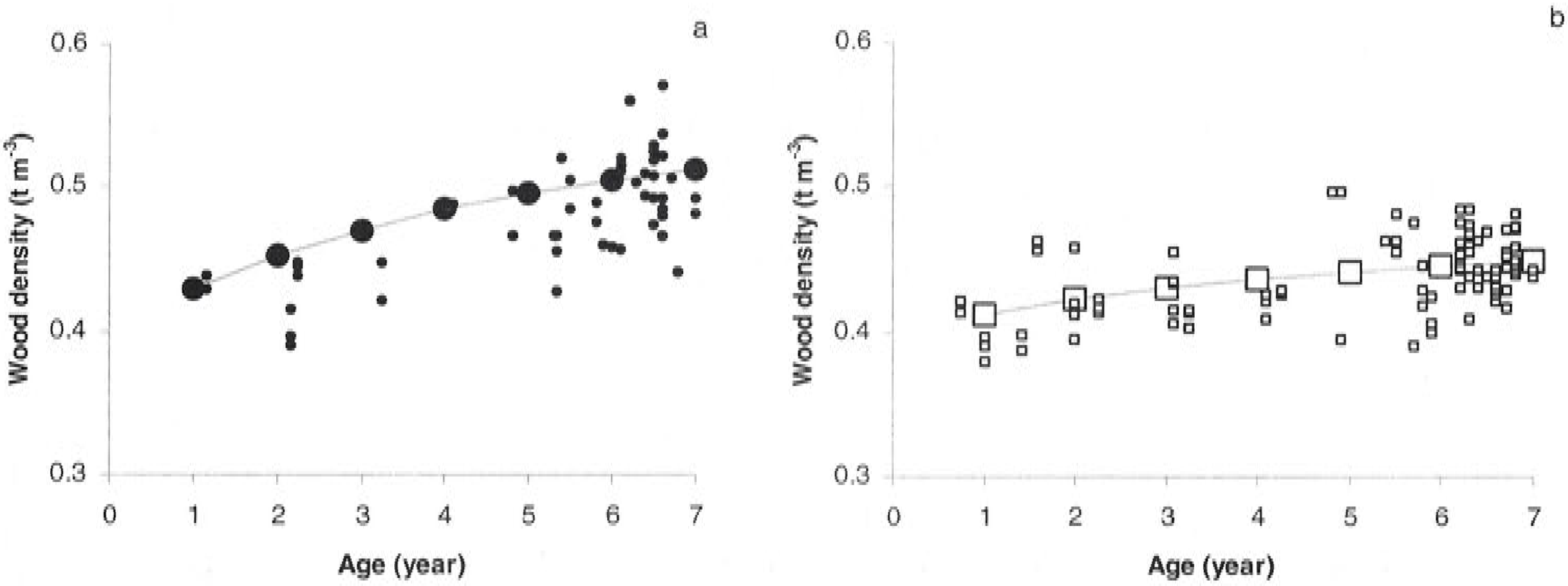


Figure 5.12. Wood density variation with stand age a) for clone 15 and b) clone 22. Small symbols are observed data and large symbols are estimates obtained by applying the 3-PG wood density function (Equation 3.29) where $\rho_m = 0.4$ t m^{-3} for both clones, $\rho_x = 0.54$ for clone 15 and 0.48 for clone 22 and $t_\rho = 3$ years.

5.5. Leaf area index

The variation of leaf area index during the *Eucalyptus* rotation has direct influence on tree growth rates. The monthly measurements using the LAI-2000 show that the peak LAI is reached at age 3 years and decay to a value of around 2. Seasonal variation can be observed in all genotypes and it appears to have a direct effect on available soil water. Figure 5.13a shows the LAI measured in MBE for clones 15, 22 and AR4 and Figure 5.13b shows the LAI differences between these clones in each month. Clone 15 has higher LAI than clone 22 during the whole rotation and is higher than clone AR4 after age 2.5 years. During the first three years, Clone 22 has lower LAI than AR4. The measured LAI values were used to compare the estimates of LAI obtained by 3-PG simulations (see Chapter 6). Figure 5.14 illustrates the LAI variation as a function of stand age and season. The peak LAI is reached between the second and the third year and during the autumn.

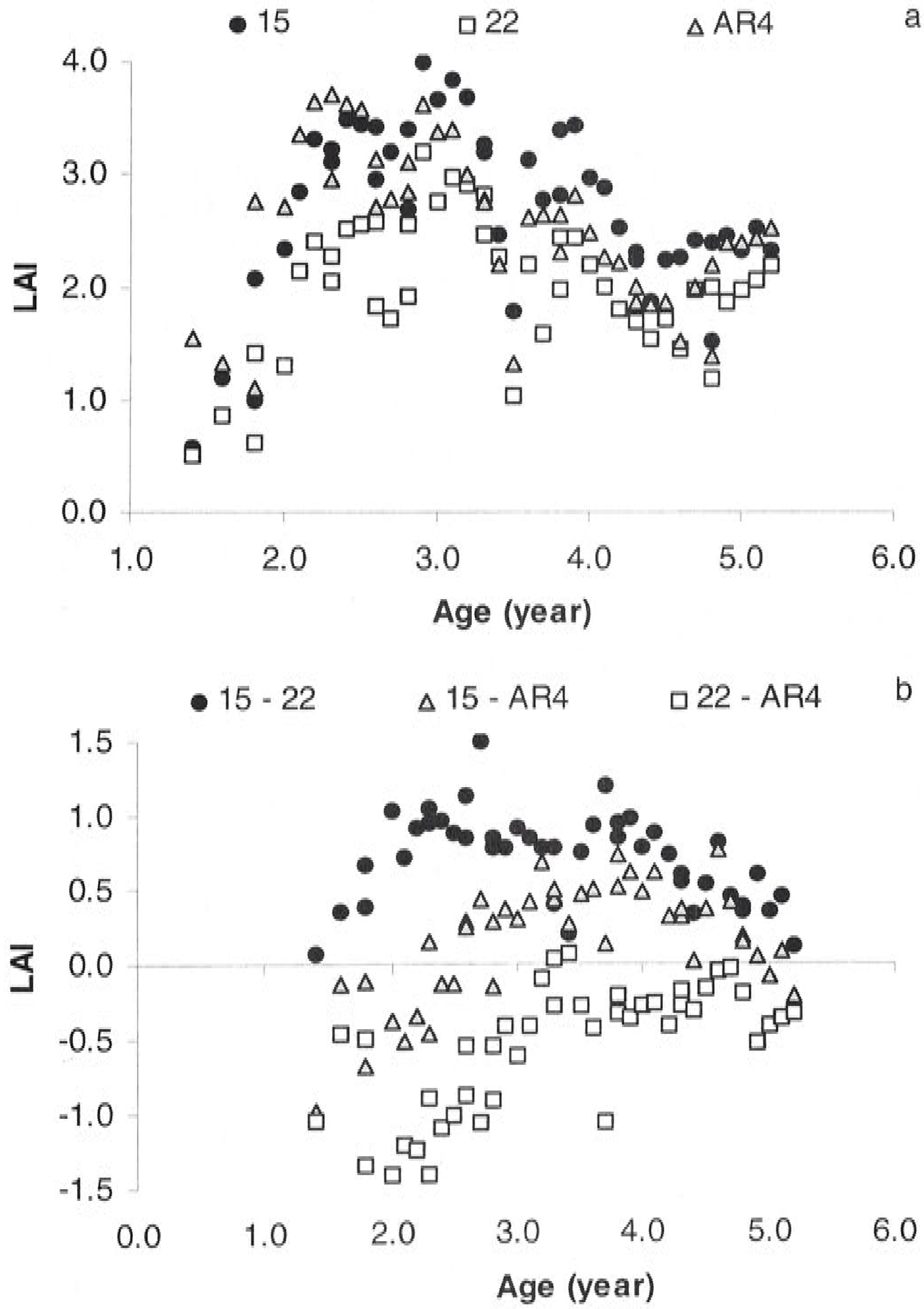


Figure 5.13. LAI variation with stand age for a) clones 15, 22 and AR4 and b) LAI differences between clones. The differences are calculated as: clone 15 - clone 22 (circles), clone 15 - clone AR4 (triangles) and clone 22 - clone AR4 (squares). The clones were planted during summer of 1997.

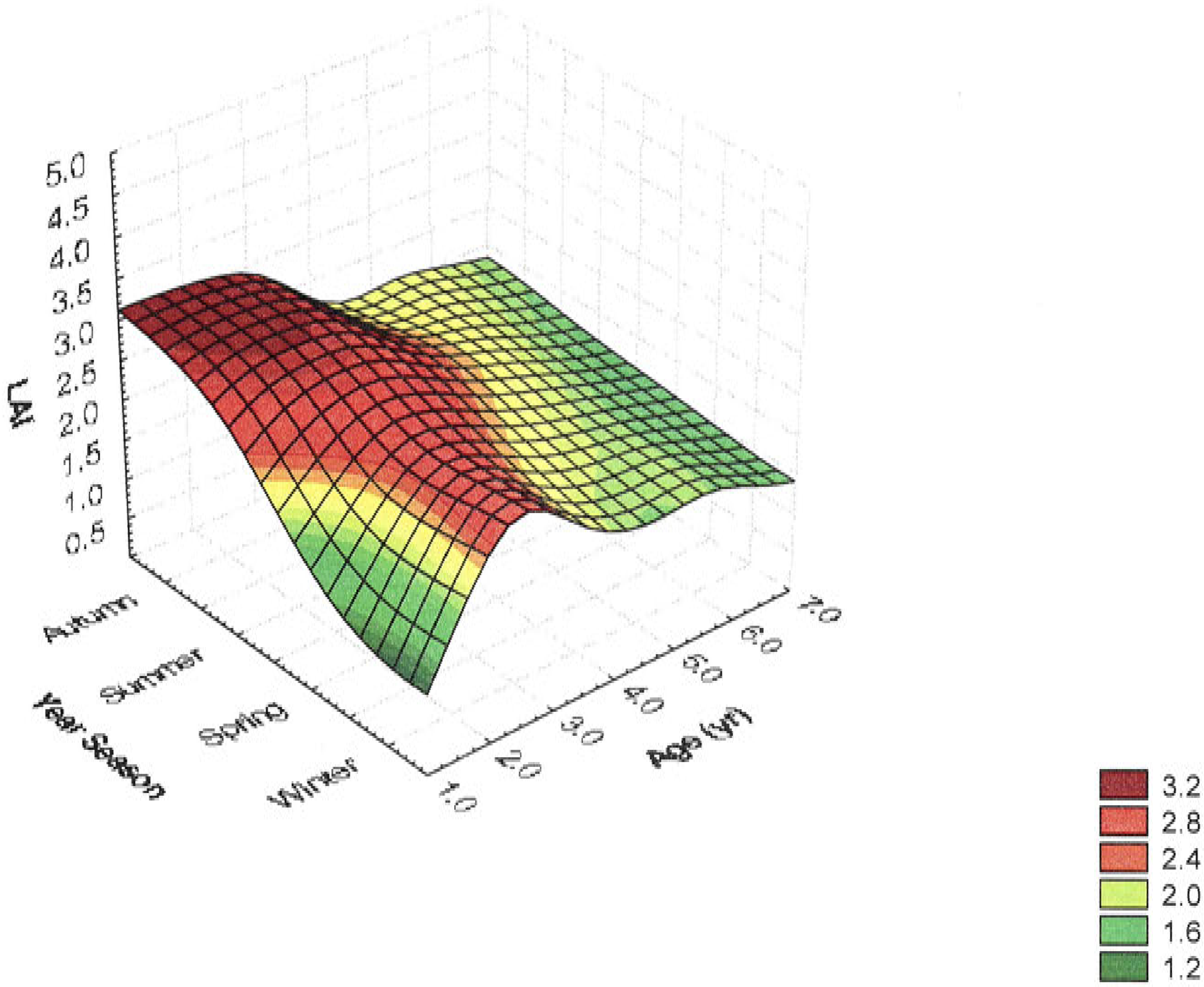


Figure 5.14. LAI variation as function of stand age and season.

5.6. Specific leaf area

Specific leaf area (σ) is defined as the ratio of foliage surface area to unit dry foliage mass. According Landsberg and Gower (1997) σ is an important factor to describe the photosynthetic surface of the plant. It is also an important parameter in ecosystem process models (McMurtrie *et al.*, 1994) to convert foliage mass to leaf area. The measurements made in the MBE provided information about age variation of σ and the differences between clones (Table 5.5).

Table 5.5. Specific leaf area ($m^2\ kg^{-1}$) in 5 genotype in three ages. The values of σ represent the average of three trees.

Genotype	Specific leaf area ($m^2\ kg^{-1}$) - Standard deviation					
	Age (years)					
	2.3		3.3		4.3	
	σ	Stdev	σ	Stdev	σ	Stdev
847	10.5	0.32	9.7	1.17	8.01	0.16
1248	8.2	0.09	7.9	0.28	6.6	0.30
22	8.8	0.09	8.4	0.72	7.4	0.43
AR4	8.9	0.21	9.9	0.14	8.2	0.12
15	10.2	0.38	8.6	0.49	8.0	0.32

The reduction of SLA with age is shown in Figure 5.15. The most recent version of 3-PG provides an equation describing the variation of σ with stand age:

$$\sigma = \sigma_1 + (\sigma_0 - \sigma_1)e^{-(\ln 2)(t/t_\sigma)^2} \quad (5.2)$$

where σ_0 and σ_1 ($m^2\ kg^{-1}$) are specific leaf area at age zero and at maturity, t is the stand age (years) and t_σ is the stand age at which $\sigma = (\sigma_0+\sigma_1)/2$.

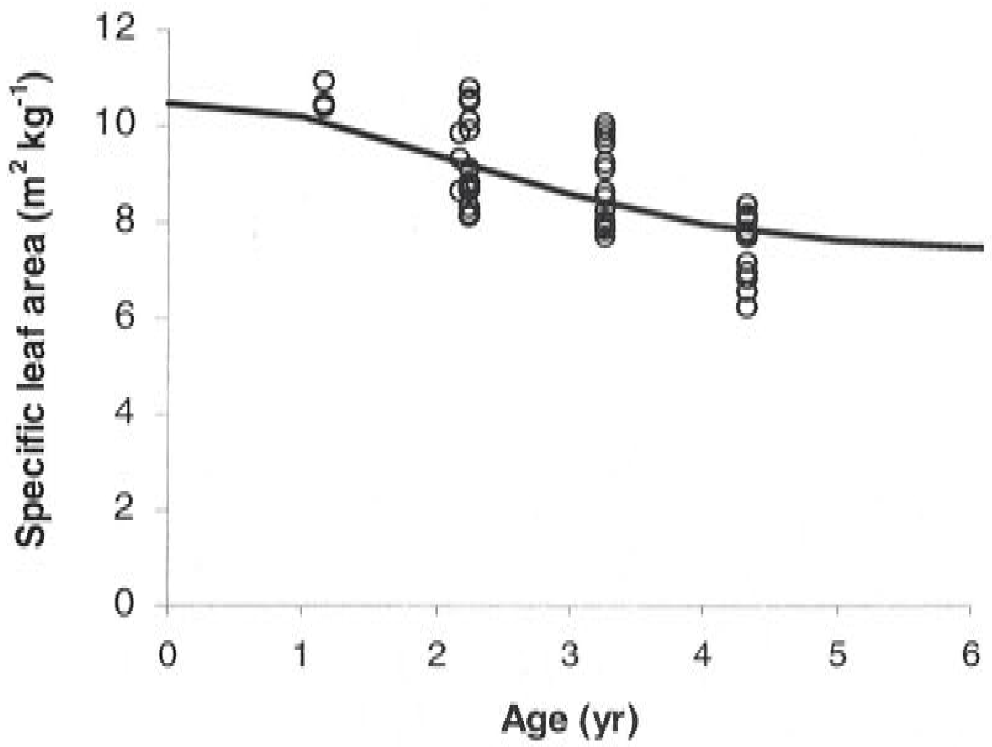


Figure 5.15. Variation of specific leaf area (σ) for all clones with stand age. The solid curve is predicted by equation (5.2) using the parameters value, $\sigma_0 = 10.5$ m^2 kg^{-1} $\sigma = 8$ m^2 kg^{-1} and $t_\sigma = 2.5$ years.

5.7. Litterfall and foliage mass

The data obtained from litterfall measurements in MBE are presented in this section. Litterfall data obtained from traps show that litterfall is highly variable. Figure 5.16 illustrates the variation of litterfall during the period December 1999 to April 2002, which shows a decrease of the litterfall rates during the winter months. January is the month of higher litterfall as result of intensive rainfall and storms.

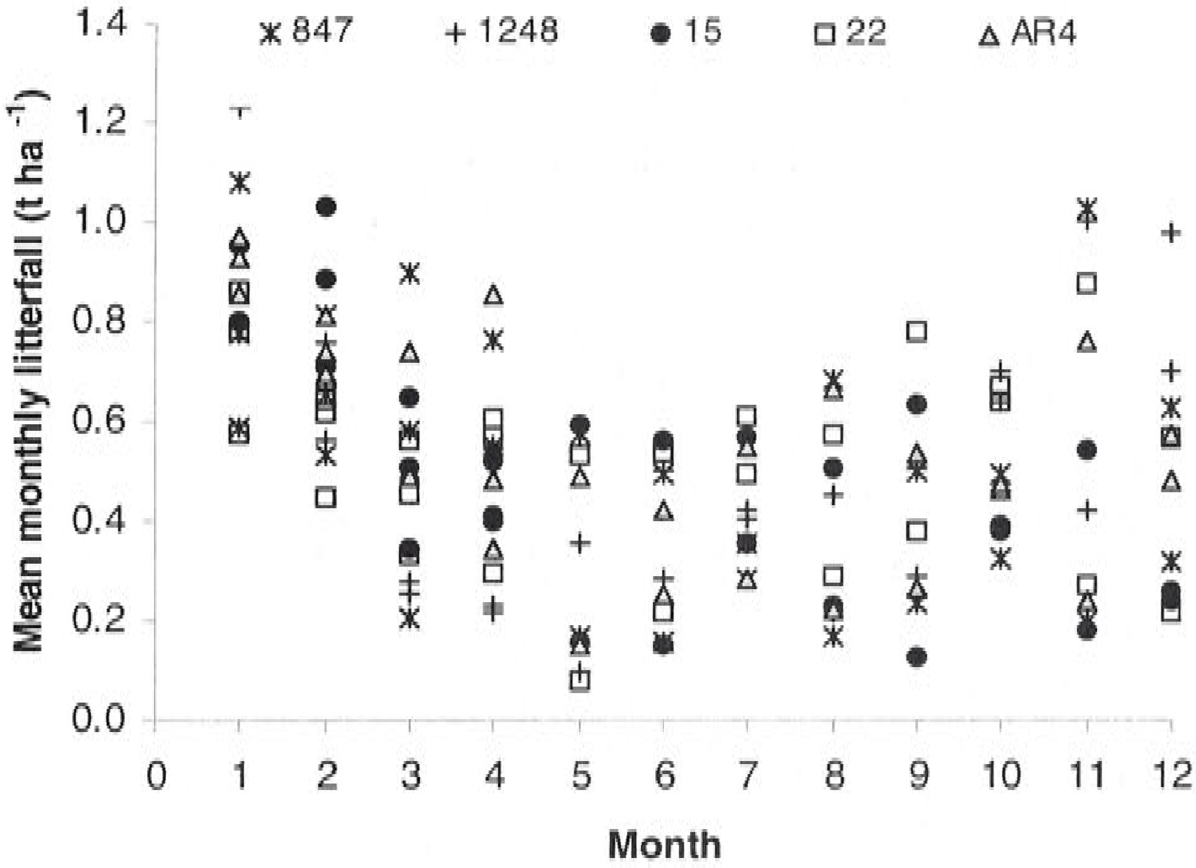


Figure 5.16. Measured monthly litterfall of five genotypes in the MBE area during the period of December 1999 to April 2002.

The rate of litterfall in 3-PG does not vary seasonally but is assumed to be constant during the year. The mean annual litterfall was 5.8 t ha^{-1} with a maximum of 6.1 t ha^{-1} for clone 1248 and minimum average of 5.3 t ha^{-1} for clone 15. These values suggest an annual leaf turnover rate around 1.7, which equated to a monthly rate of 0.14. Based on this value the litterfall parameters in 3-PG were taken as: maximum litterfall rate = 0.14 month^{-1}, rate at age t_0 = 0.00169 month^{-1} and age at which litterfall rate has median value = 13 months. Table 5.6 shows the foliage mass measured annually in the MBE.

It is clear from Figure 5.16 that litterfall is not constant during the year. The data indicate a change in litterfall rates from 1 t ha^{-1} in January to 0.3 t ha^{-1} in June, rising to around 0.6 t ha^{-1} in December. The variation is considerable and these rates have to be considered in relating to foliage mass of the tress. The 3-PG software was not altered to deal with variable monthly litterfall rates, but Figure 5.16 indicates this should be done.

Table 5.6 Foliage mass (t ha^{-1}) of 5 genotypes in MBE area at age 2.3, 3.3, 4.3 and 5.4 years.

	Age (year)			
	2.3	3.3	4.3	5.4
Genotype		**Foliage (t ha^{-1})**		
847	4.2	2.9	3.2	2.9
1248	5.9	2.8	2.7	3.5
22	1.4	3.4	2.6	2.4
15	2.5	3.9	3.3	2.8
AR4	2.7	1.3	2.3	2.9

Despite the care taken to select uniform groups of trees, there was still large variation in foliage mass per tree observed between clones, mainly in the early ages. Part of the observed variation could be attributed to deviation in specific trees as, appears to have happened in clone 1248 and 22 at 2.3 years of age. To establish the allometric equation for accumulated foliage mass as function of DBH, a litterfall rate of 0.3 t ha^{-1} $month^{-1}$ was assumed and added to the foliage mass data from operational areas and different ages, resulting in the relationship presented in Figure 5.17.

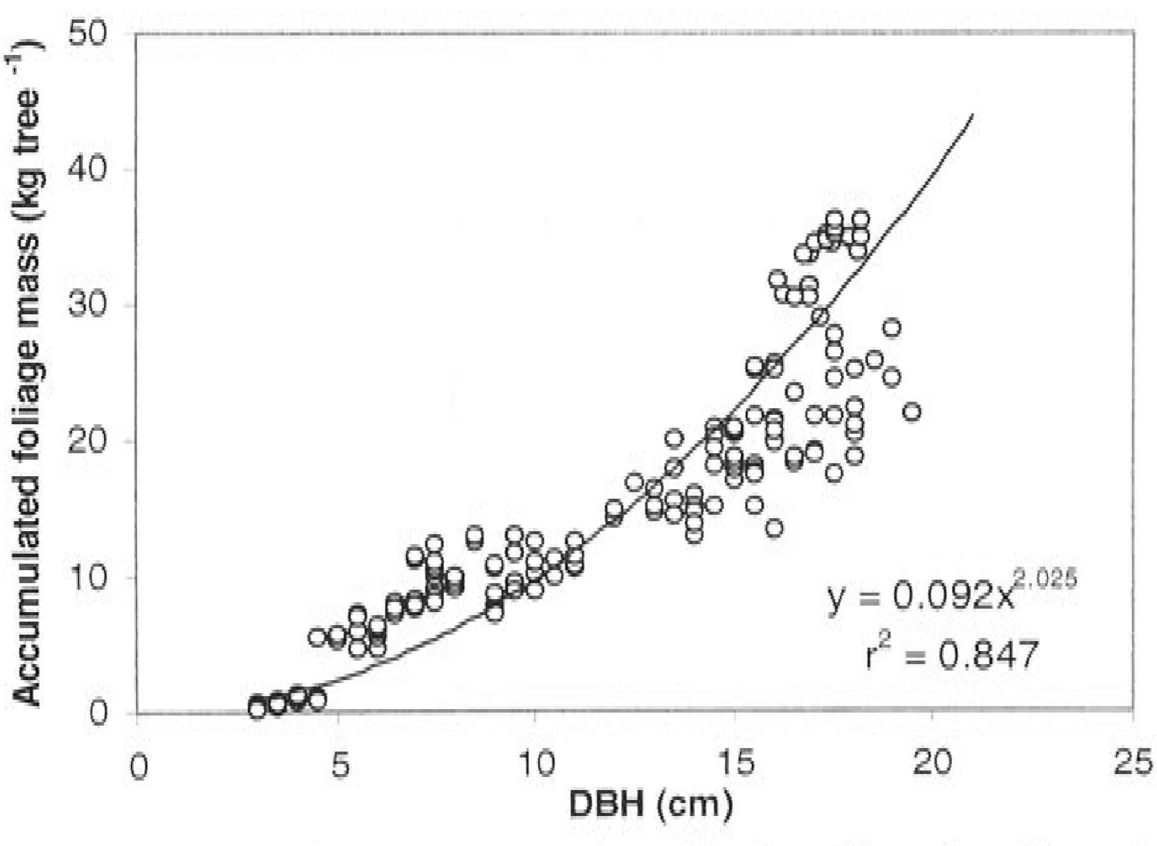


Figure 5.17. Accumulated foliage mass per tree (kg $tree^{-1}$) as function of DBH (cm). The regression (allometric equation) provides the parameter values of foliage in 3-PG.

5.8. Forest growth and yield

The data collected in the catchment experiment make it possible to analyse forest growth at monthly time steps and compare the results with 3-PG simulations. This section presents the main results of forest growth measurements from PSPs in MBE in terms of mean annual increment (m^3 ha^{-1} $year^{-1}$), stand volume (m^3 ha^{-1}), diameter at breast height (cm), basal area (m^2 ha^{-1}). These PSPs are located in areas (see Figure 4.3) where the fertilization and management practices applied were the same. Despite this, different growth rates were observed, confirming the difference existing between genotypes.

The maximum differences observed between genotypes at age 6 years were: 20% of MAI, 22% of stand volume, 10% of mean DBH and 18% of the basal area (see Figure 5.18). These differences are high if we consider that these plots were planted at the same time and in the same conditions. These observed differences in production between genotypes could be attributed primarily to differences in biomass partitioning and secondarily to differences in stomatal conductance (see section 5.9).

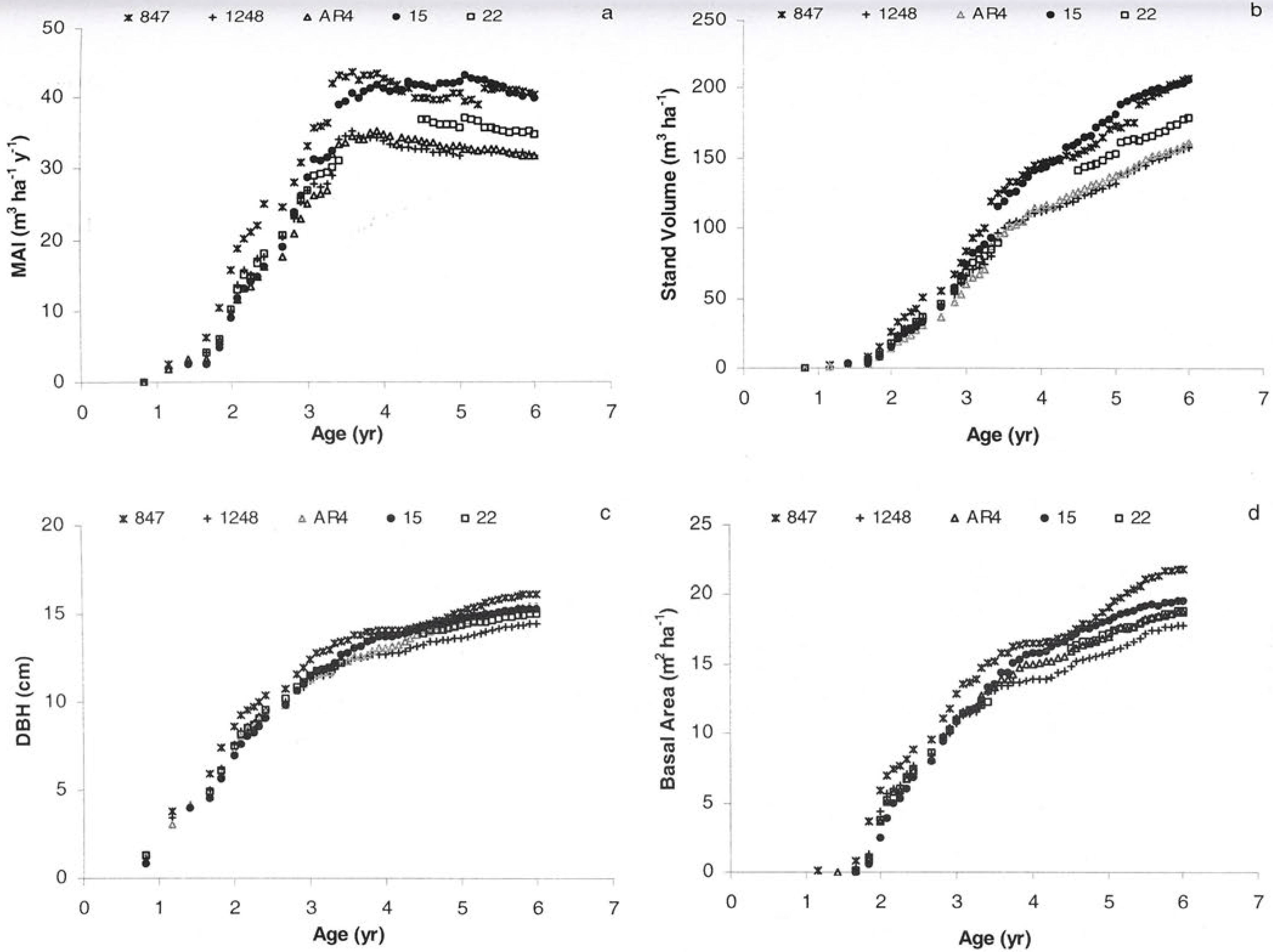


Figure 5.18. Growth in the PSPs at the MBE site. a) mean annual increment (m^3 ha^{-1} $year^{-1}$), b) stand volume (m^3 ha^{-1}), c) diameter at breast height (cm) and d) basal area (m^2 ha^{-1}).

5.9. Stomatal and canopy conductance

Stomatal conductance (g_s) was measured hourly at two levels in the canopy in trees from two clones on 12 mornings over a period of about two months in 1999. These campaigns provided the basis for estimating the maximum canopy conductance and the response of stomatal conductance to vapour pressure deficit in 3-PG. The data obtained were consistent with results from a previous campaign carried out in 1995 and 1996 in the same area, reported by Mielke *et al.* (1999) and Mielke at al. (2000). Although g_s was highly variable during the day it was possible to identify significant differences between clones: g_s in clone 22 was consistently higher than in clone 15 (see Figure 5.19). It was also possible to characterise the effects of VPD on g_s and hence on canopy conductance (g_C) as shown in Figure 5.20.

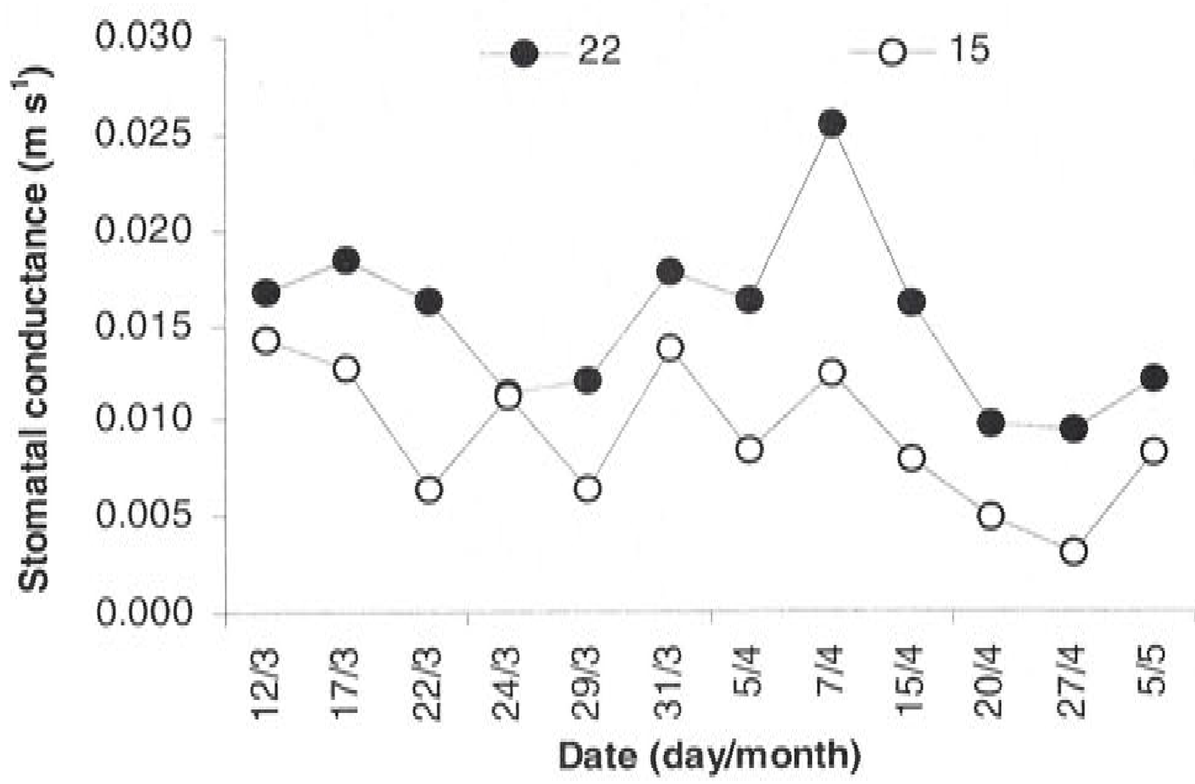


Figure 5.19. Stomatal conductance (g_s) in clones 22 and 15. Measurements were conducted during the mornings of 12 days in 1999.

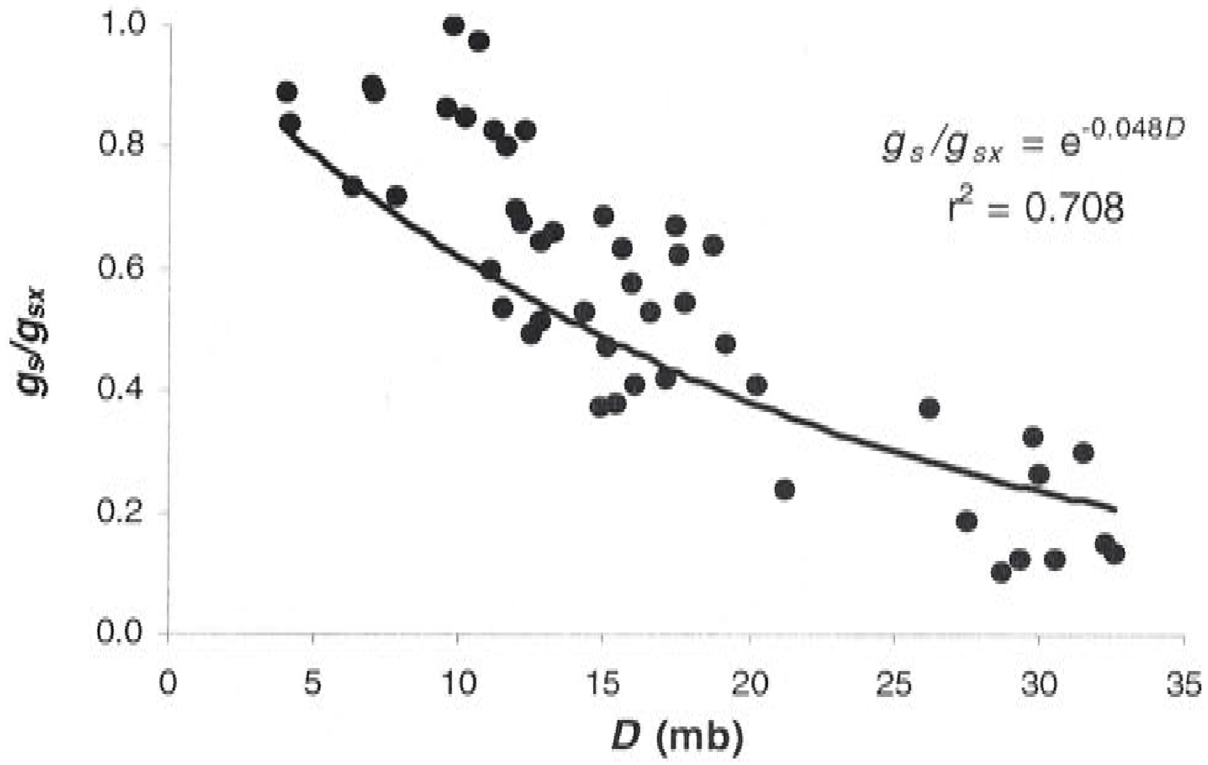


Figure 5.20. Effect of vapour pressure deficit (mb) on ratio of stomatal conductance (g_s/g_{sx}). The data were collected at hourly intervals.

To illustrate the effect of environment on g_s one example is presented in Figure 5.21 of the hourly variation of g_s during two days with significant PAR and VPD differences. On 07/05, both clones reduced g_s drastically when VPD increased from 0.3 to 1.5 kPa. The effect of increase PAR on g_s can easily be observed on 11/05 between 12:00 and 15:00 h. In both days clone 22 presents always-higher g_s than clone 15.

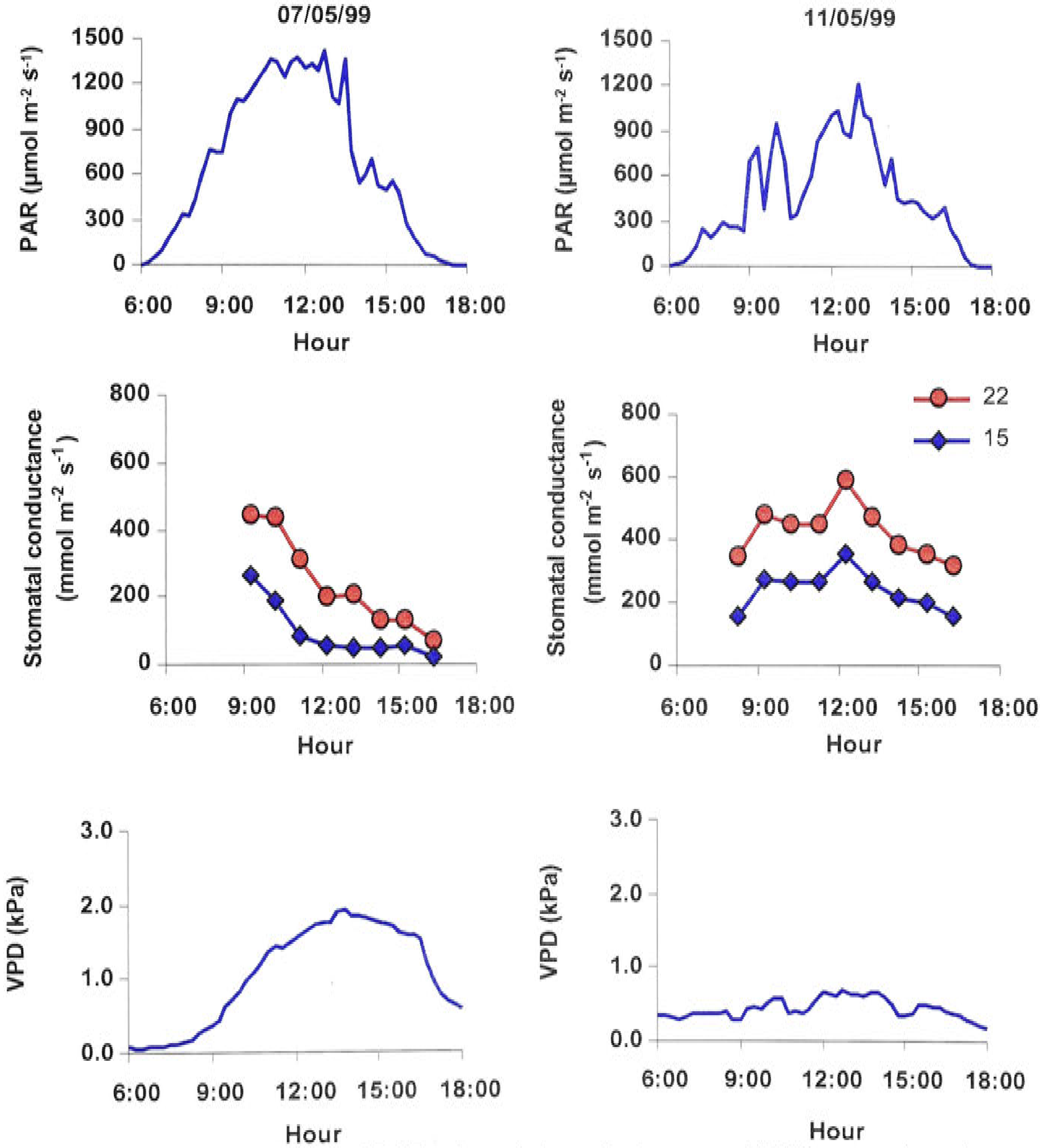


Figure 5.21. Hourly variation of PAR, stomatal conductance and VPD over a two-day period.

5.10. Precipitation interception

Rainfall interception by the canopy can vary widely depending on rainfall intensity and duration (Soares & Almeida, 2001). The capacity of the canopy to store rain is linearly related to leaf area index (van Dijk & Bruijnzeel, 2001). This concept was introduced in the last version of 3-PG based on observed data in the MBE, however, in view of the monthly time step used in 3-PG, it can only provide an approximation; a detailed interception model would deal with individual rainfall events. Figure 5.22 presents the precipitation and rainfall interception in 33 events that occurred between September 1995 and July 1996 in the MBE.

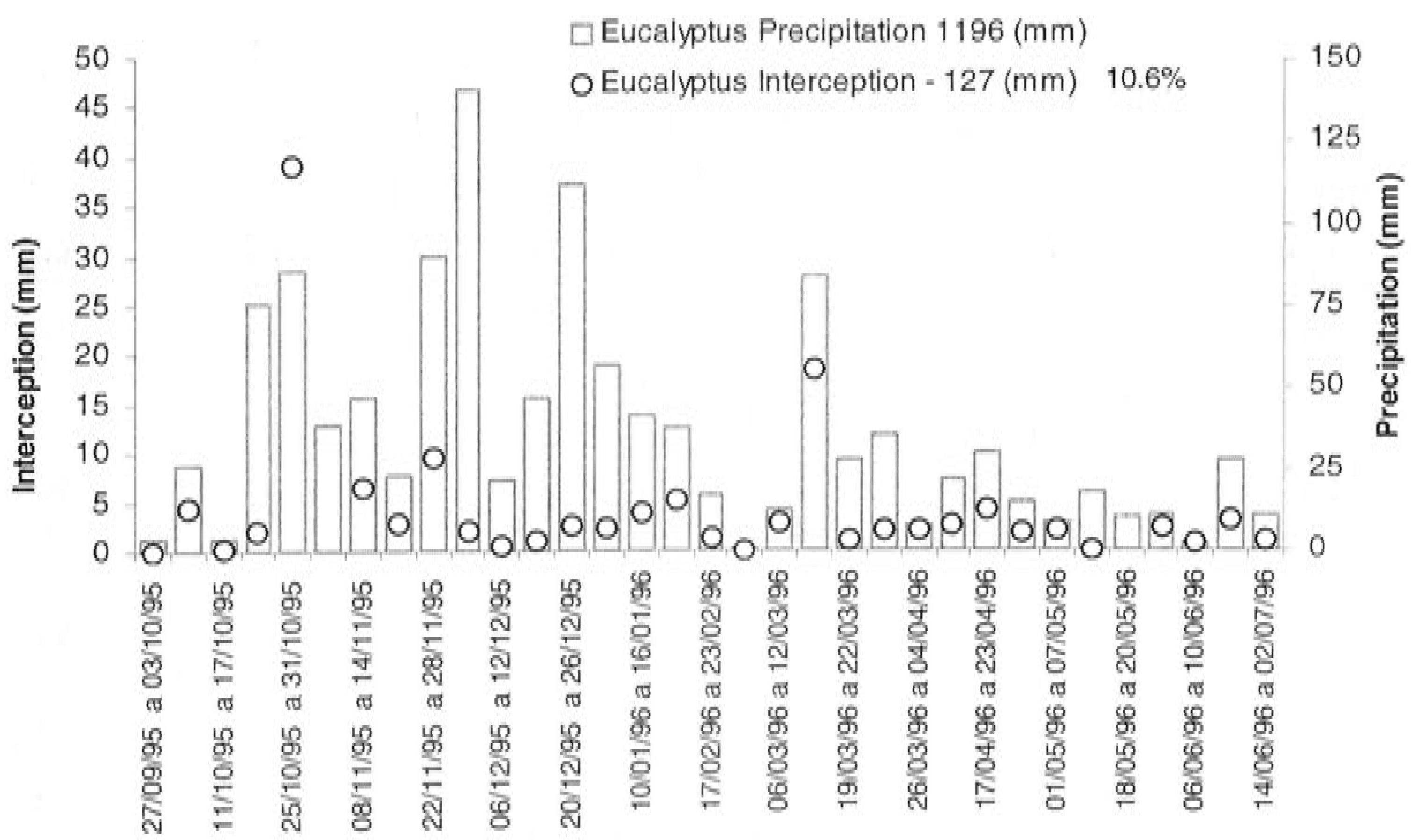


Figure 5.22. Measured precipitation interception in MBE area.

Figure 5.23 illustrates the percentage of rainfall interception as a function of leaf area index measured in MBE. It is clear that for LAI>2, increasing LAI up to 3.0 had no effect on the proportion of rainfall intercepted by the canopy.

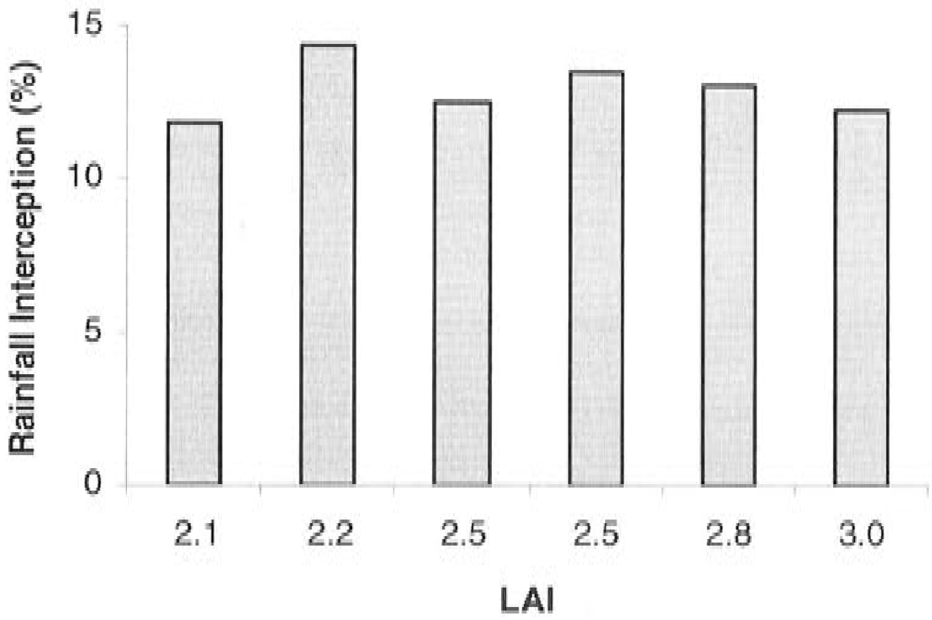


Figure 5.23. Rainfall interception (%) as a function of leaf area index. The interception measurements were made at intervals and LAI at the time of the measurements was measured with LAI-2000 (corrected, see Appendix III).

To parameterise the canopy interception in 3-PG, the maximum interception of 15% of the rainfall was adopted.

5.11. Soil water holding capacity and soil texture

In Chapter 3 the curves of soil moisture ratio based on soil texture, used in 3-PG, were presented. The soil water holding capacity was calculated for 22 soil types mapped by Aracruz soil survey. The Embrapa (2000) report analysed over 1000 soil profiles across the regions of Aracruz, São Mateus and South Bahia. The samples collected provided the basis for volumetric moisture contents at tensions of 0.1, 0.3 and 15 atmospheres potential. Associating these field measurements with soil moisture obtained through neutron probe measurements, it was possible to determine the maximum available soil water for each soil type at different depths (see Figure 5.25 in the next section). Table 5.7 shows the soil water holding capacity for three soil depths for the 22 ARCEL soil units.

The soil texture was also determined from the same soil-profile texture class. Particle soil analyses were performed on each soil layer of the soil-profile of

Embrapa (2000) survey. The information was integrated to 2 m depth, generating the soil texture classification shown in Table 5.8.

Table 5.7. Mean soil water holding capacity for the 22 ARCEL soil map units to three soil depths.

Soil No.	Soil name	Code	Soil water holding capacity			
			mm/1.5 m	mm/2.0 m	mm/2.5 m	mm/m
01	Latosol	LAx1	132	176	220	88
02	Latosol	LAx2	138	184	230	92
03	Latosol	LAx3	135	180	225	90
04	Latosol	LAx4	141	188	235	94
05	Agrisol	PAd1	129	172	215	86
06	Agrisol	PAd2	141	188	235	94
07	Agrisol	PAd3	126	168	210	84
08	Agrisol	PAd4	120	160	200	80
09	Agrisol	PAd5	129	172	215	86
10	Agrisol	PAd6	135	180	225	90
11	Agrisol	PAd7	129	172	215	86
12	Agrisol	PAd8	129	172	215	86
13	Agrisol	PAd9	144	192	240	96
14	Agrisol	PAd10	129	172	215	86
15	Agrisol	PAd11	123	164	205	82
16	Spodosol	E	126	168	210	84
17	Planosol	SXd1				
18	Planosol	SXd2	144	192	240	96
19	Planosol	SXd3	132	176	220	88
20	Planosol	SXd4	147	196	245	98
21	Hydromorfic	G	129	172	215	86
22	Quartzose Neosols	RQo	141	188	235	94

Table 5.8. Main texture and total available water capacity at 2.0 m depth by soil unit.

Soil Number	Soil name	Code	Texture			
			Sand (%)	Silt (%)	Clay (%)	Texture class
01	Latosol	LAx1	52	7	41	Clay
02	Latosol	LAx2	64	6	30	Clay loam
03	Latosol	LAx3	55	7	38	Clay
04	Latosol	LAx4	65	6	29	Clay loam
05	Agrisol	PAd1	52	7	41	Clay
06	Agrisol	PAd2	67	7	26	Clay loam
07	Agrisol	PAd3	47	8	45	Clay
08	Agrisol	PAd4	36	8	56	Clay
09	Agrisol	PAd5				
10	Agrisol	PAd6	71	7	22	Sandy loam
11	Agrisol	PAd7	58	8	34	Clay loam
12	Agrisol	PAd8	50	8	42	Clay
13	Agrisol	PAd9	71	7	22	Sandy loam
14	Agrisol	PAd10	60	7	33	Clay loam
15	Agrisol	PAd11	52	7	41	Clay
16	Spodosol	E	71	7	22	Sandy loam
17	Planosol	SXd1				
18	Planosol	SXd2	73	8	19	Sandy loam
19	Planosol	SXd3	64	7	29	Clay loam
20	Planosol	SXd4	68	13	20	Sandy loam
21	Hydromorfic	G	58	8	34	Clay loam
22	Quartzose Neosols	RQo	82	6	12	Sand

5.12. Soil moisture

Measurements of soil moisture provide important information to verify the accuracy of water balance calculated by 3-PG. The data collected weekly in MBE, using a neutron probe, allow verification of the seasonal variation of water contents in the soil profile in 2.6 m depth. The soil moisture data shown in Figure 5.24 demonstrate that the upper soil layer is drier and more affected by precipitation than the lower layers. The lower variation in the deeper layers indicates that water is used preferentially from the upper layer, where root concentration are higher.

To understand the variation of soil moisture in relation to soil depth, three days were chosen on which measurements were made, which showed different water contents in every 20 cm of soil profile (Figure 5.25). On 9/03/2001, the soil was dry but it is evident that the trees were using water mainly down to 160 cm. Despite the fact that clone 22 has higher stomatal conductance than clone 15 (Figure 5.21), the soil moisture measurements indicate that clone 15 uses more water than clone 22. The reason for this is mainly the higher LAI in clone 15 (Figure 5.13). On 1/11/2001 the effects of the beginning of the wet season can be observed and, finally, on 28/12/2001 the soil reached the maximum soil water storage. The variation of moisture in the profile is very low.

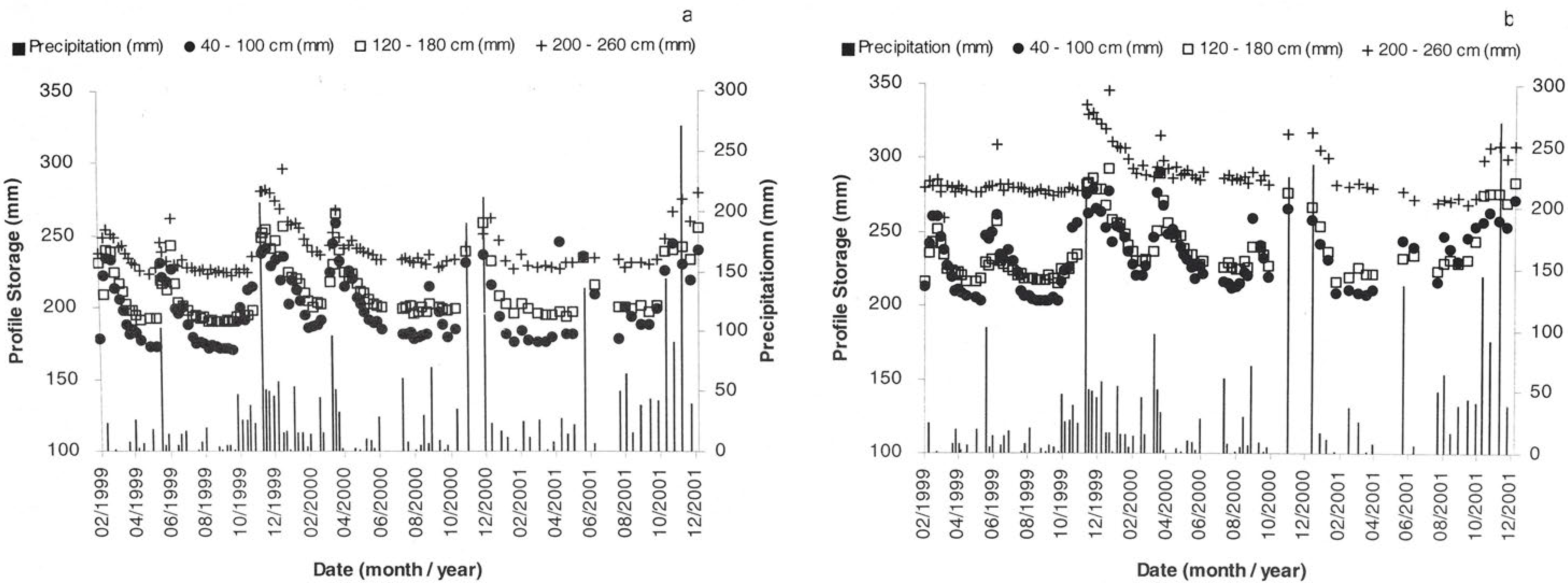


Figure 5.24. Water storage in the soil profile grouped in three depth intervals (40 - 100 cm, 120 - 180 cm and 200 - 260 cm) for a) clone 15 and b) clone 22. The points were obtained by integrating neutron probe measurements across the specified depths.

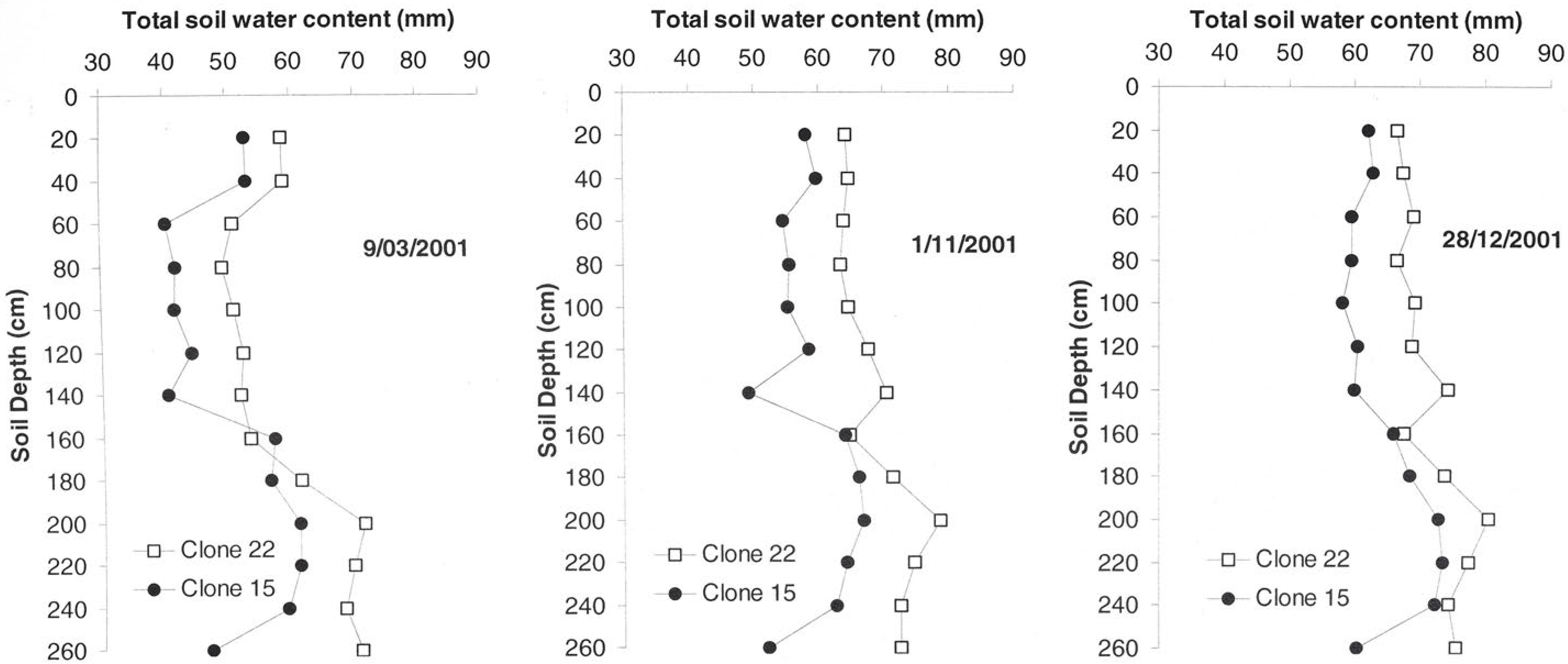


Figure 5.25. Variation of soil moisture by soil depth on three separate days illustrating differences between clone 15 and clone 22.

In terms of practical application in PBMs, it is important to determine the maximum available soil water (θ_x) rather than the total soil water content. In the catchment area, the θ_x was determined at 2.6 m depth based on the difference between the maximum and minimum soil moisture observed in weekly measurements made from December 1994 to December 2002. The results of one tube are presented in Figure 5.26, showing that only one point is higher than 200 mm and 180 mm could be considered a robust value of θ_x in this specific case because it occurred in the years with well-distributed precipitation.

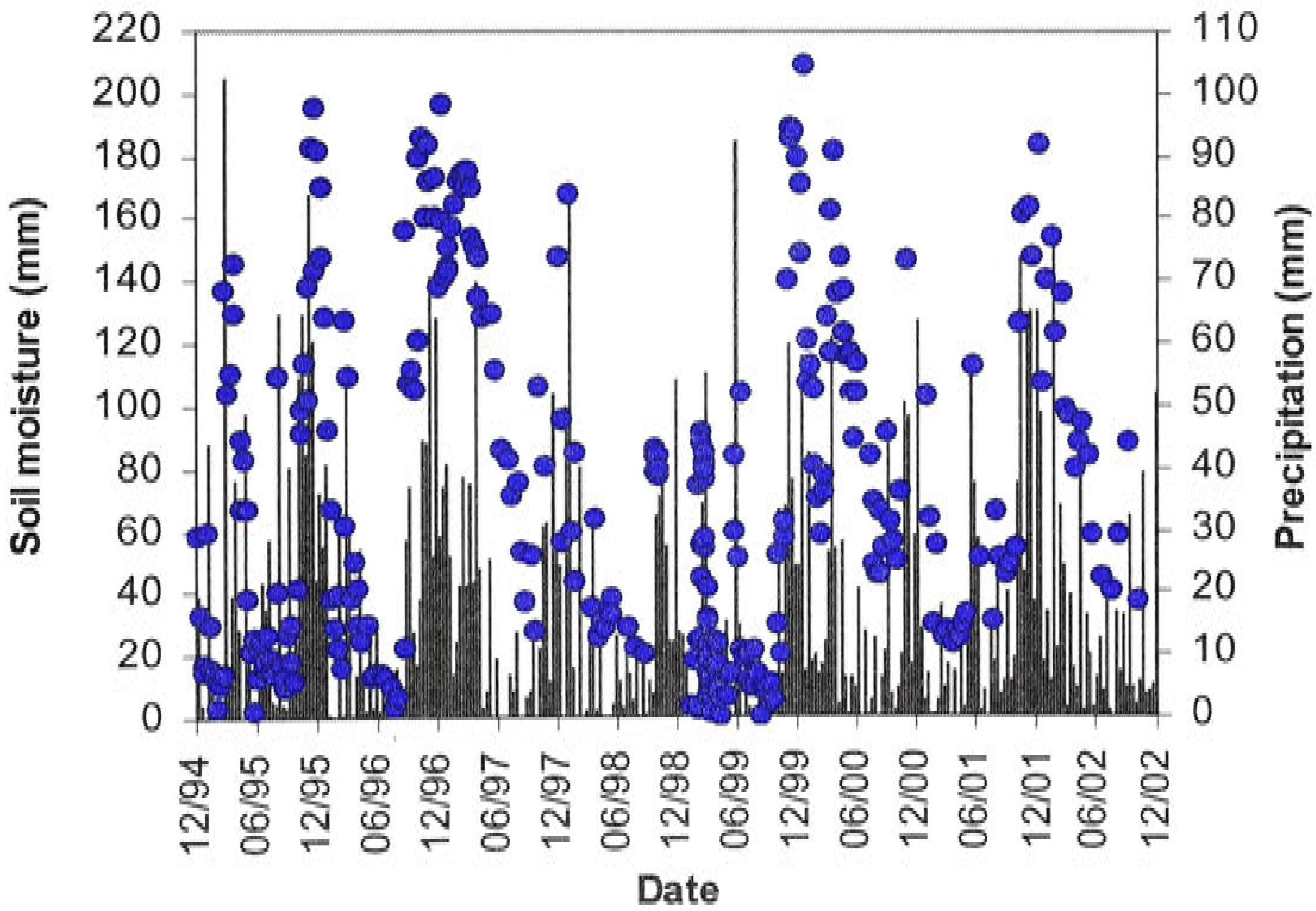


Figure 5.26. Available soil water (circles) to 2.6 m depth in a soil profile with one neutron probe access tube measured from December 1994 to December 2002. The bars represent the accumulated precipitation (mm) that occurred in the interval between soil moisture measurements.

5.13. Maximum canopy quantum efficiency (α)

In Chapter 3 values of maximum canopy quantum efficiency reported in the literature were discussed and shown to vary considerably between species and localities. 3-PG is very sensitive to this parameter (see Figure and the best estimation of α should be obtained. To estimate α, data on biomass and absorbed photosynthetically active radiation, available from the fertilisation and irrigation experiment described in section 4.3.3, were used.

The experiment provided ideal conditions to test the values of α because it guaranteed no limitations of water and nutrients. Since α is obtained from GPP / APAR (see equation 3.5) it can be estimated with some assumptions, from values of NPP and APAR. NPP values were obtained from biomass measured by destructive sampling in the planted stands at ages between 9 to 12 months, 12 to 27 months and between 27 to 36 months. The leaf area index and the total incoming PAR during the period of biomass sampling were also recorded. Absorbed PAR was calculated using Beer's law (equation 3.3), with the extinction coefficient (k) set to 0.5; the L^* values used were values measured from destructive samples. Since it could be assumed that there were no water or nutrition constraints, the only modifier that could affect the growth of the trees was the VPD, so the average VPD_{day} for each period was used to calculate the utilisable absorbed photosynthetic active radiation (APARU). The calculation of NPP included the total biomass produced in each analysed period, considering stem (plus bark and branches), foliage (plus litterfall) and roots (including estimation of root turnover). NPP was converted to GPP assuming that P_N / P_G = 0.47 giving an estimate of GPP in terms of biomass. This was converted to moles C, assuming that biomass is 50% carbon, and plotted against APAR to give Figure 5.27. The results presented here are intended to show the possible value of maximum canopy quantum efficiency for *E. grandis* in Brazil.

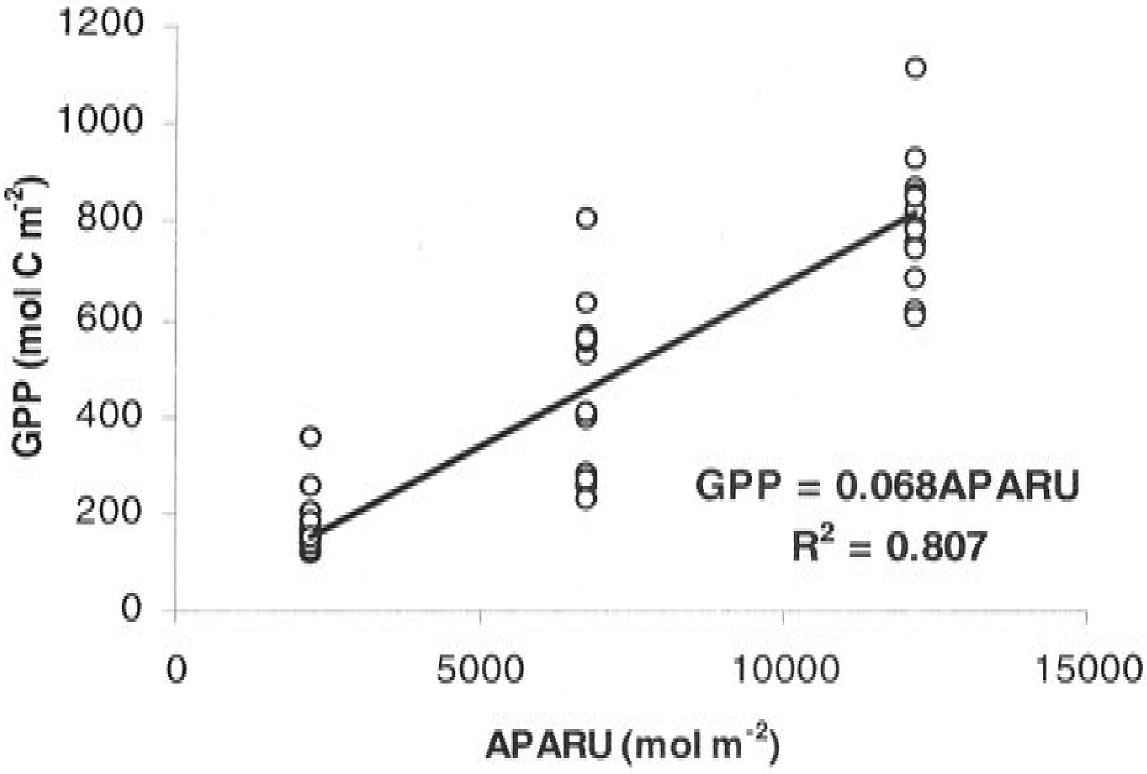


Figure 5.27. Calculation of canopy quantum efficiency as slope of the regression between APARU and GPP in the fertilisation and irrigation experiment.

5.14. Fertility rating

As mentioned in Chapter 3, the fertility rating (FR) in 3-PG is an index created to estimate the fertility status of the soils. It is an empirical and subjective index but is used because of the difficulty of describing soil nutrient status estimated by traditional soil analyses in terms usable in quantitative models of plant growth. The FR includes expert opinion, therefore remains a somewhat problematical and unsatisfactory pragmatic approach. It can also be used as a tunable parameter in the model, and in this mode holds out some prospect of providing information about effective site fertility (Landsberg *et al.*, 2001). Williams *et al.* (2002) estimated FR using a spatial soil model that included total organic carbon, cation exchange capacity and exchangeable sodium percentage to estimate FR. Stape (2002) determined FR for *Eucalyptus grandis* based on responses to soil fertilization and derived a Soil Fertility Index (SFRI) composed of (10.3 K15 + 0.58P30+0.22CEC15) where K15 is the K concentration in $mmol_C\ kg^{-1}$ at 0 - 0.15 m, P30 is the concentration of P in $mg\ kg^{-1}$ at 0 - 0.30 m and CEC is the concentration of CEC in $mmol_C\ kg^{-1}$ at 0 - 0.15 m.

The approach adopted to establish of fertility rating for the ARCEL plantations reflects the knowledge available about the amount of fertilizer normally applied during the *Eucalyptus* rotation, the natural fertility of the soils and possible limitations. Two main assumptions are made in estimating FR (Ryan, 2003):

- The application of fertiliser before the establishment of new plantations avoids having low values of FR. The NUTRICALC (Barros *et al.*, 1995) program is used to prescribe fertiliser application for the next rotation with the objective of reducing any initial soil nutrient limitations for the young eucalypt trees.
- The nature of soil fertility, with reference to eucalypt plantations, is not limited to soil chemical factors only but can also include soil physical factors not related to soil water use by the trees.

The first assumption has led to a two-phase step function for FR estimation: for the first 4 years of plantation growth FR reflects high fertility as a result of fertilisation (and other site establishment) practice but after 4 years, FR returns to standard rating, for the specific soil type standard; i.e it is assumed that the applied fertiliser has been depleted.

The Gomes & Curi (2001) concept of "Degree of Soil Limitation", which allows determination of the principal factors that limit the availability of nutrients to the trees, was used to generate a table for Fertility Rating based on soil type. This comprises the components shown in Table 5.9.

Table 5.9. Calculating FR using the Degree of Soil Limitation factors (after Gomes and Curi 2001).

Fertility Factors	Code	Weight
Natural fertility	ΔNa	1
Potential fertility	ΔNp	4
Water limitation	ΔH	2
Oxygen limitation	ΔO	1
Management impediment	ΔM	2

The fertility factors values for each soil map unit were assessed to have one of five FR restriction values;

Null	1.0
Light	0.8
Moderate	0.6
Strong	0.4
Very strong	0.2

The component fertility factors were estimated for each of the 22 soil map units and then combined using the weights in Table 5.9 to produce the final FR values for each soil map unit. The actual formulae used to combine the factors and their respective weights varies with stand age and stand regeneration practice (Table 5.11).

Table 5.10. Calculating *FR* as a function of the fertility factors of Table 5.9.

Regeneration	Stand Age 0-4 yrs	Stand Age >4 yrs
Re-establishment	$FR_{0p}=(\Delta Na*0.1) + (\Delta Np*0.4) + (\Delta H*0.2) + (\Delta O*0.1) + (\Delta M*0.2)$	$FR_{4p} = FR_{0p} - (FR_{0p}*0.1)$
Coppice	$FR_{0c}=(\Delta Na*0.1)*0.8 + (\Delta Np*0.4)*0.9 + (\Delta H*0.2) + (\Delta O*0.1) + (\Delta M*0.2)$	$FR_{4c} = FR_{0c} - (FR_{0c}*0.1)$

It is considered that after 4 years *FR* is reduced by 10% for both planted seedlings and coppice, and it is assumed that coppice regeneration nutrition is less reliant on both natural and potential fertility, presumably because the root system is well established

The full table of *FR* estimates for ARCEL plantations is presented in Table 5.11. The natural fertility (ΔNa) component of the majority of the Yellow Agrisols and Latosols are considered light/moderate (0.6-0.8) but the Spodosols, Gleyosols and Quartzose Neosols had lower values (0.2-0.4). Fertilisation reduces any nutrient limitation for most of the soil types with values of 0.9 and 0.8 for most soils but dropping to 0.7 for the Spodosols, Gleyosols and Quartzose Neosols. These latter soil types also have water and oxygen limitations (0.2 compare to 0.6-0.8 for the other soils). Management limitations are more varied reflecting interactions between several soil properties (Ryan, 2003).

The values of *FR* obtained from this classification are being tested in ARCEL areas and the model validation using the values of Table 5.11 is presented in Chapter 6.

Table 5.11. 3-PG Fertility rating (*FR*) used by ARCEL calculated from component fertility factors (Table 5.9) and classified by stand age and regeneration type.

Soil	Code*	Fertility factors					Re-establishment		Coppice	
		ΔNa	*ΔNp*	*ΔH*	*ΔO*	*ΔM*	Age 0-4	Age >4	Age 0-4	Age >4
01	LAx1	0.6	0.9	0.8	0.6	0.4	0.72	0.65	0.67	0.60
02	LAx2	0.6	0.9	0.8	0.6	0.8	0.80	0.72	0.75	0.68
03	LAx3	0.6	0.9	0.8	0.6	0.6	0.76	0.68	0.71	0.64
04	LAx4	0.6	0.9	0.8	0.6	0.8	0.80	0.72	0.75	0.68
05	PAd1	0.6	0.9	0.8	0.8	0.6	0.78	0.70	0.73	0.66
06	PAd2	0.6	0.9	0.8	0.8	0.8	0.82	0.74	0.77	0.69
07	PAd3	0.6	0.9	0.8	0.8	0.6	0.78	0.70	0.73	0.66
08	PAd4	0.6	0.9	0.8	0.8	0.4	0.74	0.67	0.69	0.62
09	PAd5	0.8	0.9	0.8	0.8	0.6	0.80	0.72	0.75	0.67
10	PAd6	0.8	0.9	0.8	0.8	0.8	0.84	0.76	0.79	0.71
11	PAd7	0.8	0.9	0.8	0.8	0.8	0.84	0.76	0.79	0.71
12	PAd8	0.6	0.9	0.8	0.8	0.6	0.78	0.70	0.73	0.66
13	PAd9	0.6	0.9	0.8	0.8	0.8	0.82	0.74	0.77	0.69
14	PAd10	0.6	0.9	0.8	0.8	0.8	0.82	0.74	0.77	0.69
15	PAd11	0.6	0.9	0.8	0.8	0.6	0.78	0.70	0.73	0.66
16	E	0.2	0.7	0.2	0.2	0.6	0.48	0.43	0.45	0.40
17	SXd1	0.4	0.8	0.6	0.8	0.6	0.68	0.61	0.64	0.58
18	SXd2	0.6	0.8	0.6	0.8	0.8	0.74	0.67	0.70	0.63
19	SXd3	0.6	0.8	0.6	0.8	0.8	0.74	0.67	0.70	0.63
20	SXd4	0.6	0.8	0.6	0.8	0.6	0.70	0.63	0.66	0.59
21	G	0.4	0.7	0.2	0.2	0.4	0.46	0.41	0.42	0.38
22	RQo	0.2	0.7	0.2	0.2	1	0.56	0.50	0.53	0.48

* Soil map unit codes: LA, Latosol; PA, Agrisol; E, Spodosol; SX, Planosol; G, Gleyosol; RQ, Quartzose Neosol.

Chapter 6

6. MODEL PARAMETERISATION, VALIDATION AND SENSITIVITY ANALYSES [6]

6.1. Model parameterisation

The objective of this chapter is to establish a set of parameter values that allow accurate description of the growth patterns of stands in terms of the output variables produced by the model, i.e. stem mass (W_S), root mass (W_R), foliage mass (W_F), leaf area index (LAI), stand volume (SV), mean annual increment (*MAI*), mean diameter at breast height (DBH) and basal area (BA).

Parameter lists for 3-PG are given in Sands (2001) and have also been published in other studies covering different regions and species: Whitehead *et al.* (2002) calibrated the model for *Dacrydium cupressinum* in New Zealand, Sands and Landsberg (2002) parameterised 3-PG for *E. globulus* in Australia; Dye (2003) presented parameters values for *E. grandis* and *E. camaldulensis* in South Africa; Stape (2002) provided a set of parameters values for a hybrid of *E. grandis* in Brazil and Williams *et al.* (2002) for *E. grandis* in Queensland, Australia. A comparison of the parameter values used by Stape (2002) and Williams *et al.* (2002) with those presented in this study reveals considerable differences in some key parameters (see Appendix V). The main reasons for these differences are the availability of specific data measured directly in the field, the number of tuned parameters and the spatial scale of the study, which can require different resolution and level of detail. Furthermore, although the studies by Stape and Williams *et al.* deal with the same species (*E. grandis*), the differences in

[6] Part of this chapter is being published in Almeida *et al.* 2004a and in Almeida *et al.* 2004b.

physiological and carbon allocation behaviour demonstrated between clones in this study indicate that such differences may occur between the clones of *E. grandis* grown at the different locations of those studies.

In this study the majority of parameters in 3-PG were assigned values for *E. grandis* on the basis of direct observations in the MBE area, as shown in Chapter 5 or, in some cases, from regional plantations or sources outside this study. The remainder were estimated by systematically varying them until a "best fit" was obtained between 3-PG output and corresponding observed data. Model calibration procedures are also described in detail by Sands and Landsberg (2002) and Landsberg *et al.* (2003). Essentially the model is run and the outputs compared against measured data. A number of parameter values can be varied to alter the output, but normal procedure is to use standard default or the best available empirical values for as many parameters as possible.

The main parameter values used in, and derived from this study, are presented in Table 6.1. The parameter values for the stem mass/diameter at breast height relationship (w_s / B) were set by the measurements obtained from destructive harvesting (Figure. 5.10); this relationship determines the stem diameters and basal area produced by the model. Adjustments to the partitioning ratios are effectively adjustments to the foliage mass/diameter at breast height relationship (w_f / B) with the aim of producing the correct time course of LAI. This in turn feeds back, through radiation interception, to NPP.

The following parameters were assigned directly (see also Table 6.1): the parameters involved in litterfall rate, specific leaf area and basic density, all of which vary with stand age; the parameters in the stem and foliage allometric relationships, and hence the parameters p_{FS2} and p_{FS20} in the ratio of foliage to stem partitioning; the parameters defining canopy conductance and its dependence on D; and the threshold temperatures in f_T were assigned nominal values such that the optimum temperature was similar to the long-term mean temperature of the study area.

The maximum canopy quantum efficiency was assigned the value obtained by fitting GPP to APAR using the data from the fertilization and irrigation experiment (see section 5.13, Figure 5.27). Finally, the minimum proportion of biomass allocated to roots was assigned by varying this parameter until predicted and observed root biomass data were in agreement with data from plots in the experimental catchment (see Figure 5.11).

This process gave an initial generic set of parameters for *E. grandis* growing in the study area. It was clear that there were differences in the quality of fit for different clones, so adjustments, based on measurements made in specific clones, were made in selected parameters to provide the best fit for each clone. For instance, where it was known from direct observation that there were clonal differences (e.g. in basic density, biomass allocation and stomatal conductance) these differences were taken into account. Finally, for each clone the parameters governing root biomass partitioning and the ratio of foliage: stem partitioning were varied to give an optimal fit of predicted values of LAI, W_S, W_F, and DBH to observed data for individual clones. For clones 15 and 22, there were differences in the values of six of the parameters listed in Table 6.1. The implications of these differences are discussed later.

Table 6.1. List and source of parameters used in the calibration 3-PG, values applied to clone 15, clone 22 and general values applied in areas containing several clones.

3-PG Parameters						
Meaning/comments	**Symbol**	**Units**	**Clone 15**	**Clone 22**	**Generic**	**Values source**
Ratio of carbohydrate allocation to foliage and	p_{FS2}	-	0.70	0.70	0.70	DO
stems at diameter at breast height = 2 and 20 cm	p_{FS20}	-	0.10	0.11	0.10	DO
Coefficients in stem allometric relationship with	a_s	-	0.049	0.033	0.045	O
diameter at breast height	n_s	-	2.822	2.912	2.812	O
Maximum fraction of P_N to roots	η_{Rx}	-	0.6	0.6	0.6	D
Minimum fraction of P_N to roots	η_{Rn}	-	0.07	0.12	0.10	DO
Minimum, optimum and maximum temperatures for growth	T_{min}, T_{opt}, T_{max}	ºC	8 / 25 / 36	8 / 25 / 36	8 / 25 / 36	D
Moisture ratio deficit for $f_\theta = 0.5$	c_θ		0.5	0.5	0.5	D
Power of moisture ratio deficit	n_θ		5	5	5	D
Power of (1-*FR*) in f_N	f_{Nn}		1	1	1	D
Value of f_N when $FR = 0$	f_{N0}	-	0.6	0.6	0.6	F
Maximum stand age used in age modifier f_{age}	-	years	9	9	9	D
Power of relative age in function for f_{age}	n_{age}	-	4	4	4	D
Relative age to give $f_{age} = 0.5$	r_{age}	-	0.95	0.95	0.95	D
Maximum litterfall rate	γ_{Fx}	1/month	0.13	0.13	0.13	O
Litterfall rate at t = 0	γ_{F0}	1/month	0.00169	0.00169	0.00169	DO
Age at which litterfall rate has median value	$t_{\gamma F}$	month	13	13	13	O
Average monthly root turnover rate	γ_R	$month^{-1}$	0.025	0.025	0.025	D
Maximum canopy conductance	g_{Cx}	$m\ s^{-1}$	0.020	0.022	0.021	O
Response of canopy to vapour pressure deficit	k_D	$mbar^{-1}$	0.045	0.050	0.048	DO

3-PG Parameters						
Meaning/comments	**Symbol**	**Units**	**Clone 15**	**Clone 22**	**Generic**	**Values source**
L^* for maximum canopy conductance	L_{gcx}	-	3	3	3	DO
Canopy boundary layer conductance	g_B	$m\ s^{-1}$	0.2	0.2	0.2	D
Maximum stem mass per tree @ 1000 trees/hectare	w_{Sx1000}	$kg\ tree^{-1}$	180	180	180	O
Specific leaf area (early stage and mature leaves)	σ	$m^2\ kg^{-1}$	11 - 8	9 - 7.3	10.5 - 8	O
Extinction coefficient for absorption of PAR by canopy	k	-	0.5	0.5	0.5	O
Maximum canopy quantum efficiency	α	mol C mol PAR^{-1}	0.068	0.068	0.068	DO
Ratio P_N/P_G	Y	-	0.47	0.47	0.47	D
Maximum proportion of rainfall evaporated from canopy	I_x	-	0.15	0.15	0.15	O
Leaf area index for maximum rainfall interception	L_{Ix}	-	3	3	3	O
Branch and bark fraction at age 0	p_{BB0}	-	0.3	0.3	0.3	O
Branch and bark fraction for mature stands	p_{BB1}	-	0.12	0.12	0.12	O
Minimum basic density - for young trees	ρ_m	$t\ m^{-3}$	0.48	0.40	0.48	O
Maximum basic density - for older trees	ρ_x	$t\ m^{-3}$	0.52	0.48	0.52	O

Values source: O = observed, F = fitted, D = default, DO = derived from observed data

Using parameter values assigned on the basis of knowledge about the growth and physiology of the trees, with some parameters obtained by calibration as described above, 3-PG can simulate accurately the time course of a number of variables that define growth. This is illustrated for 'general' genotypes by simple linear regressions of simulated values of SV ($r^2 = 0.98$), MAI ($r^2 = 0.95$), BA ($r^2 = 0.96$), DBH ($r^2 = 0.98$) and LAI ($r^2 = 0.71$), on the values measured monthly on five clones in 12 sample plots in the catchment. The simulations were calculated using the parameter values in the generic column in Table 6.1. Table 6.2 shows the goodness-of-fit between simulated and observed variable values for clones 15 and 22 planted in the growth plots in the experimental catchment. Linear regressions describing the relationship between measurements and predictions by 3-PG are presented for seven main outputs in the catchment. As in the case of the general genotypes in the catchment, the high r^2 values indicate that the simulated variable values accounted, in most cases, for more than 90% of the variance in the observed values. The notable exception is litterfall, which never showed clear patterns or trends.

Figure 6.1 shows the time course of predicted and observed SV, LAI and stem (W_S) and root (W_R) biomass for the same two clones (15 and 22). Stand volume for clone 15 was always higher than for clone 22, although the differences were smaller than those for W_S because of the lower wood density characteristic of clone 22 (see Table 3). Leaf area index for clone 15 was also consistently higher than for clone 22, being maintained at 3 - 4 from about 2.5 to 4 years of age, compared with 2 - 3 in clone 22 across that age range. The differences in W_R are perhaps the most striking of the clonal differences shown in Figure 6.1; clone 15 clearly allocates less carbohydrate to roots than clone 22 – by age 5.5 years the root mass of clone 22 was almost double that of clone 15. The differences in W_R were simulated reasonably faithfully by 3-PG. To achieve this the minimum fraction of P_N allocated to roots, under optimum growing conditions, was set to 0.07 for clone 15 as opposed to 0.12 for clone 22 (see also Figure 5.11).

Table 6.2 Details of linear regressions of predicted vs. observed values of mean annual increment (MAI, $m^3 ha^{-1} yr^{-1}$), stand volume (SV, $m^3 ha^{-1}$), basal area (BA, $m^2 ha^{-1}$), mean diameter at breast height (DBH, cm) leaf area index (LAI), litterfall (γ, t ha^{-1}) and available soil water (SW, mm) for clones 15 and 22 in the experimental catchment.

Local	Output	Clone ID	Intercept	Slope	N	r^2	Standard error
Catchment	MAI	15	4.32	0.86	40	0.97	2.09
		22	2.89	0.90	29	0.96	1.92
	SV	15	4.96	0.93	40	0.98	7.42
		22	3.65	0.95	29	0.98	6.93
	DBH	15	0.14	0.97	40	0.98	0.37
		22	0.31	1.00	29	0.98	0.32
	BA	15	1.05	0.93	40	0.97	0.90
		22	0.55	0.95	29	0.97	0.81
	LAI	15	0.52	0.91	25	0.70	0.45
		22	0.38	0.88	27	0.82	0.25
	γ	15	0.49	0.06	20	0.02	0.09
		22	0.35	0.12	20	0.12	0.06
	SW	15	30.94	0.88	28	0.76	26.13
		22	43.04	0.75	24	0.70	26.27

Figure 6.2 compares BA, DBH and MAI estimated by 3-PG and obtained from measurements. The differences between the clones in the values of these variables, over the growing period, are consistent with the differences shown in Figure 6.1, although they are generally small. The time course of observed tree height is also shown for each clone, although the version of 3-PG used in this study does not include equations to calculate tree height. Clone 15 had thinner stems than clone 22 for the same mass.

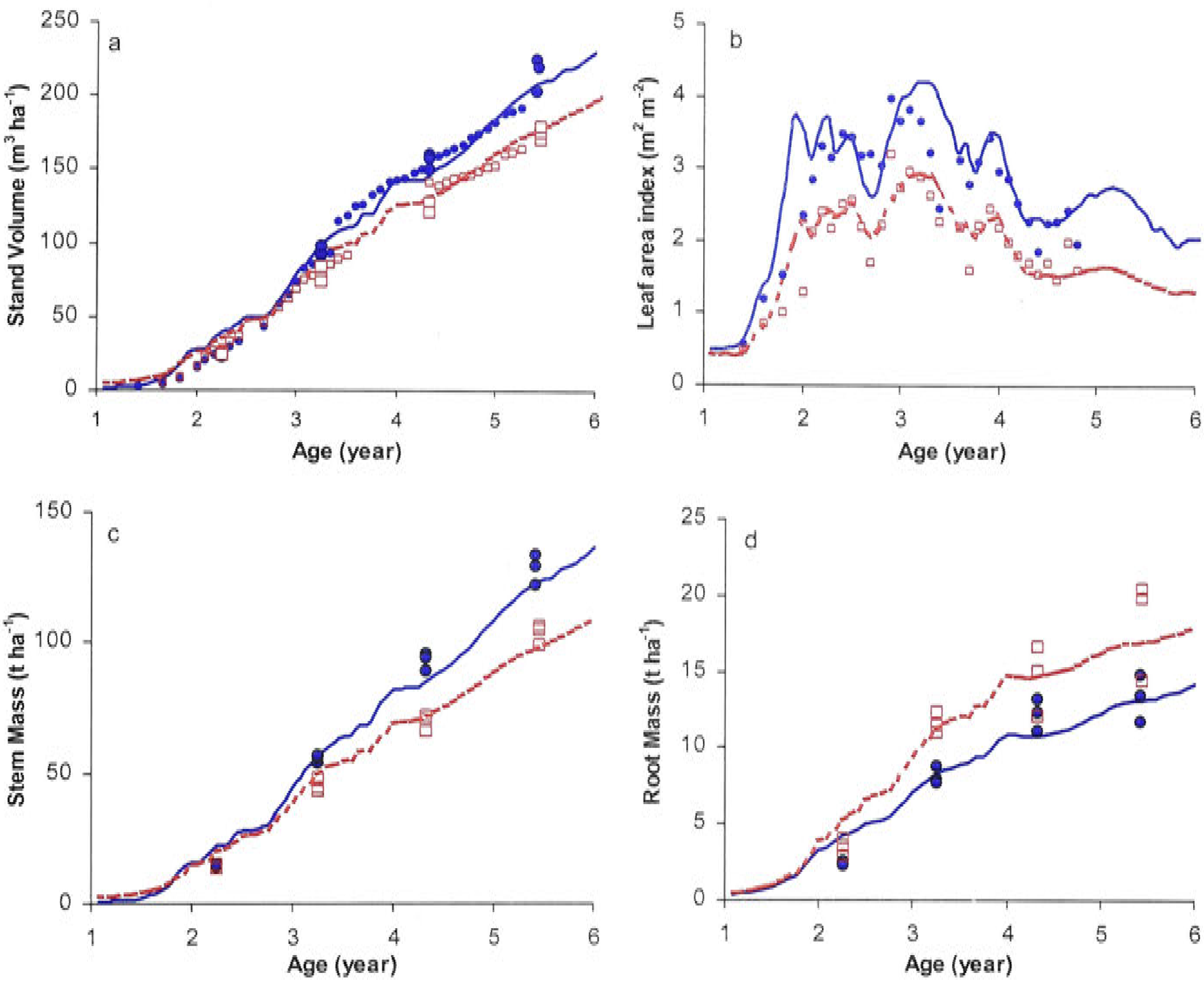


Figure 6.1. Comparison of observed (symbols) and predicted (lines) time-course of a) stand volume (SV, m3 ha-1), b) leaf area index (LAI), c) stem biomass (WS, t ha-1) and d) root biomass (WR, t ha-1) for clone 15 (filled symbols and solid lines) and clone 22 (open symbols and dashed line). Small symbols are monthly data; large symbols are annual data from destructive samples.

Soil water content affects growth in 3-PG through its effects on PhysMod (φ, equation 3.5 in Chapter 3) and hence on the effective canopy quantum efficiency (α_c). The water balance in the model is single-layered, representing the root zone of the trees. Figure 6.3 shows available soil water (SW) in the root zone measured by the neutron probe under clones 15 and 22, and the simulated values through the growing period. Simulated and observed values deviated from one another in the second half of year 2, then corresponded reasonably well through year 3, although the measurements indicated that clone 15 used more water than predicted by the model in the middle part of year 3. Through most of year 4, the model predicted more available soil water than was indicated by the measurements. There are some indications that clone 22 used less water than clone 15 in year 4, as can be seen in Figure 5.25 in Chapter 5. Taken overall the model accounted for 70% (r^2 = 0.70) of the variance in measured SW. The main reason for bias or error may be the monthly time step used by 3-PG. The variation of soil moisture observed during the month cannot be determined by 3-PG.

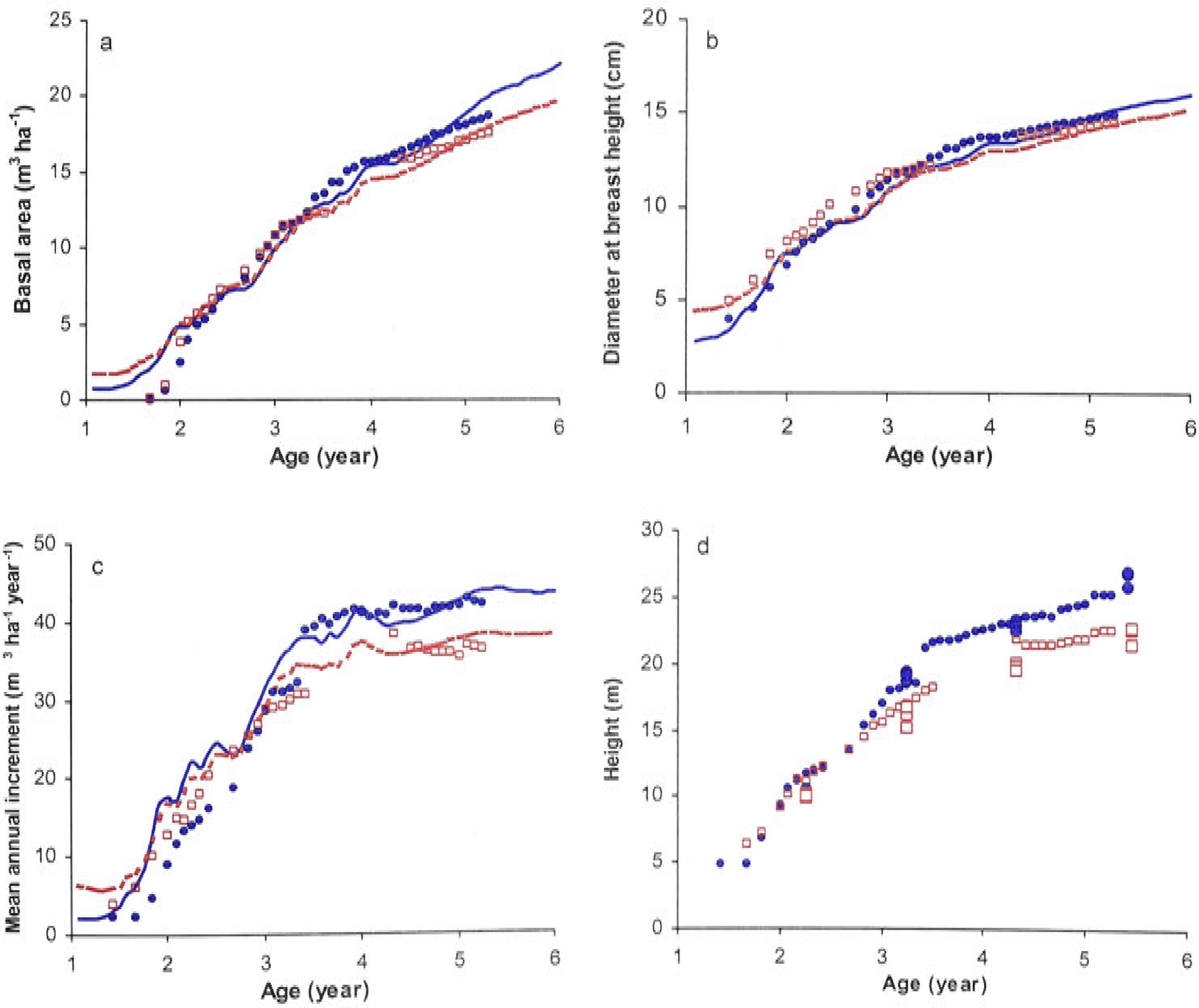


Figure 6.2. Comparison of observed (symbols) and predicted (lines) time-course of a) basal area (BA, m^2 ha^{-1}), b) mean diameter at breast height (DBH, cm), c) mean annual increment (MAI, m^3 ha^{-1} yr^{-1}) for clone 15 (filled symbols and solid lines) and clone 22 (open symbols and dashed line). Figure d) shows observed tree height. Small symbols are monthly data; large symbols are annual data from destructive samples.

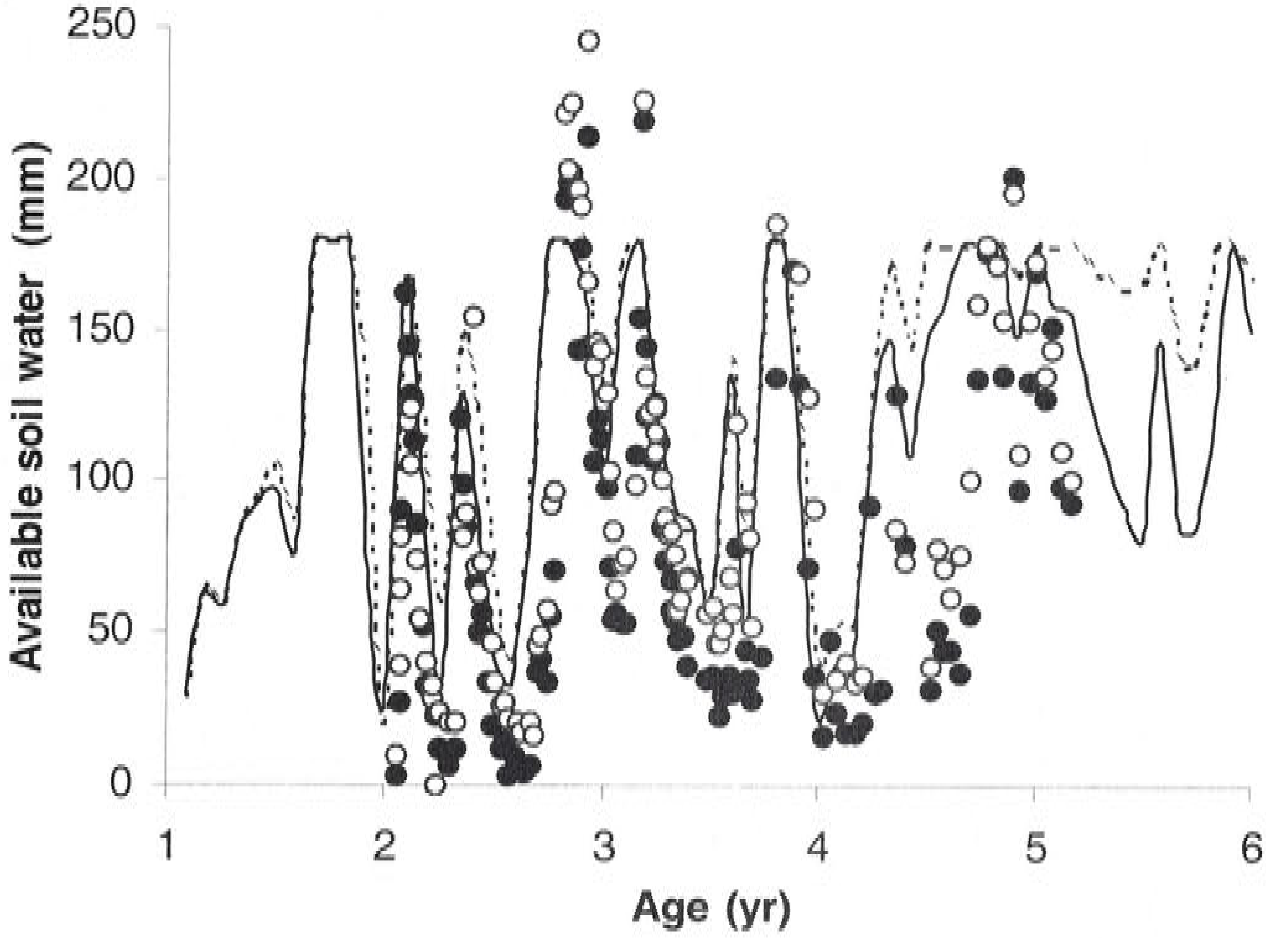


Figure 6.3. Comparison of observed (symbols) and predicted (lines) time course of available soil water (SW) in clone 15 (•) and solid line and in clone 22 (o) and dashed line.

Figure 6.4 presents residual analyses shown as bias (%) of model predictions of MAI, SV, LAI, BA and DBH for clone 15 and clone 22 from age 2 to 5 years.

The analyses of residuals between predicted and observed data shown in Figure 6.4 demonstrates the accuracy of the estimations made by the model considering five different genotypes. It is evident that estimation of the six outputs shown (MAI, SV, DBH, BA, LAI and SW) is reasonable. SW shows the biggest bias, for the reason noted earlier.

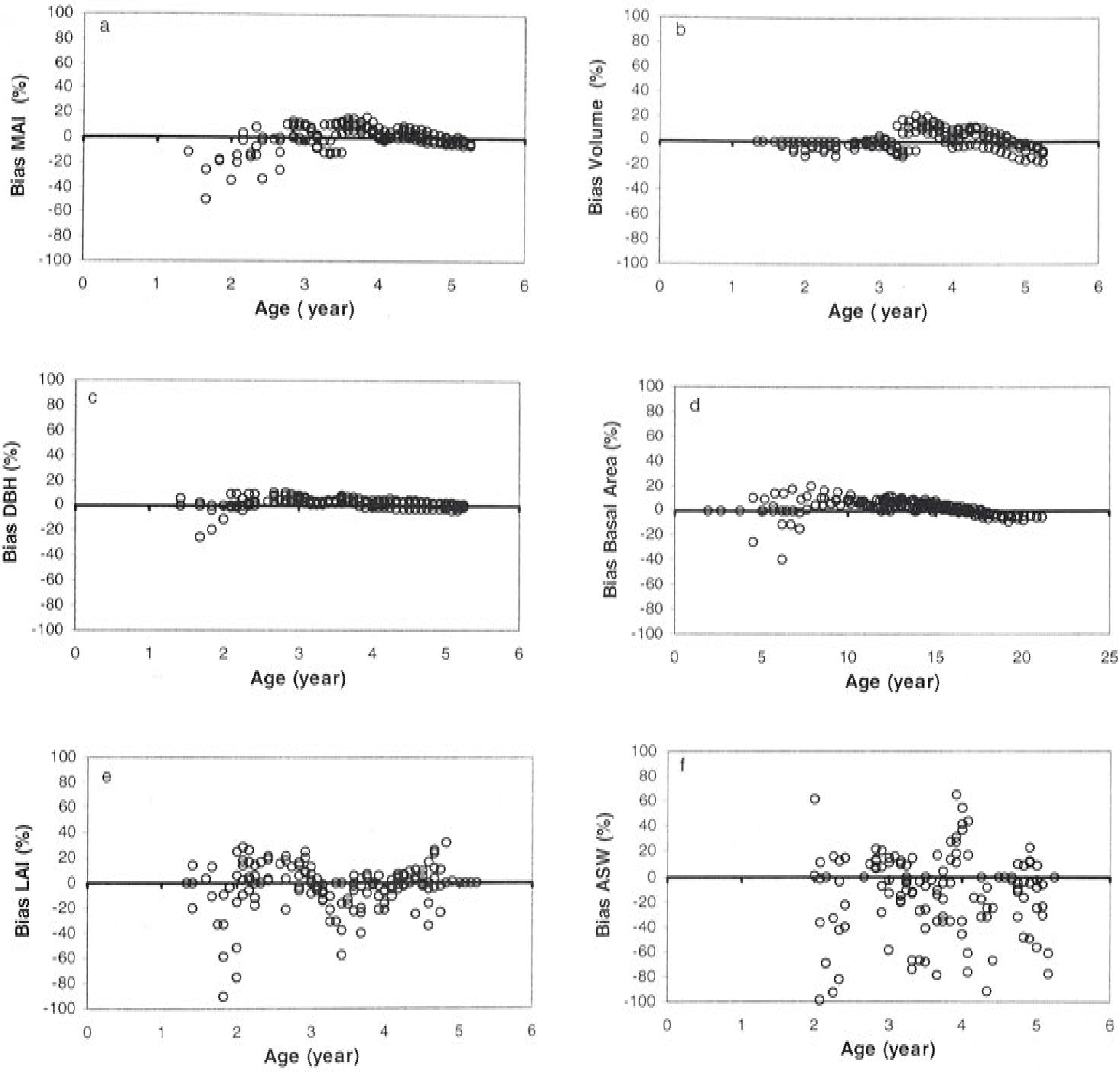


Figure 6.4. Bias (%) of model predictions to a) MAI, b) stand volume, c) diameter at breast height, d) basal area e) LAI and f) available soil water for five clones growing in the MBE area. The monthly bias (MB) was calculated as: MB = ((observed - simulated) / observed values * 100).

6.2. Model validation

The validation of 3-PG predictions was based on independent inventories made in permanent growth plots in the Viveiro and Sayonara regions, comparing the model performance for clone 15 and clone 22 (see Figure 4.4 for location). These regions were chosen because they were relatively close to automatic weather stations and contained a considerable number of permanent plots planted with clones 15 and 22, which have been a focus for this study. A wider-scale validation was undertaken by comparing predicted and observed MAI and peak MAI for a group of clones (lumped data, generic parameters) in ten different regions with stands planted in 1995 and seven regions where planting was in 1996. Details are given later.

Table 6.3 summarises the goodness-of-fit between simulated and observed values for clones 15 and 22 planted in the growth plots in the Sayonara and Viveiro regions. Linear regressions describing the relationship between measurements and estimates by 3-PG are presented. Figure 6.5 provides a test of the performance of 3-PG against SV (m^3 ha^{-1}) and BA (m^2 ha^{-1}) measurements for clones 15 and 22 made in permanent sample plots in the Sayonara and Viveiro regions. The lines on the figure are the 1:1 lines, which provide a good visual impression of the correspondence between simulated and measured values. Regression statistics for the relationships are given in Table 6.3. In the Sayonara region the slopes of the lines, for both variables, are generally less than unity, while in Viveiro they are about unity, or slightly greater.

Table 6.3. Details of linear regressions of predicted vs. observed values of stand volume (SV, $m^3 ha^{-1}$), basal area (BA, $m^2 ha^{-1}$) for clones 15 and 22 in the Sayonara and Viveiro regions.

Local	Output	Clone ID	Intercept	Std error Intercept	Slope	Std error Slope	N	r^2
Sayonara	SV	15	13.90	9.70	0.87	0.06	12	0.96
		22	26.82	6.22	0.88	0.05	16	0.96
	BA	15	-0.41	1.30	1.00	0.07	12	0.95
		22	1.15	0.77	0.96	0.05	16	0.96
Viveiro	SV	15	-28.92	8.11	1.16	0.05	12	0.98
		22	8.82	10.58	0.93	0.08	7	0.97
	BA	15	-6.88	1.11	1.40	0.06	12	0.98
		22	-2.26	2.61	1.09	0.16	7	0.90

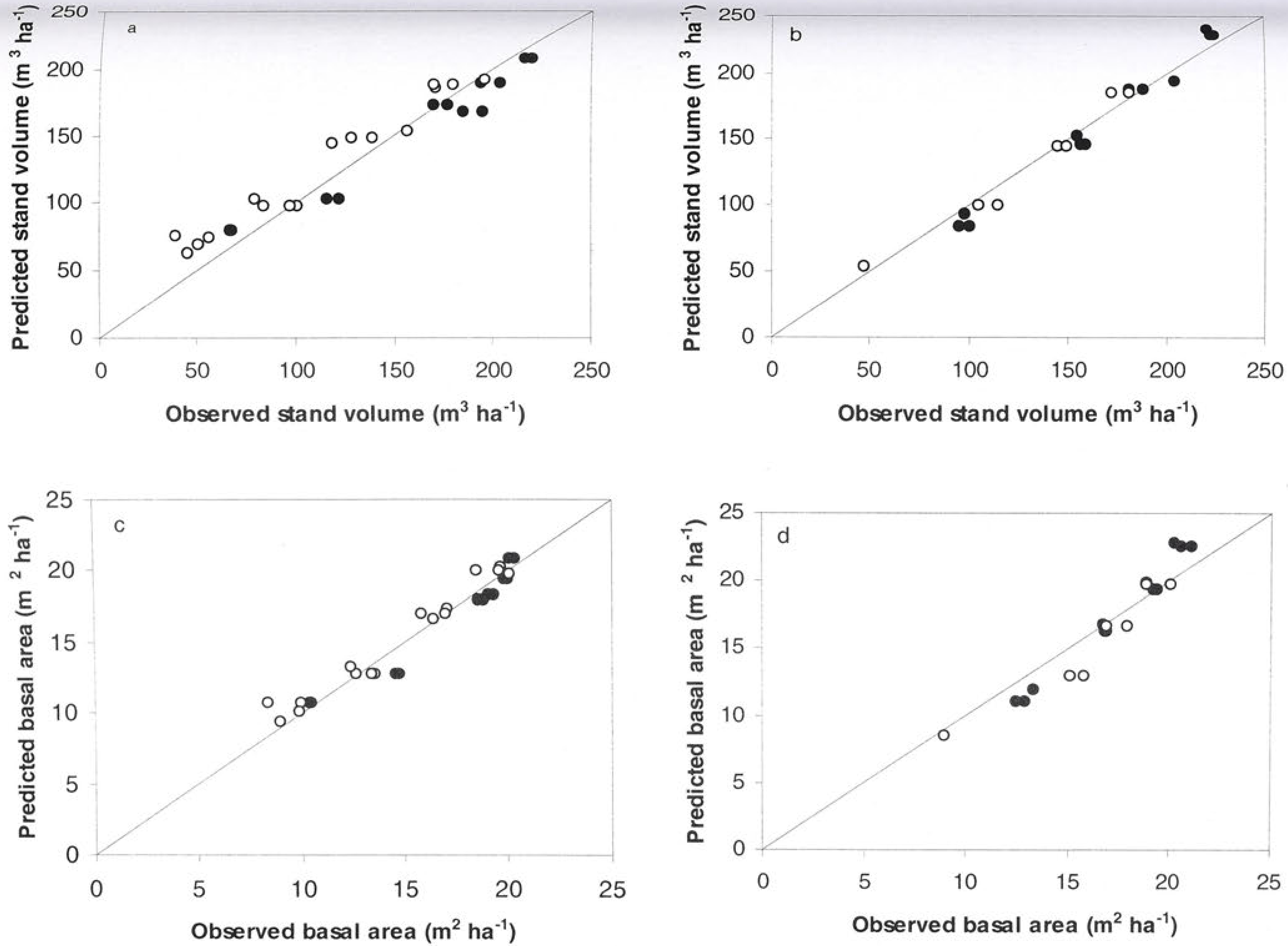


Figure 6.5. Comparison of observed and predicted stand volume, SV (a, b) and basal area, BA (c, d) in Sayonara (a, c) and in Viveiro (b, d) regions. Data from sites are (•) for clone 15 and (o) for clone 22. The regression equations are presented in Table 6.3.

In the ten regions planted in 1995 (see Table 6.4, Figures 6.7 and 6.8) the number of PSPs from which measurements were available in each region varied from 5 to 32; in the seven regions planted in 1996 (see Table 6.5, Figures 6.10 and 6.11) the number of PSPs varied from 2 to 54. Measurements were made up to stand rotation age of 7 years of age in the areas planted in 1995 and up to 6 years of age in the areas planted in 1996. The seven sites cover the main three regions of the study (Aracruz, São Mateus and South Bahia).

Data from the nearest AWS were used in the simulations and the predominant soil type in each region was used to assign the fertility rating, the maximum available soil water and the soil class required as input data for 3-PG for that region. For the regions planted in 1995, the MA*I*, peak MAI (MAI_x) and the age at peak MAI (Age_{MAIx}) for each region were estimated from the measurements as averages over those PSPs aged from 6 to 7.6 years (Table 6.4). Figure 6.6a compares observed and predicted MAI_x, and Figure 6.6b compares observed and predicted MAI. The predicted and observed ages at peak MAI were also in good agreement with those shown in Figure 6.7 and in Table 6.4. Figure 6.8 shows the MAI and MAI_x predicted and observed in which region.

For the areas planted in 1996 observed MAI and MAI_x were established as the average of those calculated from measurements made in PSPs, from 1998 to 2002, i.e. at age 5.5 to 6.5 years. Table 6.5 shows characteristics of the seven sites and the variables of interest in the PSPs at each locality. Figure 6.9 shows the goodness-of-fit between simulated and observed values of MAI_x (Figure 6.9a) and the average MAI (Figure 6.9b) of the seven regions. The age when the stands reach the MAI_x is shown in Figure 6.10. Figure 6.11 shows observed MAI_x and MAI, together with the values predicted by 3-PG across all sites planted in 1996.

In general the model is able to predict MAI with a high level of accuracy, although some deviations can be observed, mainly in relation to peak MAI.

Table 6.4 Inventory results showing predominant soil texture, soil type and fertility rating used in 3-PG, and the peak mean annual increment (MAI_x) and average mean annual increments (MAI) measured at ten studied sites planted in 1995

Region	Number of inventory plots	Soil texture	Soil code	Maximum available soil water (mm) (2m)	Fertility rating	Peak MAI (m^3 ha^{-1} $year^{-1}$)	Age Peak MAI (years)	Average MAI at inventory age (m^3 ha^{-1} $year^{-1}$)	Std Deviation of MAI (m^3 ha^{-1} $year^{-1}$)
Cachoeirinha	5	Clay	PAd1	188	0.78	34.9	6.6	30.8	3.6
Fabrica	5	Clay	PAd1	188	0.78	46.8	6.3	37.9	5.9
Microbacia	6	Clay	PAd1	188	0.78	40.8	6.7	36.6	4.6
Pastinho	3	Clay	LAx3	180	0.76	28.3	7.6	23.7	4.2
Sede	7	Clay	PAd1	188	0.78	39.3	6.3	31.0	4.8
Viveiro	27	Clay	PAd1	188	0.78	45.7	6.0	34.4	4.6
Itauninhas	32	Clay	PAd8	172	0.78	38.1	6.3	28.3	4.7
PRF	22	Clay loam	PAd10	172	0.82	44.5	6.8	29.9	7.9
Santana	16	Clay	PAd11	164	0.78	51.9	7.2	40.5	8.6
Sayonara	5	Clay loam	PAd10	172	0.82	39.3	6.3	32.9	4.1

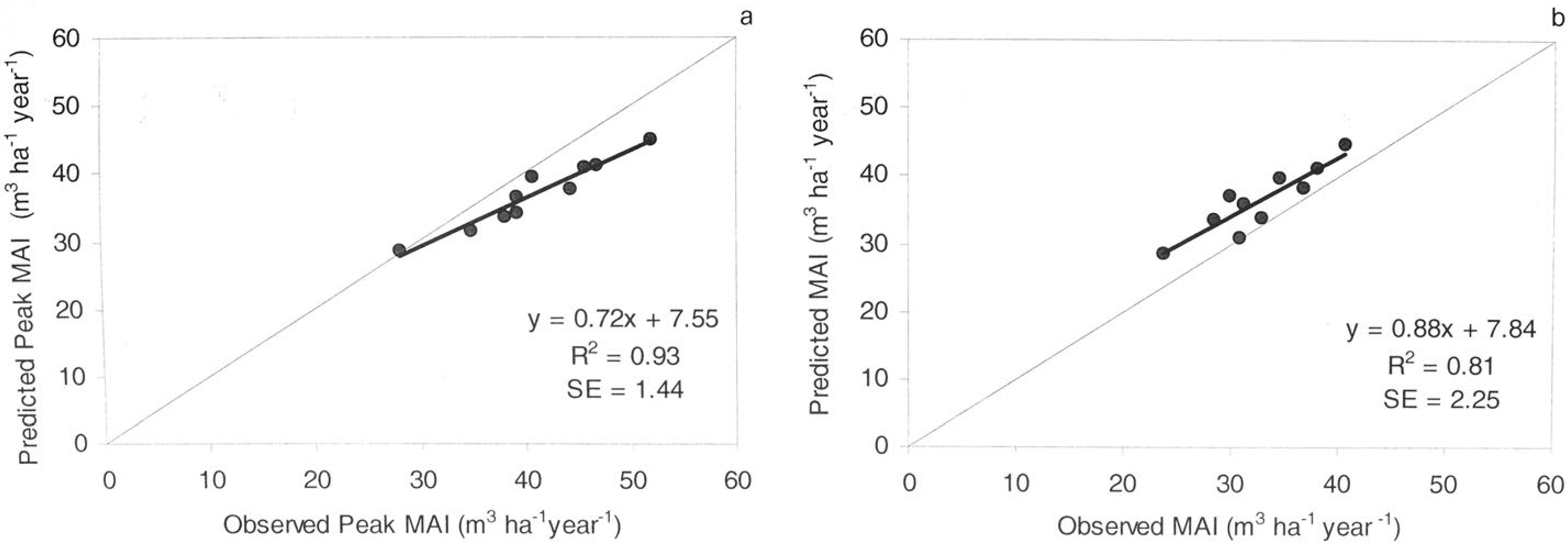


Figure 6.6. a) Peak mean annual increment ($MAI_{x)}$ and b) MAI observed in permanent sample plots aged from 6 to 7.6 years planted in ten regions in 1995, compared with predictions by 3-PG.

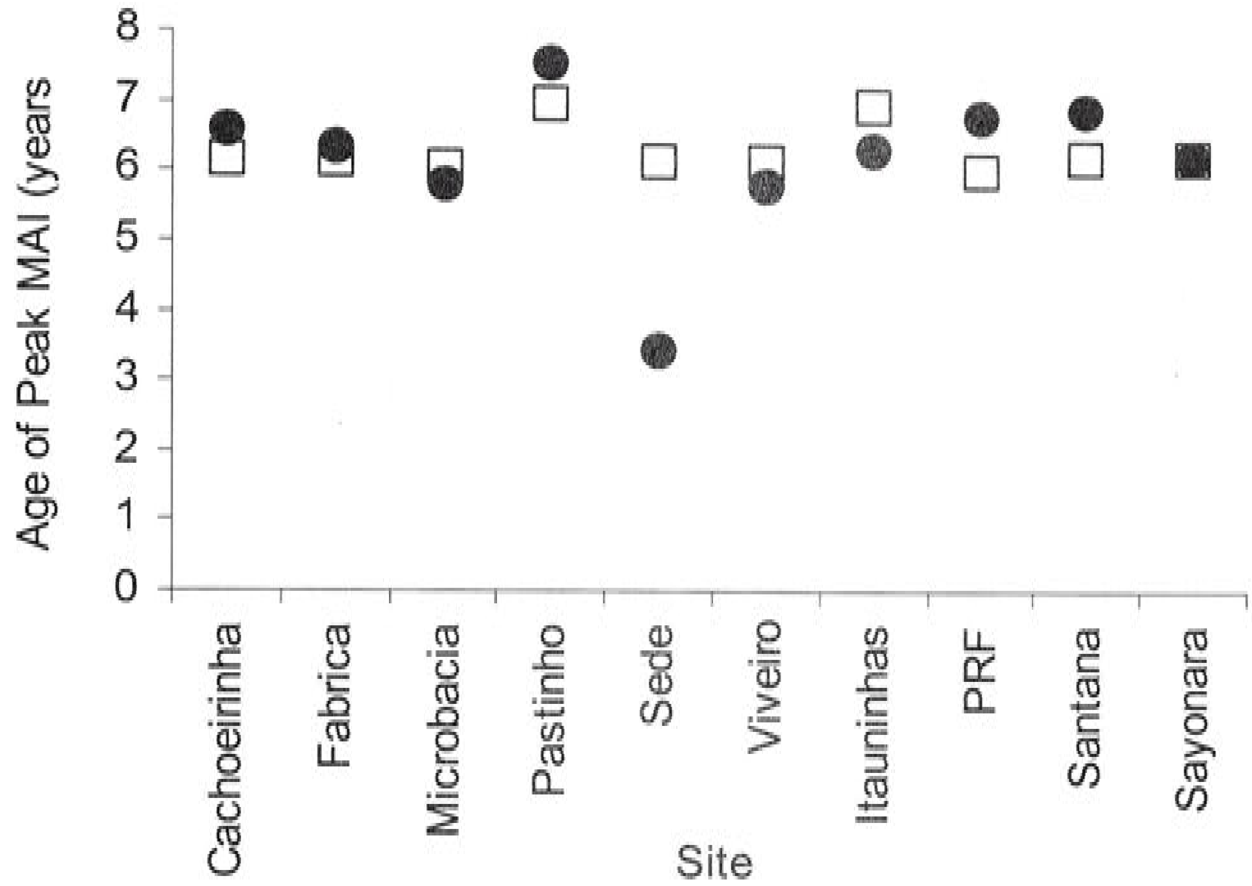


Figure 6.7. Observed (circles) and predicted by 3-PG (squares) age of peak mean annual increment (Age_{MAIx}) in ten regions planted in 1995.

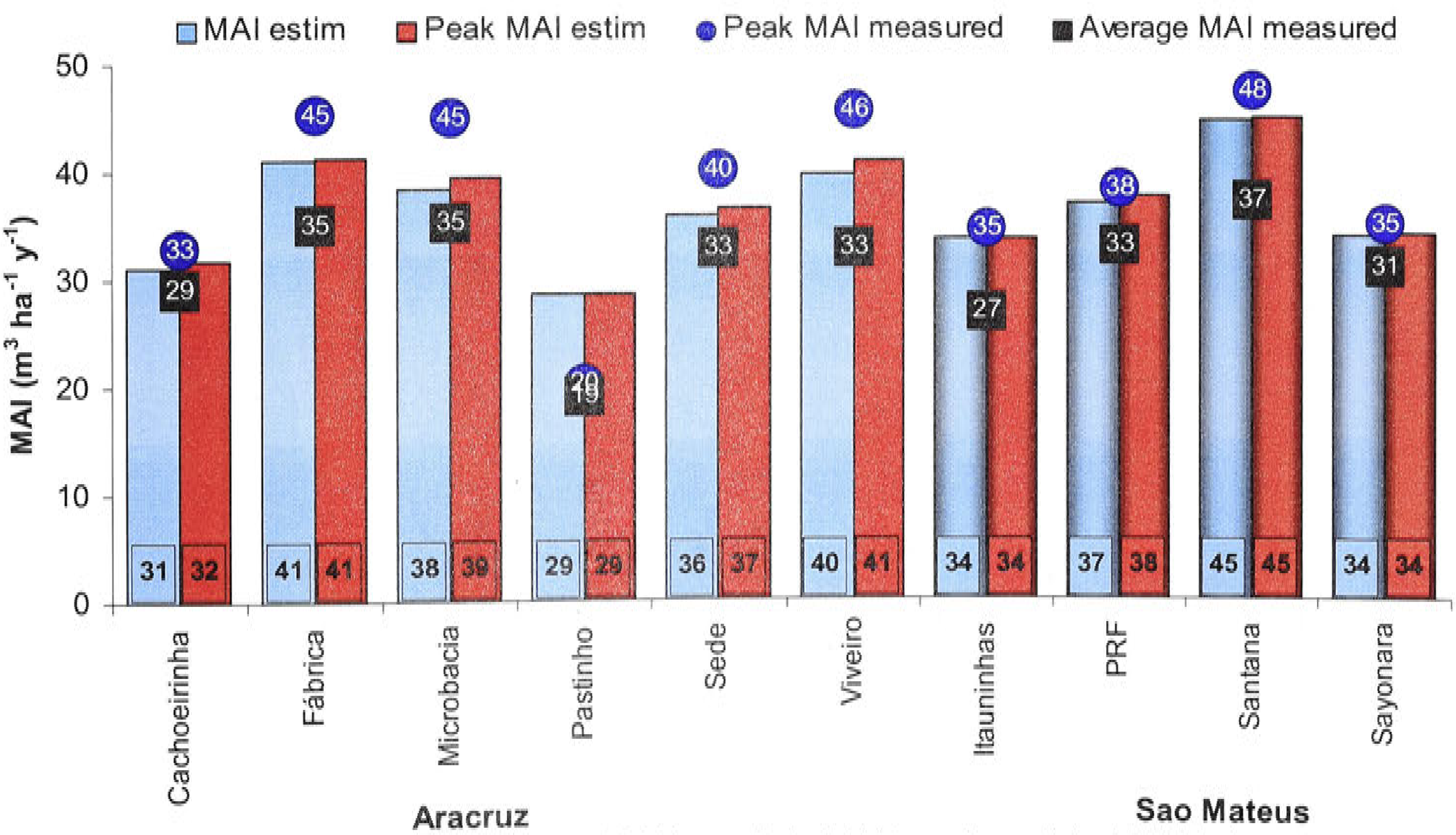
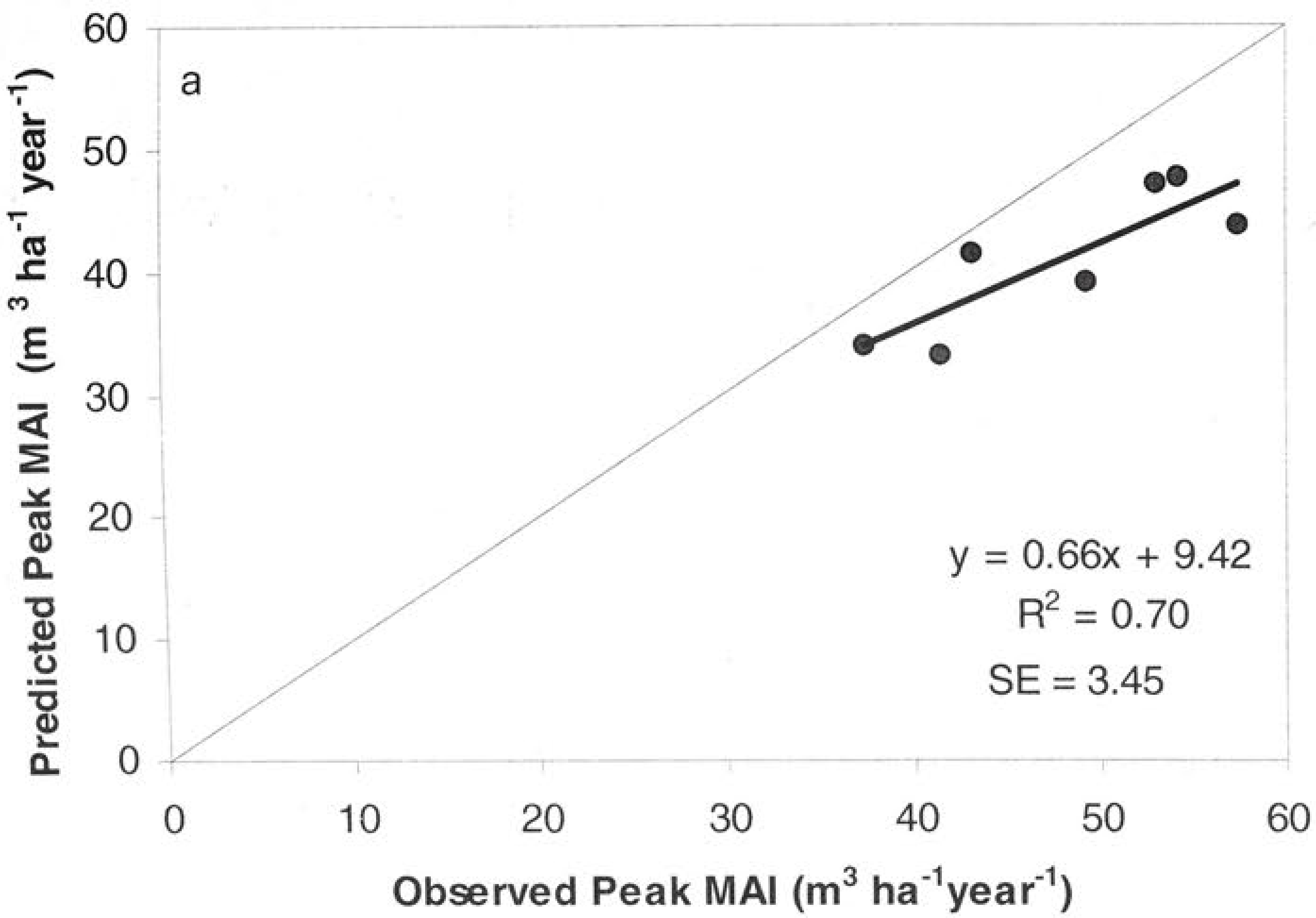


Figure 6.8. Observed MAI_x, observed MAI, predicted MAI_x and predicted MAI in ten regions planted in 1995 (shadow bars are the São Mateus region).

Table 6.5 The predominant soil texture, soil type and fertility ratings used in 3-PG for the ten regions where plantings were in 1996, together with inventory results showing MAI_x and MAI values derived from measurements in those regions.

Region	Number of inventory plots	Soil texture	Soil code	Maximum available soil water (mm) (2m)	Fertility rating	Peak MAI (m^3 ha^{-1} $year^{-1}$)	Age Peak MAI (years)	Average MAI at inventory age (m^3 ha^{-1} $year^{-1}$)	Std Deviation of MAI (m^3 ha^{-1} $year^{-1}$)
Fabrica	33	Clay	PAd1	188	0.78	49.4	5.1	38.4	4.7
Microbacia	2	Clay	PAd1	188	0.78	37.5	5.9	34.3	4.6
Viveiro	17	Clay	PAd1	188	0.78	41.6	5.7	34.8	4.4
Joeirana	7	Sandy loam	PAd9	192	0.82	53.1	5.6	44.1	9.4
Nova Vicosa	9	Clay loam	PAd10	172	0.82	54.2	6.1	48.3	3.4
PRF	23	Clay loam	PAd10	172	0.82	43.2	6.2	36.0	3.5
Santana	54	Clay	PAd11	164	0.78	57.5	6.2	40.3	8.8



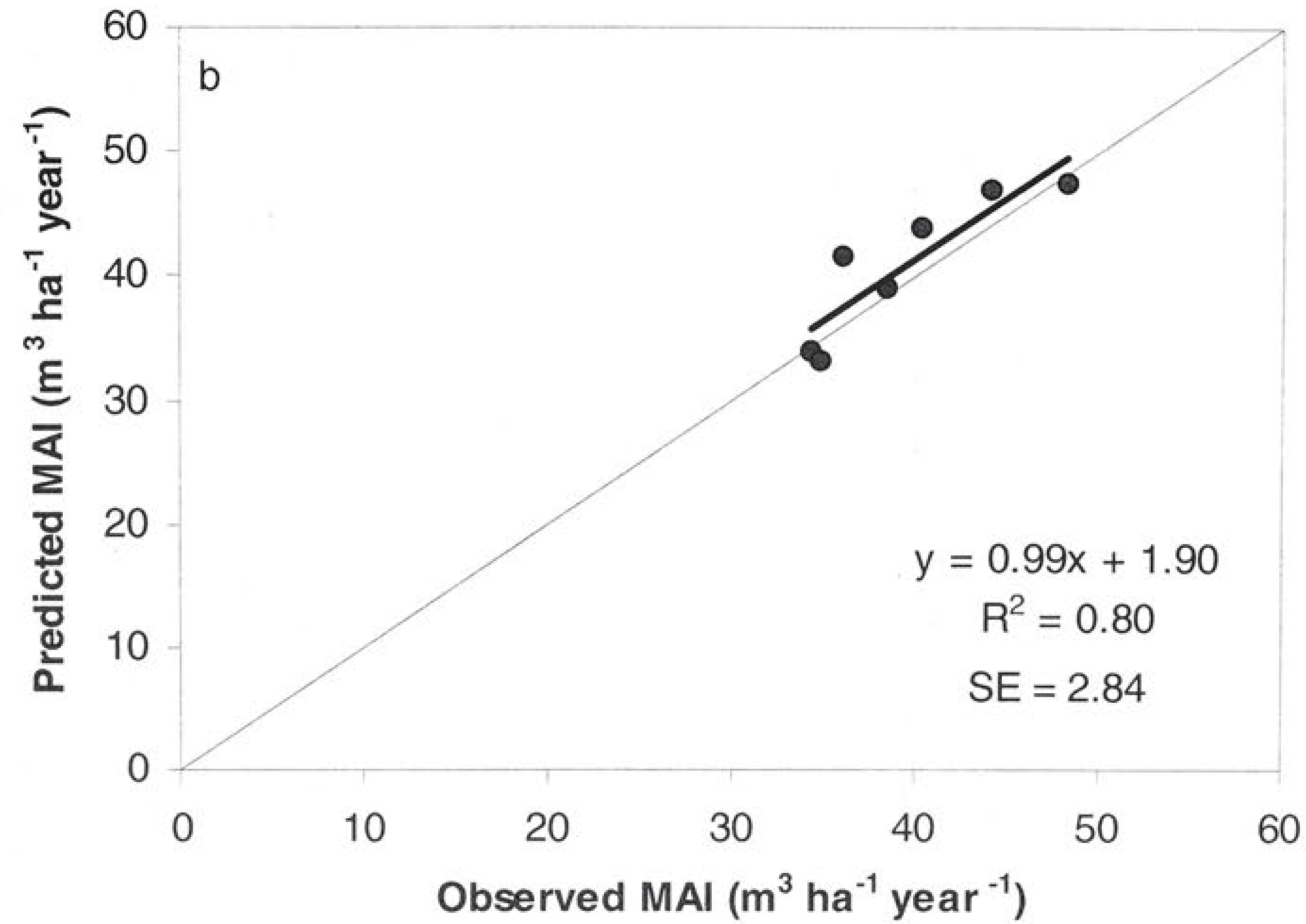


Figure 6.9. a) Peak mean annual increment and b) MAI observed in permanent sample plots aged from 5 to 6.5 years planted in seven regions in 1996 are compared with predictions by 3-PG.

Figure 6.10. Observed (circles) and predicted by 3-PG (squares) age of peak mean annual increment (Age_{MAIx}) in ten regions planted in 1996.

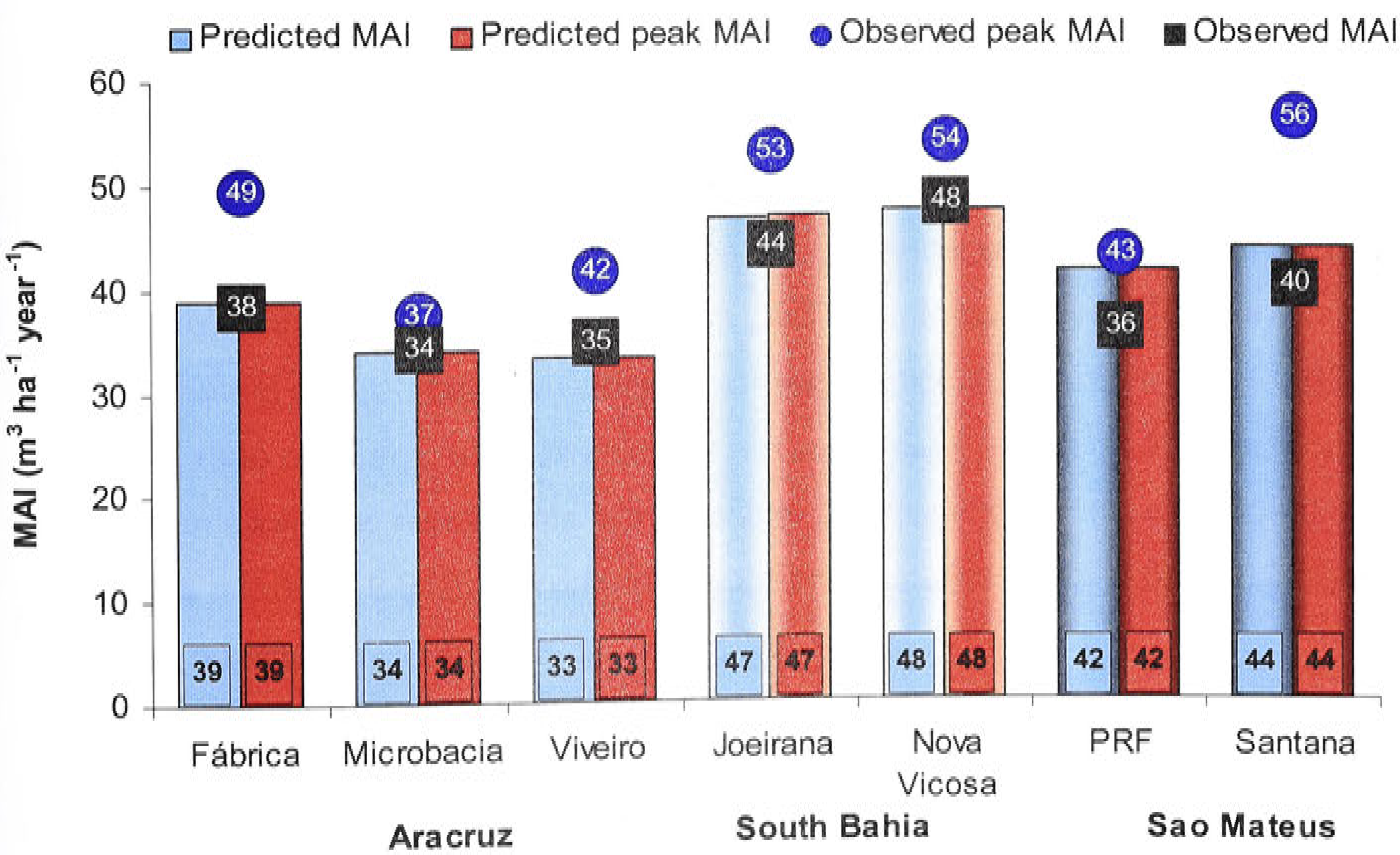


Figure 6.11. Observed MAI_x, observed MAI, predicted MAI_x and predicted MAI in seven regions planted in 1996. Fábrica, Microbacia and Viveiro are in Aracruz region, Joeirana and Nova Vicosa are in South Bahia (clear shadow bars) and PRF and Santana are in São Mateus region (dark shadow bars).

6.3. Sensitivity analyses

The effects of -20%, -10%, +10% and +20% changes in selected parameters on some predicted estimates are shown in Figure. 6.12 and Figure 6.13. The analyses were based on a standard seven-year run, using generic parameter values (see Table 6.1) and weather data from MBE site. Figures. 6.12a and 6.12b present the changes in the stem constant (a_s) and stem power (n_s) parameters in 3-PG. Mean diameter at breast height (DBH) and foliage biomass (W_F) are the outputs most affected by these changes: changing n_s by 20% can affect DBH by 85%. The 3-PG outputs showed sensitivity to maximum canopy conductance (Figure. 6.12c) but were less sensitive to the effect of VPD on stomatal conductance, g_s (Figure 6.12d). All biomass pools were highly sensitive to maximum canopy quantum efficiency (Figure 6.12f), which is to be expected since GPP is proportional to α, but only root biomass was significantly sensitive to partitioning to roots (Figure 6.12e).

The results from this sensitivity analysis are broadly consistent with the variation of parameter estimates between clones. For instance, g_s varied between clones (Figure 5.19), but the effects of VPD on g_s did not. In general the following parameters differed between clones: biomass partitioning to roots (η_{Rn} = 0.07 - 0.12), ratio of foliage: stem biomass partitioning (p_{FS20} = 0.10 - 0.11), coefficients in stem allometric relationship with diameter at breast height (a_s = 0.050 - 0.033 and n_s = 2.822 - 2.912), maximum canopy conductance (g_{Cx} = 0.020 - 0.022) and basic density (ρ_x = 0.48 - 0.52).

Figure 6.13 provides additional sensitivity analyses for parameters or site factors. The fertility modifier f_{N0} (Figure 6.13a) used when $FR = 0$ (see equation 3.24) has a small direct effect on the outputs because the simulations were carried out with $FR = 0.8$. The reductions of 10% and 20% in maximum available soil water reduce stand volume by 1.5% and 4%, respectively (Figure 6.13b). The increase in specific leaf area tends to increase biomass production (Figure 6.13c) and the increase in litterfall rate causes a decrease in the mass of roots, stem and (mainly) foliage (Figure 6.13d). Figure 6.13e shows that basic wood density affects only the stand volume and, finally, the consequence of changes on fertility rate is demonstrated in Figure 6.13f.

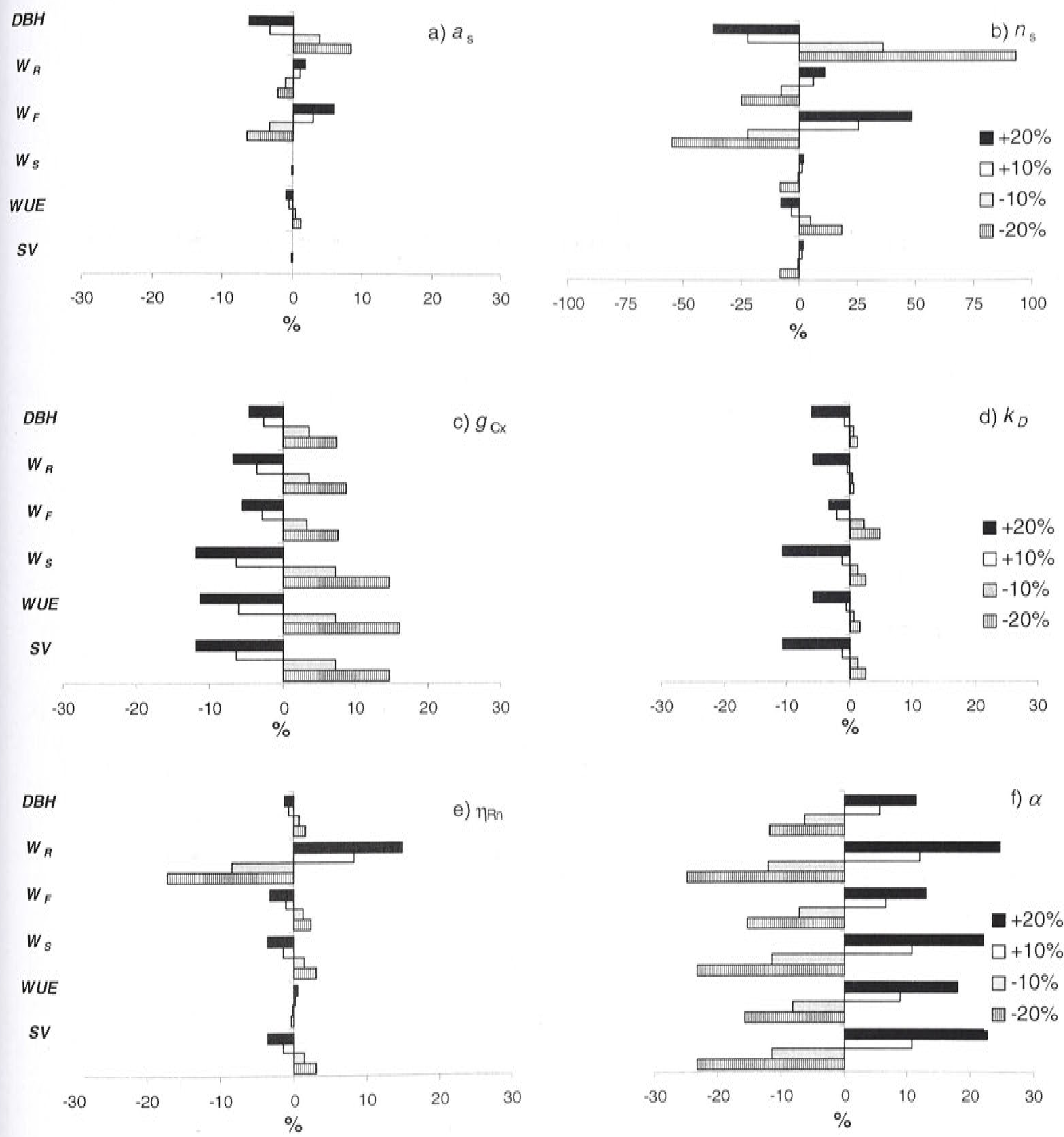


Figure 6.12. Estimated sensitivity of selected 3-PG outputs to the following parameters: a) stem constant, a_S b) stem power, n_S c) maximum canopy conductance g_{Cx}, d) effect of vapour pressure deficit, D on stomatal conductance g_s, e) minimum biomass partitioning to roots, η_{Rn} and f) maximum canopy quantum efficiency, $\propto$. The bars show how -20%, -10%, +10% and +20% variation in each parameter affects the variables on the y-axix: mean diameter at breast height, DBH, root (W_R), foliage (W_F) and stem (W_S) biomass, water use efficiency (WUE), and stand volume (SV).

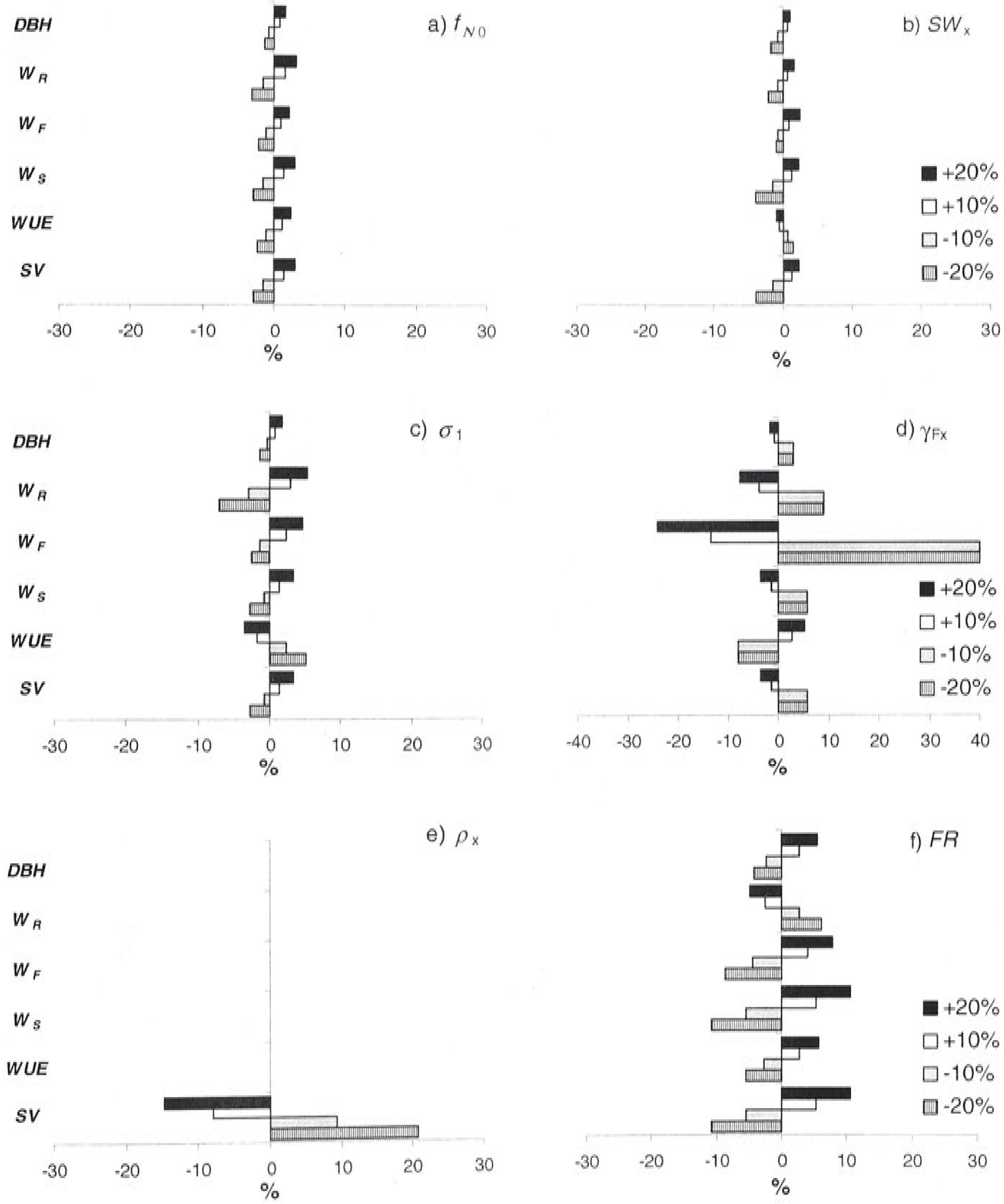


Figure 6.13. Estimated sensitivity of selected 3-PG outputs to the following parameters or site factor: a) fertility modifier when FR =0, f_{N0}, b) maximum available soil water, SW_x, c) specific leaf area for mature aged stand σ_1, d) maximum litterfall rate, γ_{Fx}, e) maximum basic wood density for mature stands, ρ_x ,and (f) fertility rate, FR. The bars show how -20%, -10%, +10% and +20% variation in each parameter or site factor affects the variables on the y-axis: mean diameter at breast height, DBH, root (W_R), foliage (W_F) and stem (W_S) biomass, water use efficiency (WUE), and stand volume (SV).

Chapter 7

7. MODEL APPLICATION[7]

7.1. Application of 3-PG as an analytical and operational tool

3-PG has been integrated into the ARCEL forest management information system and incorporated into the strategic forest improvement plan. Figure 7.1 shows the strategy adopted for using 3-PG in the decision-making process and operational activities in the study areas. The three main areas of use are:

- Estimation of potential productivity (i.e. analyses of currently planted areas and the potential productivity of proposed plantations in new lands);
- Forest growth analyses (i.e. cause-effect analyses of forest plantation growth), and
- Strategic scenarios (i.e. long-term wood-supply planning, simulation of productivity based on climate change scenarios and risk analyses).

Estimates of potential forest productivity are used as a basis for selecting and evaluating land in which the company has an interest, with a view to expansion. 3-PG is also being used to estimate biomass production for the next rotation in current operational areas, and these estimates are used to calculate the nutrient requirements and fertiliser needs for each planted block. A forest classification system using 3-PG is being developed to compare productivity between regions, to compare the results of different forest management practices, and to supply information for decision-making in relation to resource allocation. Another application analyses the performance of the forest and the effects of climate on forest growth. If productivity in an area is lower than estimated by 3-PG, this is an indication to silvicultural managers that those areas may need remedial attention.

[7] Part of this chapter is being published in Almeida *et al.* 2003 and in Almeida *et al.* 2004b.

These areas can be selected for the development of more specific analyses to identify the reason for the discrepancy. In terms of long-term forest planning and wood supply to the mills, risk analyses are developed based on 3-PG output in response to different scenarios.

To apply the model operationally across large areas a spatial approach integrating climate and soil layers through a geographical information system (GIS) and remote sensing techniques is necessary (Coops *et al.*, 1998; Coops *et al.*, 2001a; Tickle *et al.*, 2001b; Coops & Waring, 2001f). This accounts for the particular characteristics of each site, including variations of climate and soil characteristics.

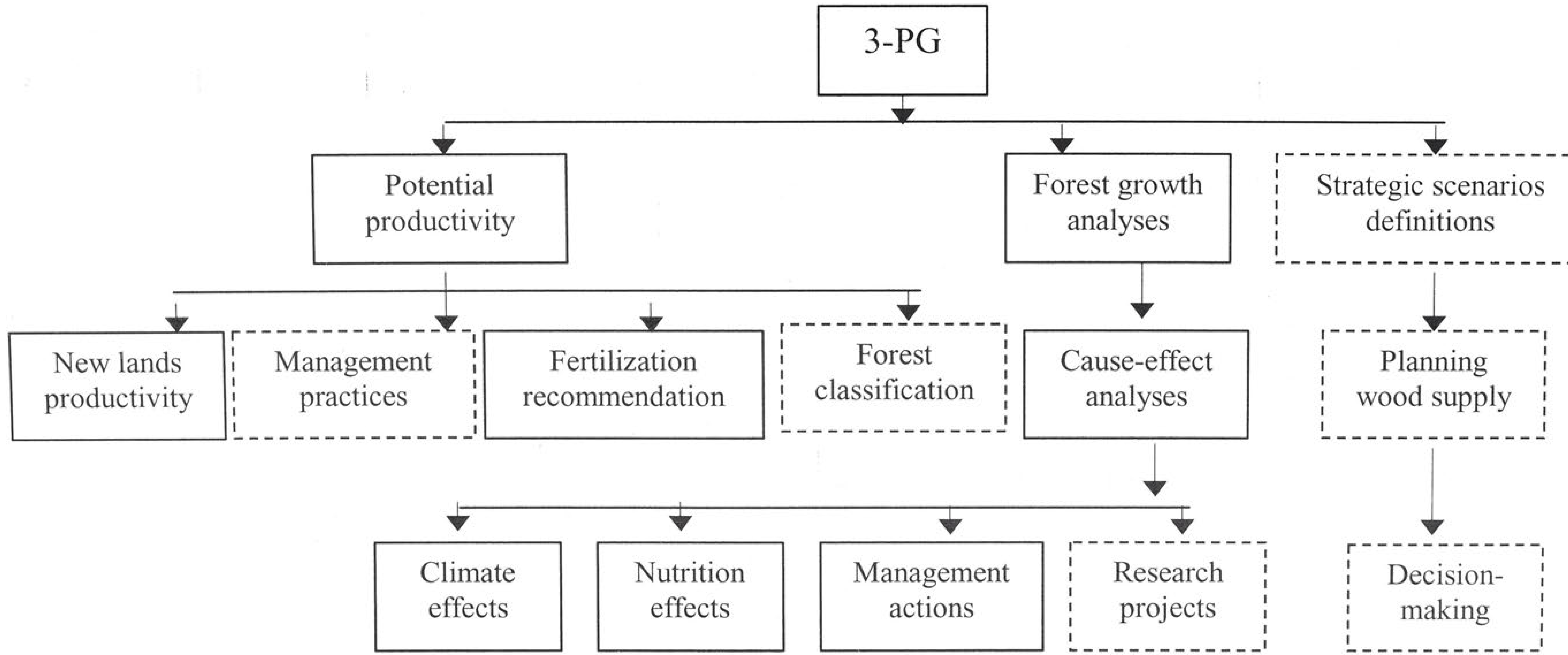


Figure 7.1. Diagram showing the application of 3-PG to the management of commercial plantations of fast growing *Eucalyptus grandis* plantations for commercial purposes. There are three broad areas of application, each of which breaks down into specific applications. Dashed line boxes represent applications still under development.

7.2. Comparison of productivity between regions and climate effect on forest growth

The fast growing *Eucalyptus grandis* plantations in Brazil (Stape, 2002; Almeida *et al.*, 2004b), and in other places such as South Africa (Dye, 1996) are strongly affected by climate. Rainfall distribution affects the availability of soil water and vapour pressure deficit may restrict forest growth. These effects can be identified by analysing data of current annual increment (CAI) for different years and regions, using 3-PG. An example of such an analysis, in which the effects of interannual climate variability are examined, is presented in Figure 7.2.

Figure 7.2a shows predicted CAI of stem wood over a 6-year growth period. The predictions were based on average monthly climatic data derived from 10 year's records in each of four different regions (see Figure 4.4 for locations). Figure 7.2b shows CAI for the same regions, but calculated using the observed monthly climate records from the first year after planting to the seventh, i.e., in this case, the years 1994 to 2000. Figure 7.2c shows observed values of CAI determined from measurements made in permanent sample plots in the Microbacia region, and demonstrates that the results produced by the model correspond well to the observed results; it reflects the effects of the low rainfall experienced in years 4 (1997) and 5 (1998) of the rotation. There was also a drought period in year 2, for which there were no measurements taken. The first point to emerge from this example is that growth and yield estimates made by 3-PG using average data are likely to overestimate forest growth because significant fluctuations, such as dry periods in particular years, are obscured by the averages. Average climate data are useful for comparing the potential production at sites, or for estimating limits imposed by site fertility. However, the prediction of probable production at specific sites must be based on actual monthly climate data. The results in Figure 7.2 also show that 3-PG can be used to estimate the probable effects of drought periods during the rotation, which is valuable information for managers and planners.

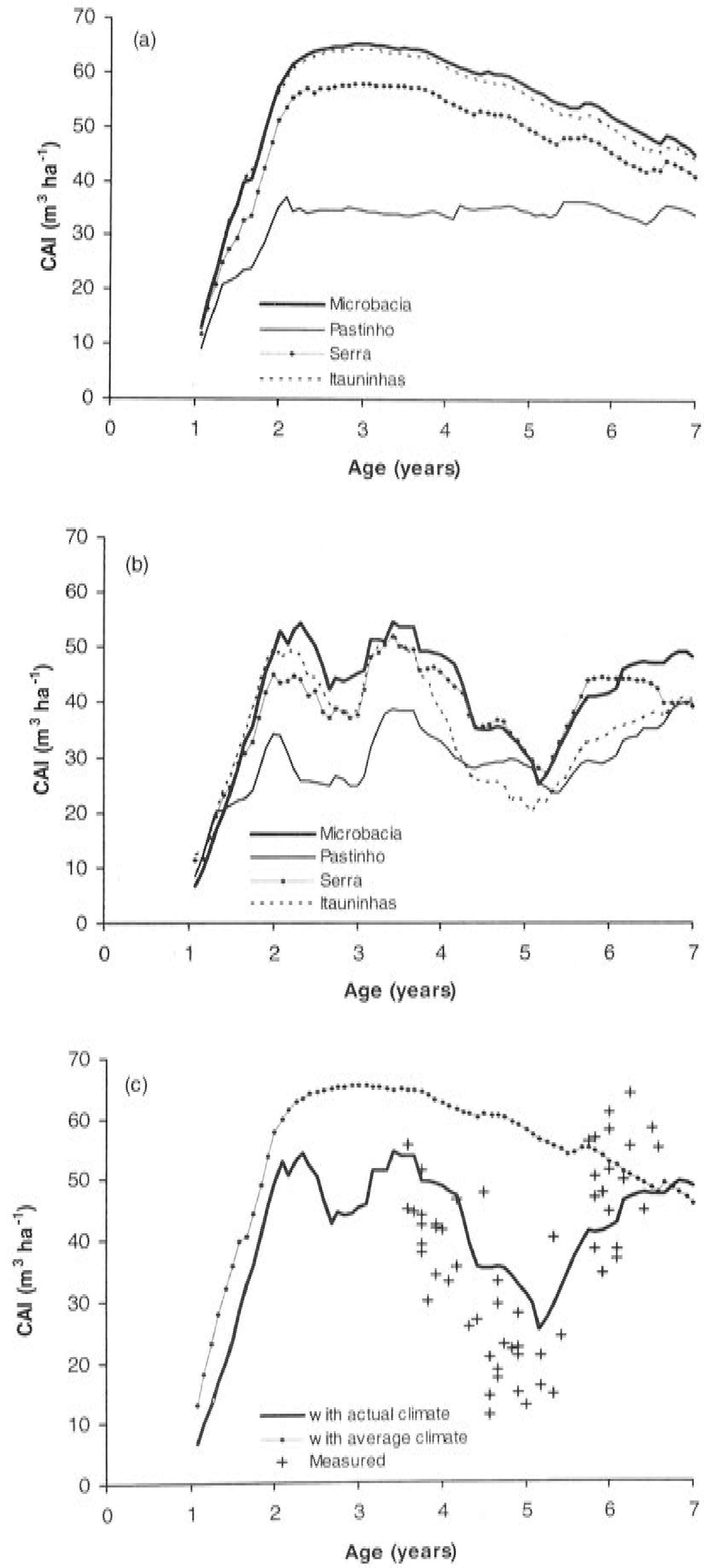


Figure 7.2. Predicted current annual increments (CAI) of stem wood at four sites, a) based on long-term average climate data, b) based on actual monthly climate data, c) predicted and observed CAI at Microbacia. In c), the dashed line (-•-) was calculated using averaged monthly weather data over a 10-year period, the solid line (—) was calculated using monthly weather data, and symbols (+) are values of CAI from measurements made in permanent plots in the same region.

Commercial forestry companies need to know the probable productivity of new land in order to make decisions about purchase and development. The influence of climatic factors on potential productivity in different regions is illustrated in Figure 7.3, which shows the results of an analysis of the effects of a hypothetical reduction of rainfall and increase of VPD on eucalypt stem volume growth in a coastal region (Alcobaca) and an inland region (Lagoinha). Alcobaca has higher rainfall and lower VPD than Lagoinha. The productivity in the coastal (Alcobaca) region was estimated from measurements at 361 m^3 ha^{-1} of wood in 7 years, and in the inland region at 207 m^3 ha^{-1} over the same period. Both areas received the same silvicultural treatments. Observed growth in field plots was accurately simulated by 3-PG (curves (a) and (d) in Figure 7.3). Calculating growth curves for Alcobaca using the (lower) rainfall from Lagoinha showed that such a reduction in rainfall would reduce yield by 16.3%. However, using the (higher) VPD values from the inland (Lagoinha) region with Alcobaca rainfall would reduce yield by 29.2%. This exercise not only shows that both rainfall and VPD can reduce *Eucalyptus* growth, as demonstrated in other studies (Dye & Olbrich, 1993; Landsberg & Hingston, 1996), but it shows that, in this region, the VPD effects on tree growth can be more severe than the effects of precipitation. It also illustrates the use that can be made of 3-PG to estimate probable growth and yield, and to separate the effects of various management and climate factors on these variables. Clearly, as illustrated in Figure 7.2, the effects of rainfall may vary depending on the age and stage of growth at which drought periods occur. The purpose of this example is to illustrate the information that can be obtained from this model. In the case of new areas it is likely that actual monthly climate data will not be available, so analyses to assess probable average productivity will have to be based on averages (see the discussion on potential productivity, and Figure 7.5, below). Since, there is an infinite number of possible combinations of rainfall amount and time of occurrence, scenario analysis, based on the likely occurrence of drought periods estimated from data for areas with similar climate, will have to be used to assess the probability, and probable frequency, of significant yield loss. This is a matter of risk analysis, which can be carried out when, as in this case, the model being used has been shown to provide accurate predictions in situations where empirical data are available to test it.

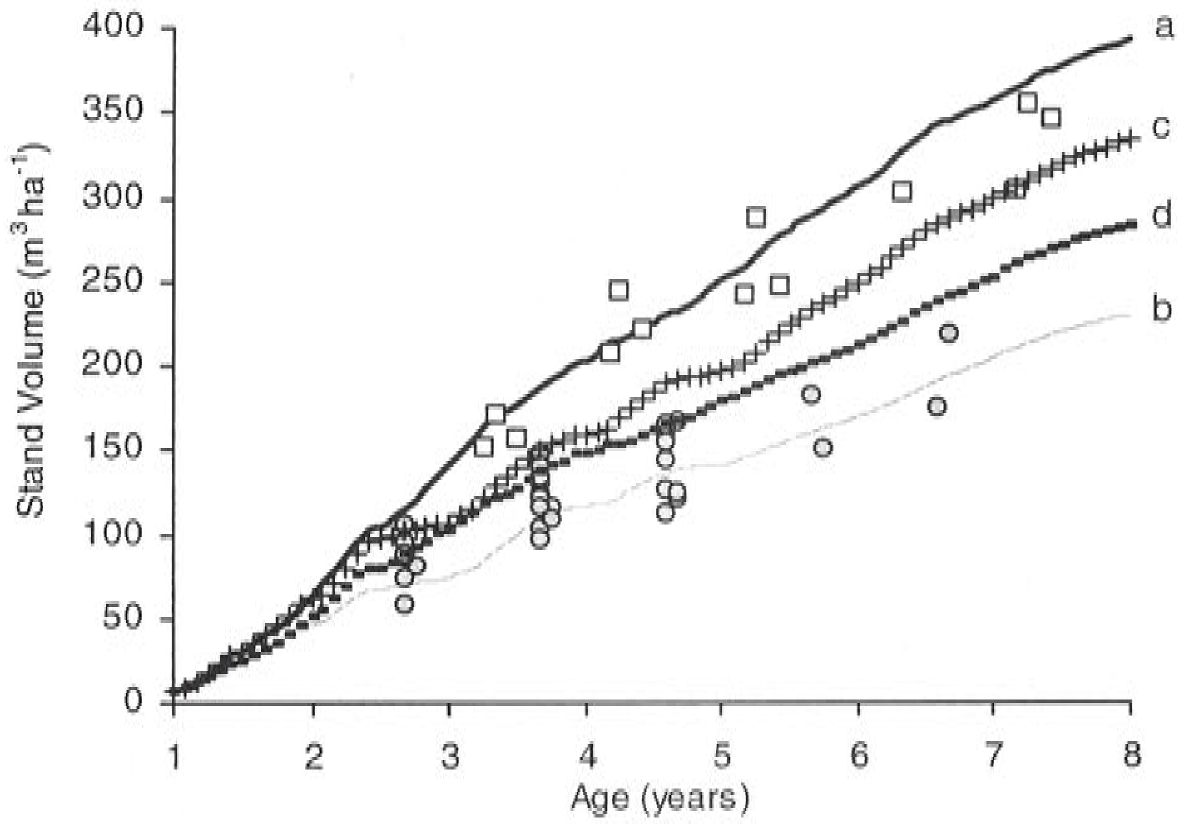
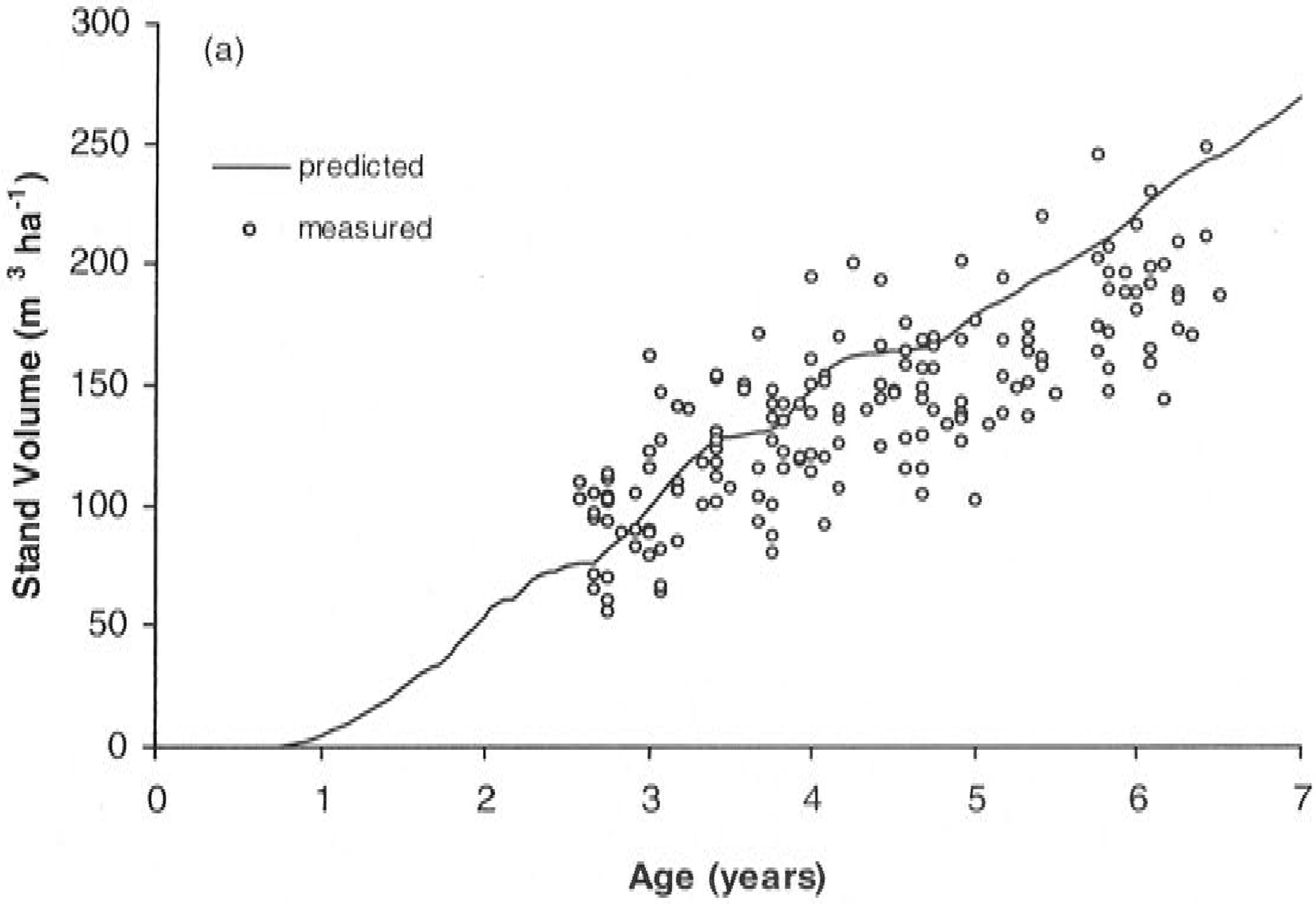


Figure 7.3. Effects of rainfall and daytime VPD on production at two sites. The curves show the prediction of volume growth for: a) Coastal region; b) Inland region; c) Coastal region using rainfall from inland region; d) Coastal region using VPD from inland region. The open squares and open circles show the volume growth measured in permanent plots in coastal and inland regions, respectively.

7.3. The effects of fertility on volume estimation

Figure 7.4 compares stand volumes predicted by 3-PG with observed volumes in Microbacia and Itauninhas regions. The predictions were made using actual climate data. The fertility rating used was 0.8 on the basis that both areas were fertilised, when they were planted, at rates expected to eliminate nutrition as a factor that might constrain growth. The observed data came from the PSPs at ages 2.5 to 6.5 years. Predicted and observed SV agreed for the Microbacia sites when $FR = 0.8$ was used (Figure 7.4a), but 3-PG overestimated SV at Itauninhas (Figure 7.4b), and FR had to be reduced to 0.4 to obtain a good agreement with observed data at that site. This implies that soil nutrient supply at Itauninhas was significantly lower than expected on the basis of ARCEL's standard soil chemical analyses. The soils in the Itauninhas region have much higher clay contents and the topsoil is more compact than in the soils of the Microbacia region. This may cause a restriction of root development and hence reduced access to water, making the trees susceptible to dry periods and leading to reduced growth. This example shows that 3-PG may produce inaccurate estimates of SV, because the information available is inadequate; it also illustrates the need for further research on the relationships between soil fertility, soil texture and the effects of forest management practices on stand growth. The FR index can be a surrogate for various factors that limit production and should not be adjusted simply to give a good fit to data. Lack of correspondence between model and reality can be as valuable as good estimates: where model estimates and empirical data are significantly different, the reasons for the differences must be investigated carefully.



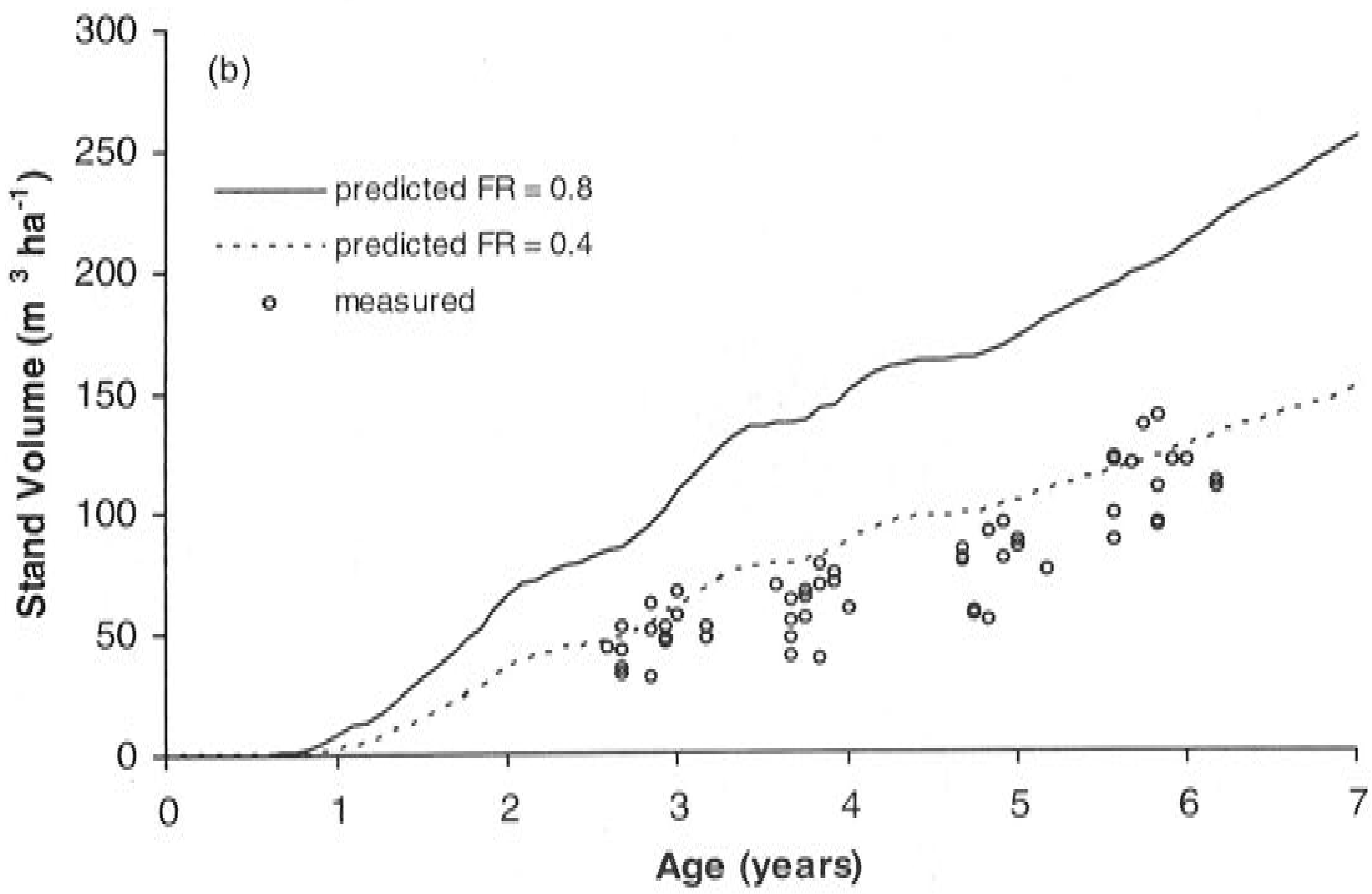


Figure 7.4. Stand volume measured in permanent plots (circles) and estimated by 3-PG (lines) are compared in a) for the Microbacia region using a fertility rating *FR* = 0.8 (line), and in b) at Itauninhas using *FR* = 0.8 (solid line) and *FR* = 0.4 (dashed line).

7.4. Predicting potential productivity

Cromer (1995) made the following statement about potential productivity:

"The potential productivity of a crop is determined by its genetic characteristics, but actual productivity is determined by the interaction between environmental constraints and genetic factors. In common with other crops, the productivity of planted eucalypts is directly related to the amount of solar energy intercepted by canopy foliage".

Potential productivity has been defined in this thesis as the maximum capacity for wood production at a specific site, assuming the adoption of forestry "best management practices", which include high quality seedlings, soil preparation, soil fertilization, weed control, and pest and disease control.

The establishment of potential productivity is an important factor affecting the decision-making process in forest management in several respects. In fast growing *Eucalyptus* plantations, a balanced supply of nutrients to the trees is essential to get growth rates compatible with the genetic potential and environmental constraints. The estimation of potential productivity can directly influence the calculation of the amount of nutrients that will be required by the trees to get the desired productivity. Several forest industries in Brazil are using programs to formulate fertilization recommendations that consider potential productivity as a key input. One example is the program called NUTRICALC (Barros *et al.*, 1995) used by ARCEL to quantify the dynamic nature of soil fertility and to target fertilisation application. NUTRICALC estimates the current nutrient amounts and balance in the soil and compares that to the potential productivity of the plantation, assuming that stand growth is not limited by nutrient availability. The recommended fertiliser prescription attempts to account for the genotype nutrient demand and growth rate of the genotype concerned, rooting depth, nutrient release from forest floor and slash, and nutrient supply capacity of the soil. Currently, in the Aracruz case the predicted potential stand productivity comes from the 3-PG model (Ryan, 2003).

The main limitation to establishing potential productivity running the 3-PG_{PJS} version is that the climate input data are associated with a specific weather station and climate and soil spatial variation are not considered. This reinforces the need to use a spatial version of the model.

Estimates of potential productivity may be used in forest management for long term planning to evaluate silvicultural practices and achieved production, to decide on fertilisation recommendations and to assist in the evaluation of new lands. As noted earlier in relation to the use of actual and average climate data, different values of potential productivity can be obtained for the same area, depending on the assumptions made and the final purpose of the analysis. The assumptions made in relation to long term planning should be more conservative than those used when deciding on a fertilization program. It is important to define and state clearly the assumptions made when using 3-PG to determine potential productivity.

Figure 7.5 shows estimates of potential productivity, in terms of MAI, made by applying 3-PG to stands planted in 1996 in nineteen regions. The final age of all stands was 6 years. Actual climate data for the period were used, obtained from the AWS (see Tables 5.7 and 5.8 and Appendix 6 and 7); soil fertility ratings and soil water holding capacity were determined by the predominant soil of each region. Figure 7.5 also shows the MAI estimates over 6-years obtained using the average monthly climate for the same period. The graph illustrates clearly the possibility, noted earlier in relation to estimates of actual SV, of obtaining different estimates of potential productivity depending on the data used; these different estimates may serve a useful purpose when the analysis is made for different objectives and applications. For the purposes of estimating fertilization, the average climate data are likely to be the most appropriate, but for long-term wood supply, planning and silvicultural evaluation actual climate data should be used. Figure 7.5 shows that considerable differences may arise when the results obtained using different climate datasets are compared. These differences are higher in the most productive areas.

Estimates of potential productivity for all the ARCEL estates are shown in Figures 7.10 and 7.11, in the section dealing with the spatial application of 3-PG.

7.5. Evaluating the accuracy of monthly estimates of current volume increment

3-PG produces monthly outputs that can be compared with observed data, such as MAI, SV, BA, DBH as demonstrated in Chapter 6. The model also produces current annual or monthly volume increment. To assess the performance of the forest in terms of growth rates, and to quantify the effects of the climate over short periods of time, such as monthly or three-monthly (quarterly) intervals, the analysis has to be in terms of current volume increment (CVI). To evaluate the accuracy of estimates of this variable CVI values calculated for four different periods are shown in Figure 7.6, where they are compared with values calculated from monthly diameter and height measurements from which 'observed' CVI are calculated as described in section 4.5.12. It is clear from the figure that the correspondence of monthly estimates of current volume, and observed values, is poor ($r^2 = 0.22$), but when the period of estimation is three months the correlation between model estimates and observed accumulated volume is better ($r^2 = 0.49$). When the calculation interval is extended to four and five months (Figures 7.6c and 7.6d) the correspondence between observed and predicted values improves still further ($r^2 = 0.83$ and $r^2 = 0.86$ respectively). This exercise indicates that six months is a reasonable interval across which to evaluate forest growth rates. The result is important for the managers of fast growing *Eucalyptus* plantations, who need to follow the status of the forest plantations and may need to make decisions about forest management or harvest schedules based on that information.

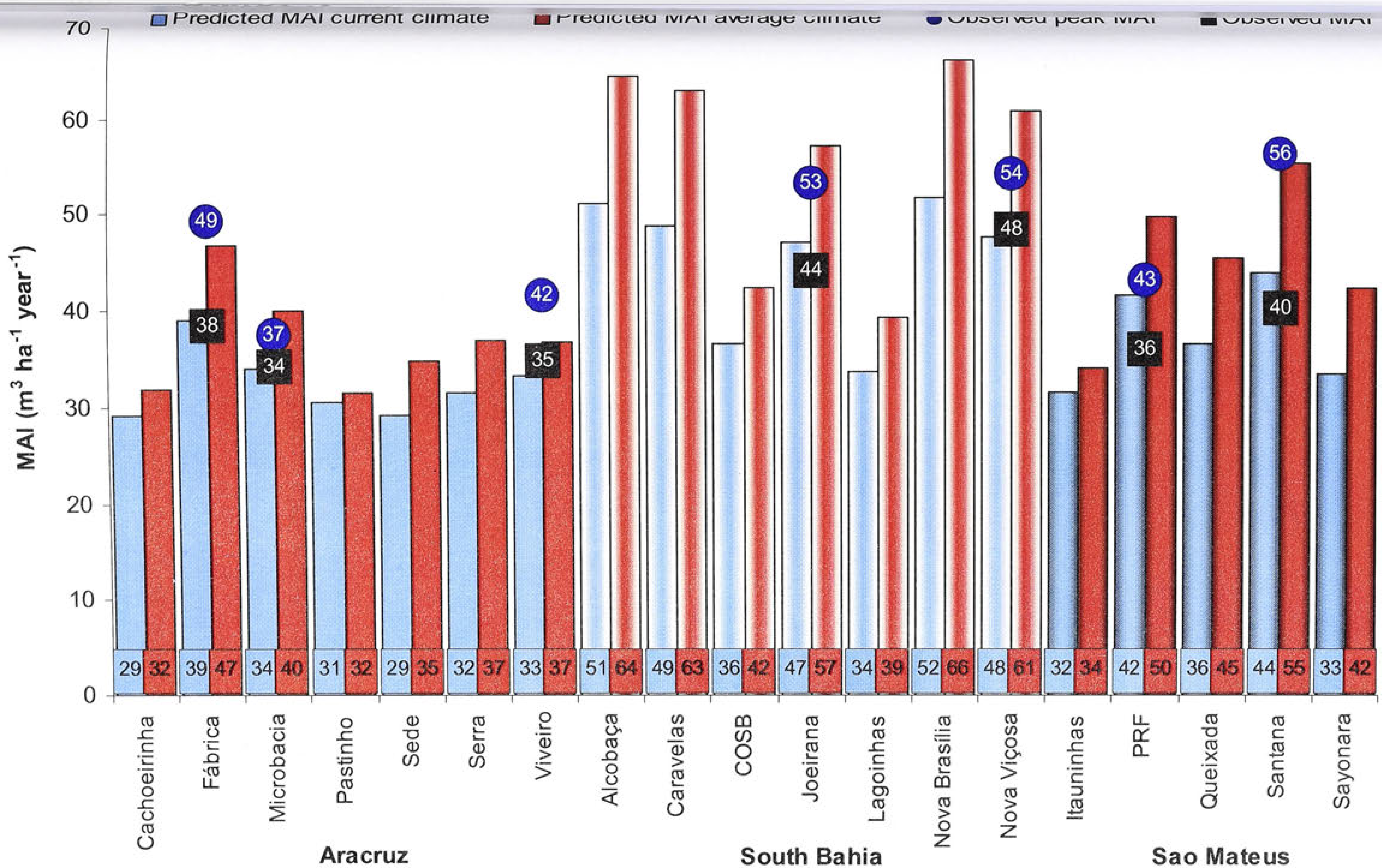


Figure 7.5 Estimation of potential productivity for nineteen sites in the three production regions (Aracruz, South Bahia - clear shadow bars - and São Mateus - dark shadow bars). The blue bars represent the potential productivity estimated using the actual climate data for each region for the period 1997 to 2002 and the orange bars are the estimates of MAI over 6 years made using the long-term monthly average climate data for the same regions. The black squares and blue circles are the observed average MAI and observed peak MAI respectively.

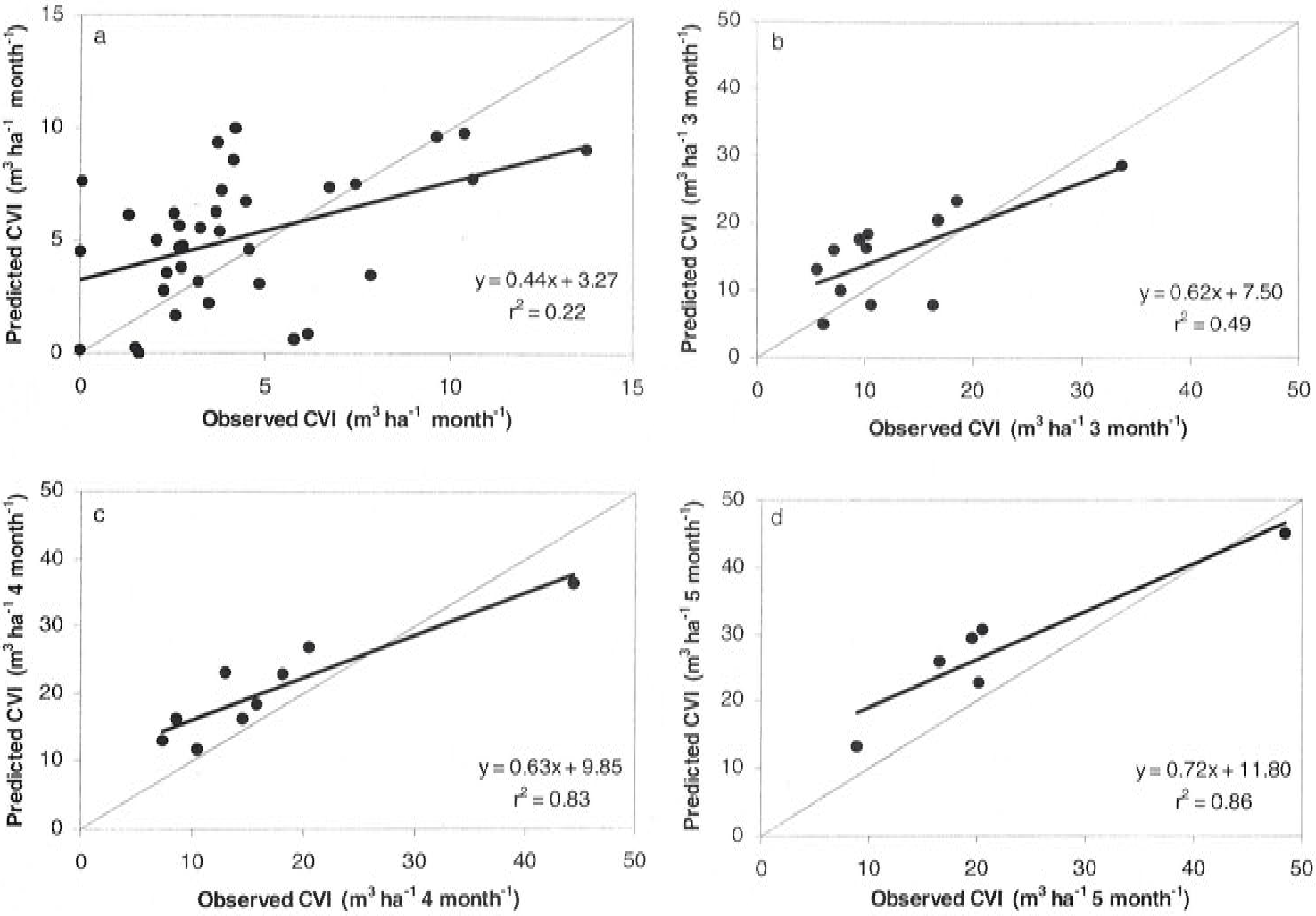


Figure 7.6. Current volume increment calculated from monthly diameter measurements (observed) and predicted by 3-PG in different intervals. a) one month interval, b) volume accumulated in 3 months, c) volume accumulated in 4 months and d) volume accumulated in 5 months.

7.6. Spatial application of 3-PG (3-PGS)

The ARCEL operation, which includes the use of GIS technology, in which information such as genotype, planting dates, fertilizer application and cutting dates are recorded for each management unit (coupe), provides ideal conditions for incorporating 3-PG within a GIS framework. The extensive testing and development work done with the model, reported in this thesis, was also essential for this development. A specific project was therefore undertaken in collaboration with CSIRO (Australia) Division of Forestry and Forest Products to develop a spatial version of 3-PG (Coops *et al.*, 2003) customized to ARCEL. The spatial version adds significant potential power to 3-PG because it allows the inclusion of information specific to each locality, including topographic information, climate data, soil properties and stand characteristics such as genotype, age and number of trees planted. Detailed description of 3-PGS is not provided in this thesis, but only some examples of the results obtained from its application are presented.

The information layers required for the spatial version of 3-PG (3-PGS) are latitude, a digital elevation model – to provide the topographic data – mean monthly temperature and vapour pressure deficit, rainfall and total incoming solar radiation (all interpolated from the automatic weather stations), soil fertility and maximum available soil water, and soil texture. The Digital Elevation Model (DEM) in 3-PGS is one of the most important layers used to produce the climate surfaces. This is because most climate and environmental variation can be related to location and elevation. The ARCEL DEM's have been produced using the ANUDEM program (Hutchinson, 1989). Long-term meteorological station data were interpolated across the ARCEL plantation areas using the program ANUSPLIN (version 5.1) (Hutchinson, 1991) producing long-term data points for average temperature, rainfall and global radiation. The VPD surface has been produced based on linear regression analysis using a statistical package. These long-term surfaces represent the best estimates of average climates over a year, based on all the climate data available from meteorological stations across the studied areas. However, because there are differences between these long terms estimates and actual monthly climate in any given month and year (the importance of these differences is clearly demonstrated by the results presented in sections 7.2 and 7.4), a new strategy based on residual correction analysis (RCA), was developed to produce climate grids that have been adjusted to follow the weather station data (Coops *et al.*, 2003).

Once these layers were developed and the parameter values appropriate to the stands in the management units added, together with the necessary initial values of stem, foliage and root mass, a series of 3-PG simulations was run and the results compared with those obtained from measurements in the PSPs distributed over the studied areas.

The results of the climate surface, produced using RCA program, can be seen in Figures 7.7 and 7.8. The grid cell size is 30 m x 30 m. The figures show the monthly rainfall surfaces for the Aracruz region during the years 2001 and 2002. The year 2001 had low precipitation during the first 7 months, except in May; during the last three months of the year the rainfall was well distributed and close to the historical average. In 2002 a better rainfall distribution occurred during the first six months, with low precipitation during the last three months of the year. Clearly, rainfall is not homogeneous across the region; monthly distributions vary spatially as well as annually. The picture that emerges from these grids illustrates the difference between reality (detailed spatial distribution of rainfall) compared with the fixed zones based on distance from AWS shown in Appendix VI 1, VI 2 and VI 3, which were the data originally used to estimate tree growth.

The effect of climate on forest growth can be determined by a monthly index (varying between 1 - no limitation and 0 - total limitation) based on the constraints embodied in 3-PG. The best representation of it is through the parameter Physmod (φ) (Equation 3.4 in Chapter 3 $[\varphi = f_{age} \min\{f_D, f_\theta\}]$). If the age effect is eliminated (f_{age} = 1) the parameter value becomes the minimum of the f_D and f_θ constraints. Figures 7.9 and 7.10 show monthly values of φ calculated for the Aracruz region during the years 2001 and 2002 respectively, taking into account the actual planted forest in this area and respective stand ages. The months between March to May 2001 show strong climatic limitations for tree growth, brought about by low precipitation, high temperature and high VPD (these two last layers are not shown). The conditions became better for tree growth during the last six months of 2001 and first six months of 2002 and worse in the last six months of 2002.

This exercise provides an example of how 3-PGS can be used to access the probable performance of plantations in general terms, and identifies the aspects likely to limit production at different sites. It can be used to explore the effect of varying soil water holding characteristics, which could be influenced by management actions such as deep ripping.

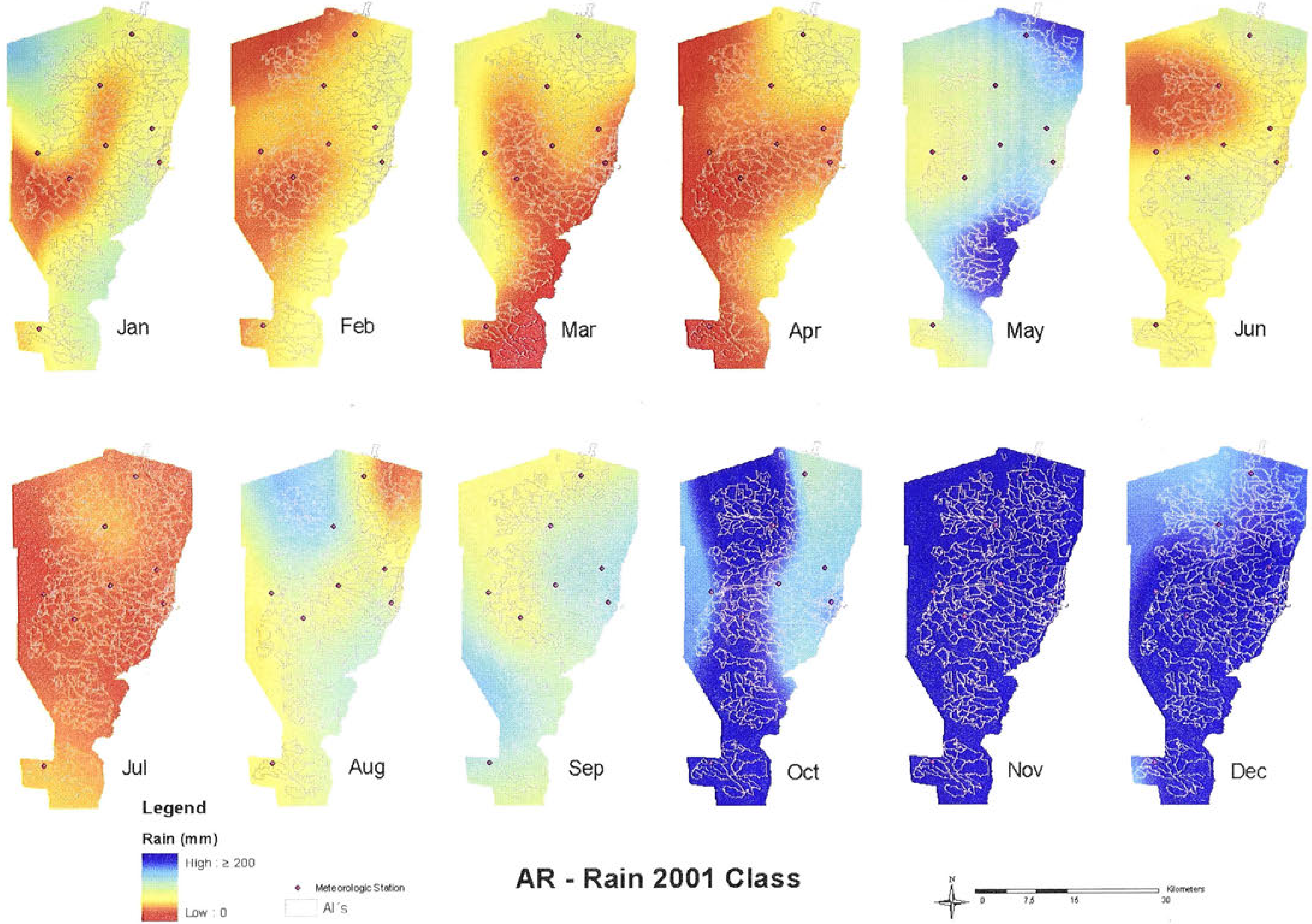


Figure 7.7. Monthly rainfall distribution at Aracruz region in 2001.

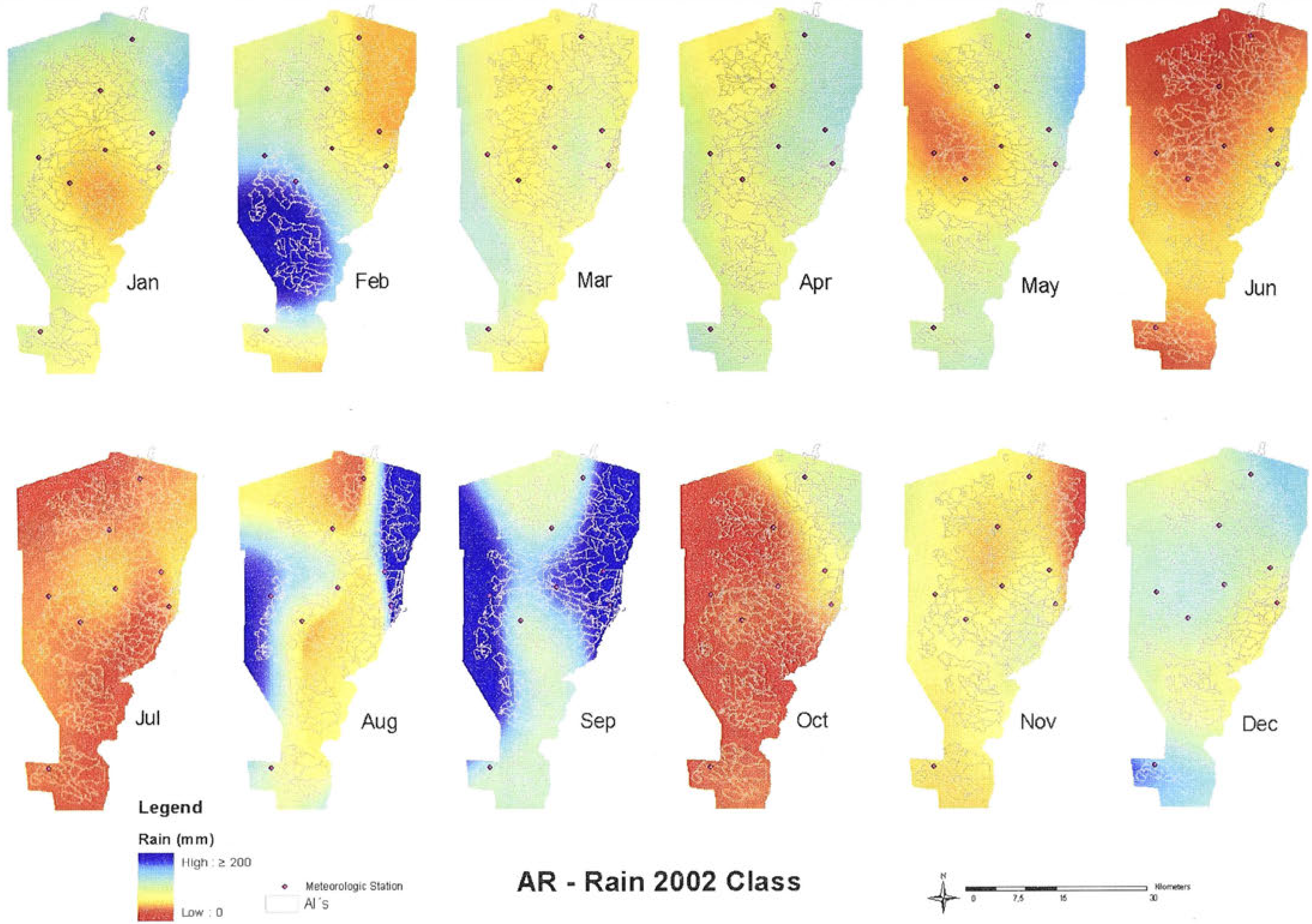


Figure 7.8. Monthly rainfall distribution at Aracruz region in 2002.

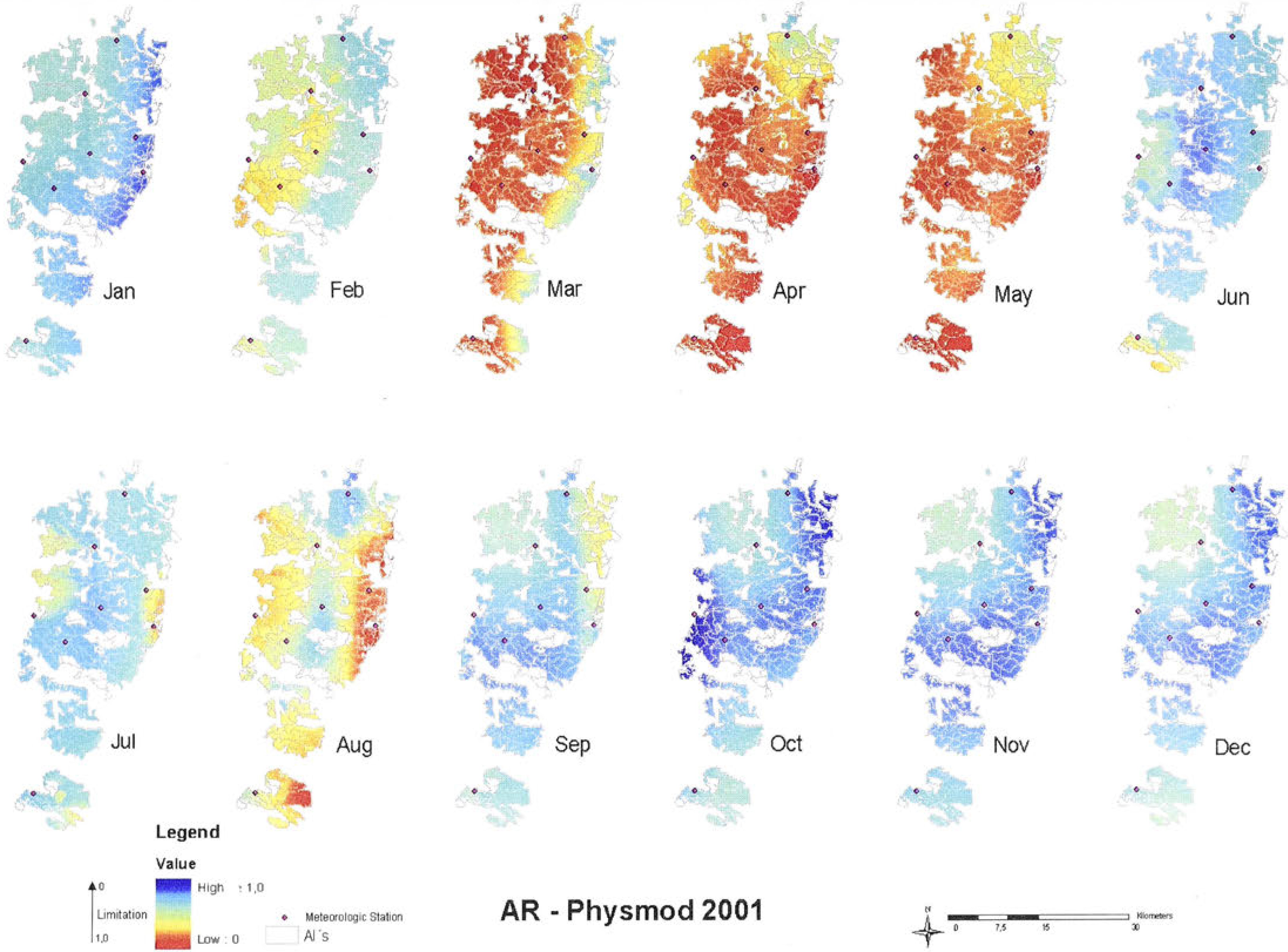


Figure 7.9. Monthly spatial distribution of Physmod factor in planted areas at Aracruz region in 2001.

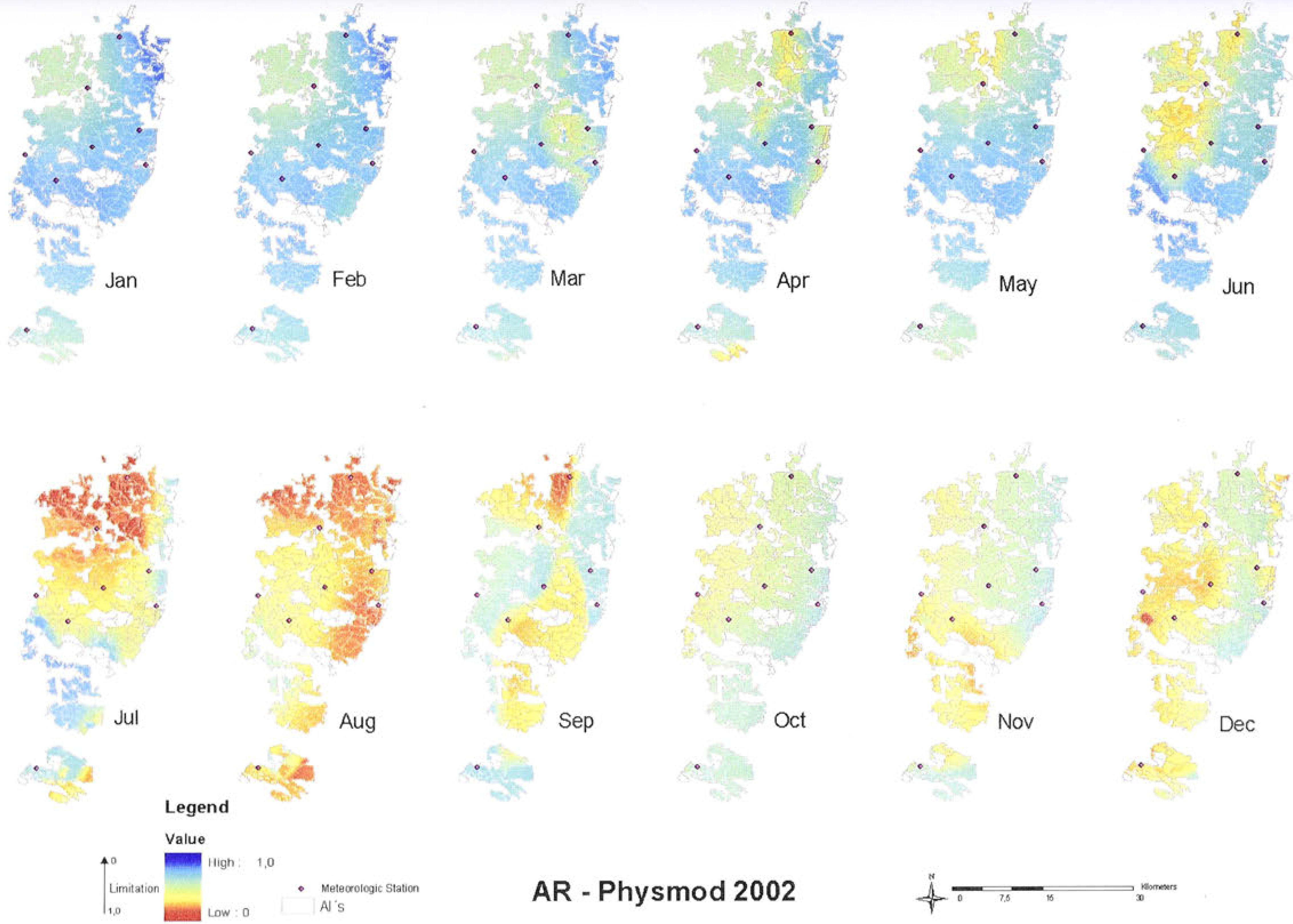


Figure 7.10. Monthly spatial distribution of Physmod factor in planted areas at Aracruz region in 2002.

Figure 7.11 shows potential productivity represented as a) MAI and b) SV across the Aracruz region, estimated by 3-PGS using general parameter values (see Table 6.1), considering all areas planted in June 1996 and running the simulation to stands at age 6 years (May 2002) using the occurred weather data for this period. Figure 7.12 illustrates the 3-PGS output of: a) mean annual increment (MAI), b) stand volume (SV), c) diameter at breast height (DBH) and d) basal area (BA) in January 2003 using the actual month and year planted of each stand.

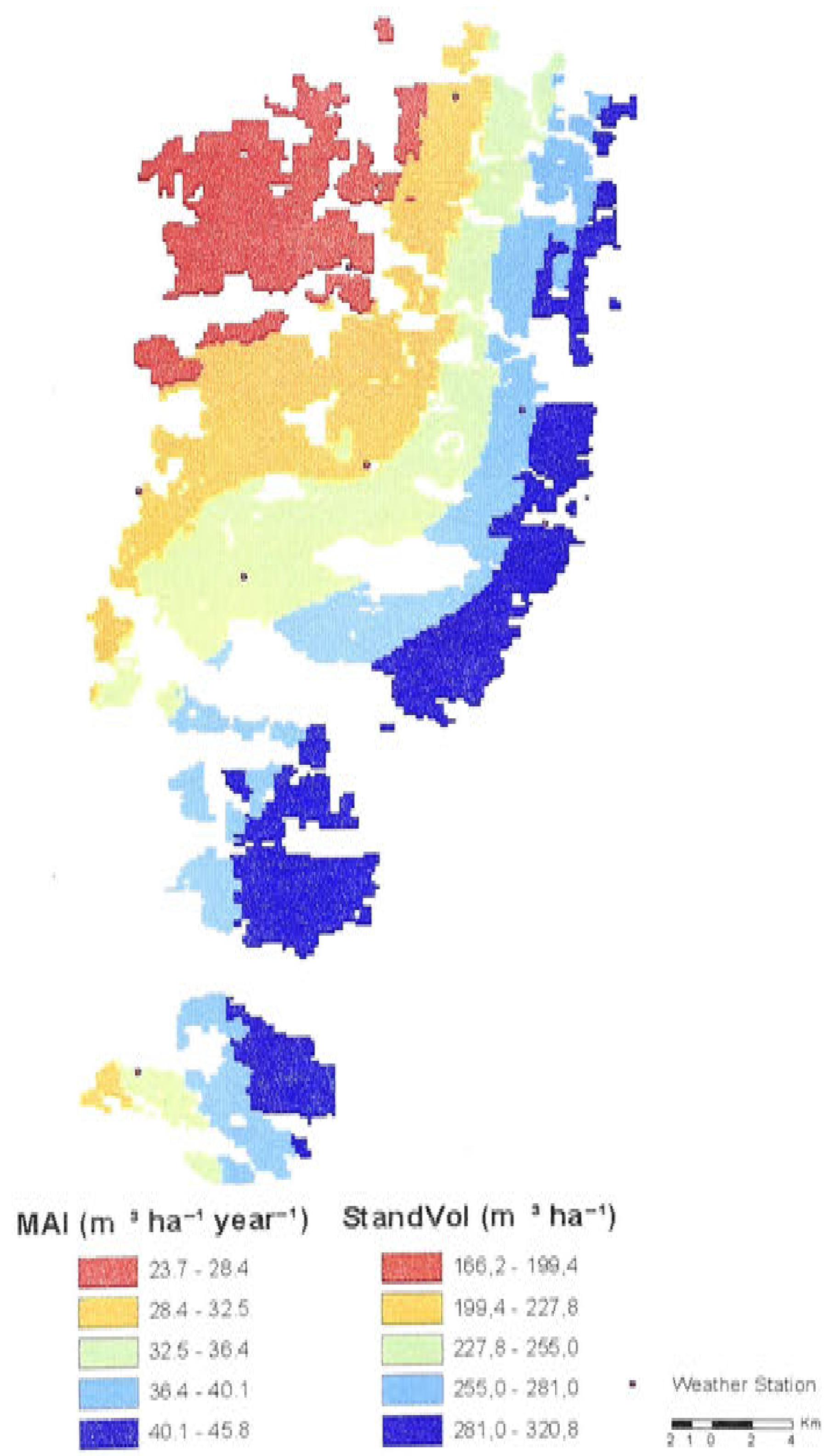


Figure 7.11. Potential productivity at Aracruz region as MAI (m^3 ha^{-1} $year^{-1}$) and SV (m^3 ha^{-1}) at age 6 years. The climate data represent the years from 1996 through 2002.

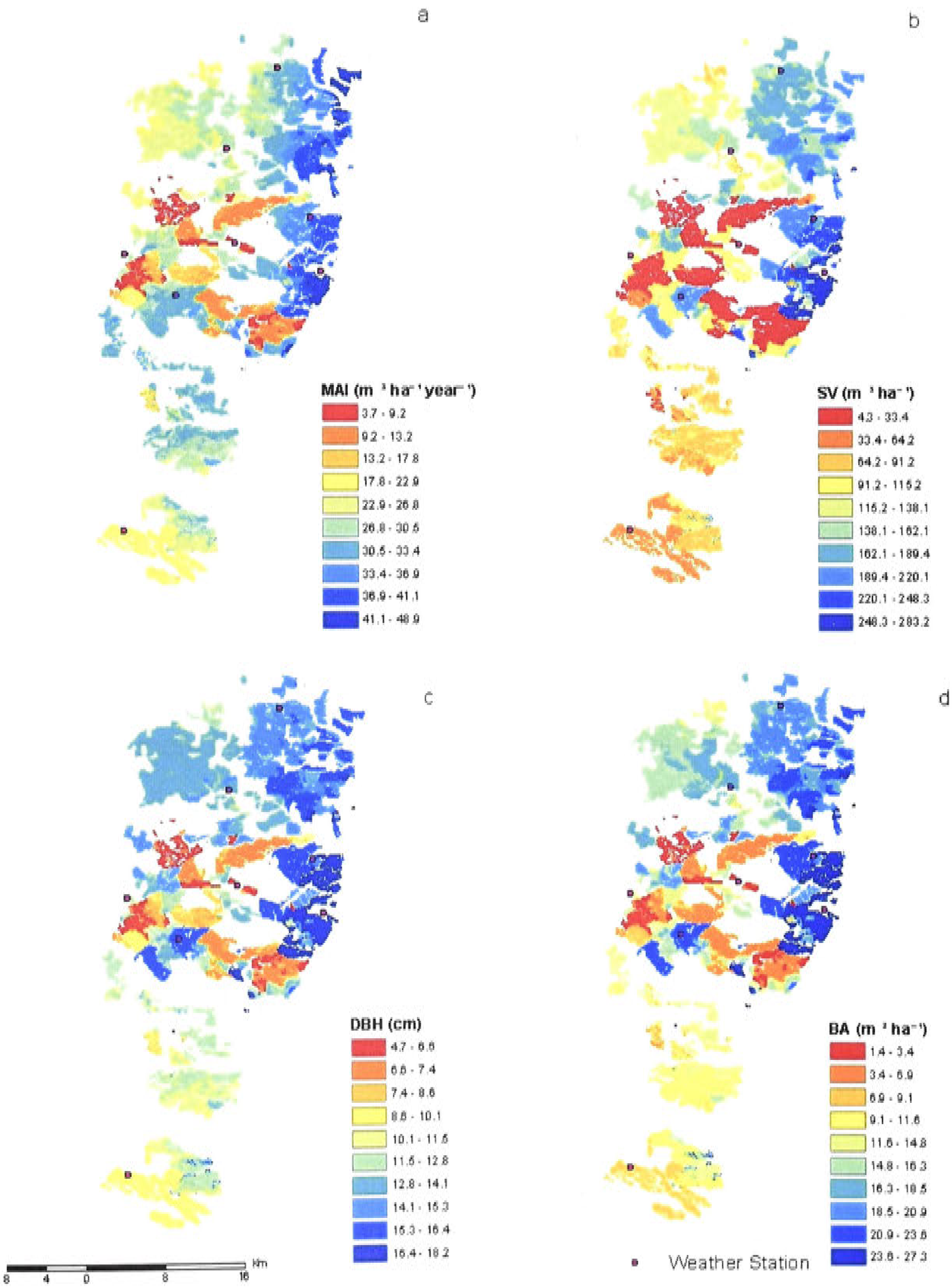


Figure 7.12. Estimation of current a) MAI (m^3 ha^{-1} $year^{-1}$), b) SV (m^3 ha^{-1}) c) DBH (cm) and d) BA (m^2 ha^{-1}) in January 2003 at Aracruz region.

7.7. Model improvement and uncertainties

Improvements to an ecophysiological model such as 3-PG can be brought about through the availability of high quality plant and environmental data, such as those available from the experiments in the Aracruz catchment project. These data allow the establishment of the most important paremeter values, sensitivity testing of those parameter and improvements in the relationship assumed, and in sub-models. 3-PG is being used successfully in many parts of the world in different environments, with a range of tree species (Bernier *et al.*, 2003) and there have been several improvements to it since the original publication by Landsberg and Waring (1997). Most of these were listed in Sands and Landsberg (2002), however the main concepts of the model were maintained, reinforcing confidence in the robustness of the principles incorporated in the model. Some of the changes made during the period from 2000 to 2002 came from the results obtained in this study, supported by the database collected in Aracruz and technical discussions involving mainly Dr. Joe Landsberg, Dr. Peter Sands and myself. The more important of these, introduced into the 3-PG code by Sands (2002) were: the dependence of rainfall interception on canopy LAI; wood basic-density can be age dependent; the effects of silvicultural events (e.g fertilization, irrigation) can be interpolated between tabulated values; the establishment of spreadsheet-based database of climatic data; multi-site runs allowing many sites to be run simultaneously; an increase in the number of output variables that can be monitored , i.e. current volume increment, water use efficiency and intercepted rainfall.

All ecophysiological models can be improved by the incorporation of more detail, however if the main purpuse is to use the model as an operational and decision-making tool a balance between the level of model detail and accuracy must be maintained. It is, nevertheless, important to constantly upgrade and improve models as new information and data become available from the field and specific experiments. Sensitivity analysis is a valuable tool that should be used to evaluate the influence of various parameters in the model on its final output, but we should note that such analyses must always be constrained by biophysical reality; as far as possible parameter values should be set by experimental data (as has been done here, in most cases) and the amount they are allowed to vary in sensitivity analyses should not exceed sensible limits. Some areas for improvement in 3-PG were listed by Landsberg (2001) and some points are reinforced below:

Early-stage growth. It is important to have an accurate method of describing biomass partitioning during early-stage growth (see Sands and Landsberg, 2002), and to include a more precise water balance for small trees and the ground surface they occupy during this phase, with options. It would also be valuable to be able to specify clean cultivation or the level of weedy competition.

Fertility rating. As described in Chapter 3, fertility in 3-PG influences carbon allocation to the roots, and the canopy quantum efficiency (α). The influence of fertility on α is taken to be linear. It would be very useful if research could focus on the relation between soil nutrient status and α. If this could be combined with measurements of photosynthesis the information provided would be immensely valuable (Landsberg, 2001). There are also various other approaches to this. An approach being developed at Aracruz is the use of some PSPs as check plots. There is a limited number of paired plots PSPs located in the same area adjacent to one another. One plot receives the standard (recommended) amount of fertilizer and the second plot receives much higher fertilization, designed to eliminate nutrition as a limiting factor. These plots will be monitored and sampled; the data from them should allow improvement in the quality of *FR* estimates and allow identification of the key nutrients and combination between them in the soil and in the leaves. Stape (2002) used a similar procedure. He used a series of paired calibration plots in the forest area to which the 3-PG model was to be applied. One of each pair was irrigated and frequently fertilized, to provide an approximation to an optimum fertilizer regime, and the other had normal management. Frequent measurements of growth, L^* and litterfall provided the data needed to establish the extent to which the fertility of any soil type limited forest productivity. Plotting stand responses to fertilization against a soil fertility index based on extractable K, P and total cation exchange capacity of the soils provided a linear relationship which allowed empirical determination of FR values.

Water balance. As demonstrated in Chapter 6 the water balance in 3-PG may lead to bias in the estimates of soil water content, caused by the monthly time step (Figure 6.3). In tropical regions, the availability of water in the soil can change rapidly depending on the season and the distribution of the precipitation. The model uses a fixed soil water content independent of the tree age and root system. Improvements in this area could be made if we had enough data on the speed with which root systems exploit the soil, although it is doubtful whether the labor involved in obtaining such data would be justified. Jackson *et al.* (1996) reviewed the data on biome root systems available from around the world; the data indicate that, in most tree biomes 60-70% of the root mass is found in the top 50 cm of the profile. It is reasonable to assume that water uptake is proportional to root mass per unit volume of soil, so it seems likely that there will be relatively little change with tree size, after the first few months in regions where growth is very rapid.

It would also be possible to improve the prediction of soil water by the model by calculating the water balance daily. However, this would increase the weather data requirements by a factor of 30, and eliminate one of the important advantages of 3-PG – its relative simplicity and economical data requirements. The advantages of such a change would have to be considered and analysed carefully.

Litterfall rate. Litterfall was found to be the most inconsistent output of 3-PG when compared with observed data. An important reason is the age dependence of the process, and the fact that litterfall is almost certainly affected by environmental factors such as drought. There is also evidence (Figure 5.16) that litterfall in terms of tons biomass ha^{-1}, varies seasonally. This will be investigated in more detail. In the work done so far, I was unable to establish any signficant relationship between litterfall and any external factor, so the fixed rate for mature stands was retained. We should note, however, that in the case of some tree species (e.g. loblolly pine (*Pinus taeda*)) litterfall is seasonal and the use of a constant rate is not justified (J.J. Landsberg, personal communication). See also Landsberg *et al.* (2001) and Walker (1981).

Allocation to roots and the way it changes with conditions is clearly an area that requires attention. Errors in the allocation of carbon to roots, in the model, can be buried in calibrations, and it may well be that the variability in this process – across species, management systems and environmental conditions – is such that attempts to establish deterministic relationships are doomed to failure (Landsberg, 2001). It is certainly an area where any additional information will be valuable, particularly if it helps to identify significant differences between clones. Note, in this respect, the analysis in Chapter 6.

NPP/GPP. The assumption of a constant NPP/GPP ratio, initially somewhat controversial (Mäkelä & Valentine, 2001), is standing up remarkably well to testing (see Landsberg and Gower (1997), Figure 5.7; Law *et al.* (1999; 2000)); The increasing number of flux measurement sites round the world offer excellent opportunities to test the carbon balance aspects of models such as 3-PG. The ideal approach is a combination of detailed ecophysiological measurements on the vegetation around the towers, with the flux measurements (Landsberg, 2001; Landsberg & Waring, 2003).

Chapter 8

8. DISCUSSION AND RECOMMENDATIONS[8]

The results presented in this thesis show that it is possible to determine a set of parameters for 3-PG that allow the model to reproduce detailed time-series growth patterns. The parameter values are consistent with those from other studies (Sands & Landsberg, 2002; Landsberg *et al.*, 2003) and are sufficiently generic to allow use of the model as a practical tool in forest production and management depending of the scale and level of detail required. Important parameters such as maximum canopy quantum efficiency (α) take values that can be applied universally (Sands & Landsberg, 2002; Williams *et al.*, 2002; Landsberg *et al.*, 2003). A number of others, determined explicitly in this study (such as those for specific leaf area, canopy conductance, the time dependence of branch plus bark fractions, the time dependence of litterfall) can be given default values, for the species and management system in question, that will not cause significant errors in the output values of the variables of concern to commercial foresters (Landsberg *et al.*, 2003). The measurements made to find specific parameter values provided the robustness required to apply the model to large areas. Tests against independent measurements indicate that the model provides accurate estimates of growth and yield in areas for which it has not been calibrated and that it can be used to evaluate the effects of factors such as drought and fertility differences that affect plantation growth and yield. Where detailed growth data are available, as in this study, 3-PG can be used to analyse and provide insights into the subtle differences in growth patterns of different genotypes (Figures 6.1 and 6.2).

[8] Part of this Chapter is being published in Almeida *et al.* 2004a and in Almeida *et al.* 2004b.

Photosynthetic capacity (at leaf level) and maximum canopy quantum efficiency (α) were assumed to be the same for all clones: there was no evidence for any other assumption.

On the basis of the analysis presented here the observed differences in production between clones can be attributed primarily to differences in biomass partitioning and secondarily to differences in stomatal conductance. Sands and Landsberg (2002) reported values for the allometric coefficients, a_s and n_s of 0.095 and 2.4, respectively for *E. globulus* and Williams *et al.* (2002) presented the values of 0.174 and 2.4 for old stands of *E. grandis* in Queensland, Australia. The general values (including five genotypes) obtained in this study were 0.045 and 2.812 respectively. The small but significant differences between these allometric coefficients for clones 15 and 22 (Figure 5.10 and Table 5.3) are clearly important since they cause the differences in stem biomass (W_S), stand volume (*SV*) and L^* shown in Figure 6.1. The differences in root mass (W_R) were, as already noted, caused (in the model) by differences in the minimum allowable fraction of net primary production (P_N) allocated to roots. Reduced allocation of biomass to roots in clone 15 makes more biomass available for the growth of above-ground components.

Litterfall in this version of 3-PG (3-PG_{PJS}) is calculated as a constant fraction of current foliage mass, so the actual value varies as foliage mass varies with growing conditions. As noted in the previous chapter, I have not yet been able to establish causal relationships between litterfall and growing conditions, but the correspondence between observed and measured LAI (Figure 6.1b) indicates that this is not a major problem. Differences in LAI result from varying amounts of biomass being allocated to foliage as P_N varies and changing growing conditions cause changes in the proportion of P_N going to roots. There is also an inherent feedback in the model because litterfall is a fraction of current foliage mass.

3-PG takes into account the variation of specific leaf area (σ) with age and Figure 5.15 demonstrates this variation for this study. The range of variation in *E. grandis* is lower than in *E. globulus*: σ for *E. grandis* varies from 10.5 m^2 kg^{-1} at age 1 year to 7 m^2 kg^{-1} at age 4 years while for *E. globulus* it varies from 10 to 5 m^2 kg^{-1} at similar ages (Sands and Landsberg, 2002). The values of σ used in 3-PG have a strong influence on predicted L^*, and hence on P_N and growth. In the simulations reported here the generic maximum value of σ (10.5 m^2 kg^{-1}) was adopted on the basis of the data in Figure 5.15.

The measurements of stomatal conductance (g_s) presented in Figure 5.19 allow comparisons between clones 15 and 22, despite the high variability characteristic of g_s measurements made in the field (Ewers & Oren, 2000). Because g_s was consistently higher in clone 22 than in clone 15, transpiration per unit leaf area in clone 22 is likely to be higher than in clone 15. However, because of the higher L^* in clone 15 (Figure 6.1), this genotype appeared to use more water than did clone 22 (Figure 6.3). Comment was provided earlier (Chapter 6) on the sensitivity of the model to the effects of VPD on g_s, and the influence of the maximum value of g_s.

A major obstacle to accurate prediction of available soil water (SW) by 3-PG is the use of a monthly time-step, which makes the model insensitive to variations in the distribution of rainfall during the month. The problem could be solved by using a daily water balance, but this would increase the model complexity and requirements for data (Landsberg & Waring, 1997). The benefits of doing this must be examined carefully, taking into account the inherent vertical and horizontal spatial variability of soils (Landsberg and Gower, 1997; pp 97-105), the uncertainty of root distribution – and hence the difficulty of precise definition of root zones – and the uncertainties of moisture constraint functions. The predawn water potential measurements on twigs of *Eucalyptus* would provide a more direct measure of when available water in the root zone begins to be exausted (Running, 1994). There is no evidence from this study that the deviations of simulated *SW* from the real values (Figure 6.3) in some periods are serious enough to constitute a significant limitation to the ability of the model to account for environmental constraints on the growth of plantations over a number of seasons.

The generic parameters obtained in the calibration process are being applied to estimate growth in 181 000 ha of *E. grandis* hybrid plantations (Almeida *et al.*, 2004b). A network of 19 automatic weather stations provides the meteorological data to run 3-PG, while 500 growth check plots, in which measurements of growth (i.e. height and diameter at breast height) are made twice a year, to check the model performance and provide data for re-calibrating 3-PG, have been established in areas for which appropriate soil data are also available. In some of these plots, leaf area index, litterfall, soil moisture and biomass allocation are also being measured to check the model performance (Almeida *et al.*, 2004b). The use of the model in this way will greatly reduce costs of mensuration. ARCEL currently maintains more than 2000 permanent sample plots, but as the estimates of growth and volume made using the PBM become accepted, we expect a considerable decrease in the amount of sampling and measurement needed. Evaluation of the output of the model against field measurements indicates that 3-PG can provide accurate stand biomass and wood volume during rotations that can achieve up to 360 m^3 at age 6 years (Almeida *et al.*, 2003).

The use of the model will improve the information available to management and make it possible to quantify effects of climate and clonal material on plantation growth (Almeida *et al.*, 2004b).

3-PG can be run for any land unit at any time to estimate standing volume for reporting, economic evaluation and forest planning. In this study it was used to estimate the productivity of established *Eucalyptus grandis* plantations and their potential productivity in new areas, to analyse changes in productivity across currently planted areas, to determine whether these are attributable to climate or management, and as a tool for defining strategic scenarios. The model's capacity to provide immediate information about growth in any area of a large plantation estate makes it a powerful tool for forest managers. To improve its support for economic analyses, 3-PG is being used to estimate MAI as the input to an empirical model that predicts the range of log products derived from plantations (Almeida *et al.*, 2003).

To realise the potential of a process-based model, it is important to use spatial databases. All the ARCEL estates are mapped in a GIS which contains soil, climate and crop information layers. The climate layers are based on the automatic weather station network located across the Company's estates, and interpolation procedures are used to estimate monthly climatic conditions at any location. It is possible to run 3-PG for any compartment over any time to estimate current growth rates, standing biomass and volume, or the impact of any change in management practice that may have occurred. Forward predictions of growth will usually have to rely on averaged weather data. However, past streams of climate data can be used for the future weather to provide a means of estimating the probability of variations in yield predictions for risk analyses.

It is important that actual rather than average weather data are used when the model is applied to evaluate the impact of variations in weather or management options on productivity across a large estate. This is because the effects of climatic deviations from the average can depend on the stand age. In addition, such impacts can have important effects on wood supply to mills, and hence on the ability of the company to meet contracts and on general planning. In future, this type of analysis will be used in association with risk analysis to assess the effects of various climate or management scenarios imposed on any compartments in the GIS.

The amount of fertiliser that should be applied in the ARCEL plantations in order to realise the potential (i.e. climate-limited) productivity of each site can be estimated from predicted biomass productivity, the nutrient content of the various biomass pools and the ability of the soils to provide nutrients. For this purpose the nutrition model called NUTRICALC is being used (Barros et al., 1995). Since it has been shown that 3-PG can estimate potential growth over time at each site with a precision adequate for management applications, this allows accurate estimation of fertiliser requirements that minimize the risk of productivity losses caused by nutrient deficiency, and of over-fertilization and subsequent off-site contamination.

The availability of data to accurately calibrate and validate a PBM, and the freedom to adapt the model for operational needs and organisational decisions, are important factors that encourage the practical use of PBMs. So also are the involvement of intended users in defining the objectives and applications of the model, and the availability of good software and documentation for any models used. These points apply particularly to PBMs (Sands *et al.*, 2000), which have yet to achieve widespread acceptance in forest industries.

In terms of future research, a number of key recommendations come out of this thesis.

- **Climate input data** - A comprehensive network of weather stations providing monthly climate data is desirable to produce accurate estimations using 3-PG. This would apply to any model driven by similar climate variables and biophysical processes. There has been a great deal of progress made in the extrapolation of weather measurements, (see, for example, Running *et al.*, (1983); Thornton and Running, (1999)). Forestry companies and management agencies should recognise the fact that good quality meteorological data are essential to analysing and predicting the performance of their forests and they should move to establish weather measurement networks. The standard 3-PG software allows the calculation of average daily VPD ($VDP_{del.T}$) in terms of maximum and minimum daily temperatures, but since the primary effect of VPD is on stomatal conductance during daylight hours the preferred variable must be the average daytime value of VPD (VPD_{day}). The analysis of weather data presented in Chapter 5 showed significant differences between $VPD_{del.T}$ and $VPD_{day.}$; $VPD_{del.T}$ is, not surprsingly, consistently lower than VPD_{day}. It is recommended that for operational use VPD should be calculated from mean daily temperature and relative humidity using daylight hours. This is possible in the ARCEL application because of the excellent high-density coverage of meteorological stations, which provide representative coverage for the whole area. The number and spatial distribution of weather stations is a key point to be considered in other commercial applications; in most cases, extrapolation procedures will have to be used. The spatial version of 3-PG is sensitive to this distribution and the quality of climate data. If for any reason station data are in error, the program will produce surfaces that may distort the actual climate predictions over the plantation estates (Coops *et al.*, 2003). The errors in yield prediction that could result from this have to be evaluated.

- **Model initialisation** - In the case of fast growing *Eucalyptus* plantations good estimates of initial biomass distribution in roots, stem and foliage will results in accurate estimates of standing biomass in the early growth stage of the stands. Sands and Landsberg (2002) tested this facet of the model thoroughly and found that early-stage errors were not propogated into later growth. Nevertheless, the development of a strategy based on simple inventory measuring stem diameter (at ground level or at some standard height, such as 30 cm above the ground) and height at, say, one year could provide estimates of biomass distribution that would be very valuable for model initialisation and would eliminate any errors that may arise from this source. The initial research would require some destructive harvesting to determine standing biomass and calibrate it by regression on the stem diameter and height measurements, after which these measurements could be made in all the check plots. Differences in the first-year growing conditions, particularly in terms of the availability of water to the seedlings, and weed competition, are important points that need to be noted in establishing such relationships.

- **Water balance** - The questions of using daily data, or estimates of root growth rates, in relation to this problem, have already been discussed. Keeping the monthly time step, one way to improve the quality of the water balance sub-model in 3-PG may be by including a function which estimates the number of rain days during the month on the basis of historical records. It would then be assumed that total monthly rainfall is divided between that number of days, spread uniformly through the month.

- **Fertility rating** - The establishment of a quantitative measure of FR remains a challenge, that can be met by data from fertilization and irrigation trials and the paired check plots. In all these cases, detailed soil and plant analyses will have to be carried out. Because of the dynamic nature of foliage nutrient concentrations (see, for example, Nambiar & Fife (1991), Leuning *et al.* (1991a) and Crane & Banks (1992)) it is very difficult to establish useful relationships between soil chemical properties and foliar nutrient concentrations, but Ågren (1983) showed, many years ago, that the productivity of a conifer stand is directly related to the mass of nitrogen (leaf N-concentration x leaf mass) in the canopy; if such a relationship could be established for eucalypts it would contribute considerably to the solution of the FR problem. It may be that it will be necessary to link 3-PG with a soil N-mineralisation model, such as CENTURY (Parton *et al.*, 1988), as has been done by McMurtrie and Comins (1996) in the G'DAY model (see also Dewar and McMurtrie (1996a; 1996b) and Medlyn *et al.* (2003)). This would, however, increase considerably the number of parameter values required, and the difficulty of determining appropriate values for those parameters. It may be that a better solution lies in the suggestion made by Landsberg (2003), that an empirical model of N-mineralisation such as SNAP (Paul *et al.*, 2002) should be used to predict N-mineralistion across a wide range of sites. The *FR* values for 3-PG could then be derived from these data.

- **Coppice** - Despite the differences in growth between re-established and coppiced trees, coppice was not studied in detail in this thesis. It is recommended that research to study the differences in biomass allocation between coppiced trees and trees planted as seedlings, and the physiological behaviour of the two systems, should be undertaken.

- **GIS** - The adoption of the spatial approach appears to be the best option for using a PBM as a practical tool for forest management. It is recomended that further research should be carried out on the development of the input layers for 3-PG, including climate interpolation, soil water holding capacity, soil fertility rating and biomass initialisation. The situation at ARCEL is essentially satisfactory, but if the model is to be widely adopted and used, we have to develop principles and guidelines that will help others use it successfully.

- **Alternative inventory** - It is recommended that some aspects of traditional forest inventory should be reviewed, with the objective of reducing the number of measured plots. The use of a relatively small number of check-plots in which LAI, biomass partitioning, soil moisture, soil fertility and soil texture measurements are made, will provide the information needed to understand the differences between local conditions of forest growth and provide values to parameterise a PBM such as 3-PG. The additional work in a reduced number of PSPs (relative to the large number of PSPs normally measured) will not only be less than that involved in measuring all the PSPs, but far more information can be obtained from the spatial version of 3-PG, than can be obtained from conventional models. The spatial version provides the possibility of immediate values of stand volume in any management unit, as well as the subsidiary information about the effects of weather conditions or management actions, and reliable forward projections. Combining 3-PG with a product quality model (EGROW ARCEL (Almeida *et al.*, 2003)) removes the objection that the PBM does not provide the detailed information needed for financial analysis of the forest product.

- **Parameter values** - Further testing and development of 3-PG parameters should be done for most planted and new genotypes established in the studied area and in other areas where the model is being used, for example in South Africa (Esprey *et al.*, 2002; Dye *et al.*, 2003). In the ARCEL areas this is being done using the inventory check-plots described earlier. The use of a parameter-fitting package to help to determine the optimum parameter values, as used by Williams *et al.* (2002) is recommended, but the caveat provided earlier – i.e that the range allowed in parameter values must be consistent with sensible biophysical values, and experimental estimates, must be remembered in using such packages: it is possible, in a multi-parameter fitting package, if the constraints are inadequate, to obtain absurd parameter values which may result in apparently sensible output values. (However, this is not likely if a range of outputs – e.g. stand biomass or volume, LAI and soil water, is examined).

- **Risk analyses** - The development of risk analyses, discussed earlier in relation to potential yields and productivity in new areas, based on results obtained with the model, provides a significant opportunity for the practical applications of PBMs. For the long-term, it is of interest to forest managers to have estimates of the possible impacts of climate change, as well as a tool that can provide the basis for cost-benefit analysis in relation to the purchase of new lands. However, we have to recognize that 3-PG is not a good tool for evaluating the effects of climate change; it can only do so through temperature, which is a relatively coarse modifier, being based on ecological rather than physiological considerations, or through the water balance. It may be that changes in climate will affect rainfall amounts and distribution, but our capacity to forecast these changes is extremely limited and we can only resort to stochastic analysis, i.e risk analysis. One of the major factors contributing to climate change is the increase in atmospheric CO_2 concentrations, which may affect photosynthesis rates and hence GPP. To make 3-PG useful for the analysis of this factor it would be necessary to re-write parts of the model, e.g. by introducing a much more mechanistic description of canopy photosynthesis. It would also be necessary to link canopy photosynthesis and soil organic matter decomposition. This sort of development is well beyond the scope of the present work, and in any case there are already excellent and well-advanced models concerned with these matters (see (Comins & McMurtrie, 1993; McMurtrie & Wang, 1993; Medlyn *et al.*, 2000). These should be used for futuristic analyses.

- **Remote sensing** - The use of remote sensing integrated with PBMs in fast growing *Eucalyptus* plantations is still at an early stage, but considerable progress has been made, in other contexts, in the application of 3-PG as a tool for estimating forest growth from satellite measurements. Coops and Waring have been the leaders in this; they have produced a series of papers illustrating the power of remote sensing and GIS, combined with a process-based model, to estimate forest growth across large areas (Coops *et al.*, 1998; Coops *et al.*, 2001a; Coops & Waring, 2001a; Coops & Waring, 2001b; Coops *et al.*, 2001b; Coops & Waring, 2001f). The application of this technology in large-scale plantations does not seem likely in the immediate future, unless progress is made in determining canopy nutrient content from radiation reflectance signatures monitored by satellites.

- **Users** - The involvement of the potential users is one of the most important aspects in implementing PBMs as practical tools in forest management. Moves towards active collaboration, and the implementation of mixed models in operational systems, as well as improving communication between model developers and users, should ensure that practical problems are identified and fed back to modellers, which should lead to rapid progress. In the case of ARCEL, the process of implementation has been acceptable; it has been essential to keep the company management informed at each step, to ensure that they have confidence in the work being done and are convinced that the use of 3-PG as a management tool offers practical and financial advantages. The investment in a new technology like this is considerable, and there are always people who are sceptical of the value and effectiveness of calculations based in concepts that are not familiar to most foresters. It is particularly important that those concerned with the standard, conventional, mensuration program, and the analysis of the data from PSPs, should recognize that the new tool does not make them redundant, but requires their skills. There is still much work to be done in testing the predictions of the model against check plot measurement and harvest data, and against the throughput at the pulp and saw mills.

Chapter 9

9. CONCLUSIONS

In terms of the objectives stated in section 1.3, I conclude that:

- It is possible to calibrate a process-based model (3-PG) to reproduce accurately and analyse the performance in terms of the growth and yield of *Eucalyptus grandis* plantations in Brazil. Many of the parameters take generic values and the model can be used to simulate production over large areas in regions for which it has not been calibrated. The results obtained for seven 3-PG outputs (MAI, SV, W_S, W_R, LAI, DBH and BA) show that the model is robust and balanced. When high-quality, detailed data are available for calibration, it is possible to detect differences in the parameter values applicable to different clones, despite the fact they have similar growth patterns. It appears that the primary reason for differences in the growth and yield of different clones lies in differences in the way they allocate the biomass produced by canopy photosynthesis.

- The model has provided valuable insights into environmental factors affecting the growth of *Eucalyptus grandis* in Brazil (Chapter 7).

- Progress made in, and results obtained from, applying 3-PG at ARCEL demonstrate the valuable role that PBMs can play as operational tools in forest management, as well as the role they have as research tools that allow us to test hypotheses about the way trees function and respond to environmental changes.

- The use of a spatial version of 3-PG within a GIS framework adds significant value to use of the model and makes it a powerful tool that can very rapidly provide information needed by managers and planners (Chapter 7).

- The work described in this thesis has demonstrated that process-based models are tools that can, and should, be adopted as operational tools in forestry.

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11. APPENDICES

11.1 Appendix I ARCEL weather stations network

11.2 Appendix II Meteorological data

11.3 Appendix III Conversion of plant area index (PAI) to leaf area index using LAI-2000

11.4 Appendix IV Neutron probe calibration

11.5 Appendix V Comparison between parameter values of 3-PG applied to *E. grandis* in three different studies

11.6 Appendix VI Climate regions determined by weather stations

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11.1. Appendix I ARCEL weather stations network

Table A I 1. Weather stations location, type, period of measurements and variables measured.

Station Name	Type	Period	Altitude (m)	Geographic Coordinates		Parameters
				Latitude S	Longitude W	
Alcobaca	Conventional	Nov/89 - Dec/96	71.4	17º 25' 00"	39º 17' 33"	Precipitation and Temperature
	Automatic	From Jan/97				Precipitation, Wind Speed and Direction, Temperature, Relative Humidity, Global Radiation, PAR and Net Radiation
Caravelas	Conventional	May/88 - Dec/96	69.3	17º 33' 58"	39º 18' 20"	Precipitation and Temperature
	Automatic	From Jan/97				Precipitation, Wind Speed and Direction, Temperature, Relative Humidity, Global Radiation and PAR
Joeirana	Conventional	May/88 - Dec/96	89.8	17º 44' 25"	39º 32' 13"	Precipitation and Temperature
	Automatic	From Jan/97				Precipitation, Wind Speed and Direction, Temperature, Relative Humidity, Global Radiation, PAR, Net Radiation and Barometric Pressure
Nova Vicosa	Automatic	From Jan/97	70.5	17º 56' 50"	39º 33' 34"	Precipitation, Wind Speed and Wind Direction, Temperature, Relative Humidity, Global Radiation and PAR
COSB	Conventional	May/88 - May/00	88.8	17º 53' 35"	39º 50' 20"	Precipitation and Temperature
	Automatic	From Jun/00				Precipitation, Wind Speed and Direction, Temperature, Relative Humidity, Global Radiation and PAR
Nova Brasilia	Automatic	From Jan/97	94.0	18º 08' 00"	39º 42' 56"	Precipitation, Wind Speed and Direction, Temperature, Relative Humidity, Global Radiation and PAR
Lagoinha	Conventional	Feb/94 - Dec/96	-	18º 00' 30"	40º 05' 21"	Precipitation and Temperature
	Automatic	From Jan/97				Precipitation, Wind Speed and Direction, Temperature, Relative Humidity, Global Radiation, PAR and Net Radiation
Queixada	Conventional	May/88 - Aug/96	86.0	18º 23' 35"	39º 49' 48"	Precipitation and Temperature
	Automatic	From Sep/96				Precipitation, Wind Speed and Direction, Temperature, Relative Humidity, Global Radiation, PAR and Net Radiation
Santana	Conventional	May/88 - Aug/96	72.5	18º 31' 32"	39º 47' 26"	Precipitation and Temperature
	Automatic	From Sep/96				Precipitation, Wind Speed and Direction, Temperature, Relative Humidity, Global Radiation and PAR
Sayonara	Automatic	From Sep/96	108.0	18º 31' 29"	39º 56' 12"	Precipitation, Wind Speed and Direction, Temperature, Relative Humidity, Global Radiation and PAR
PRF	Automatic	From Sep/96	90.5	18º 38' 30"	39º 53' 61"	Precipitation, Wind Speed and Direction, Temperature, Relative Humidity, Global Radiation, PAR and Net Radiation

Station Name	Type	Period	Altitude (m)	Geographic Coordinates Latitude S	Geographic Coordinates Longitude W	Parameters
Itauninhas	Conventional	May/88 - Aug/96	144.0	18º 31' 25"	40º 06' 46"	Precipitation and Temperature
	Automatic	From Sep/96				Precipitation, Wind Speed and Direction, Temperature, Relative Humidity, Global Radiation and PAR
Pastinho	Automatic	From Jan/96	79.5	19º 39' 06"	40º 06' 51"	Precipitation, Wind Speed and Direction, Temperature, Relative Humidity, Global Radiation, PAR and Net Radiation
Cachoeirinha	Conventional	Jul/88 - Dec/95	61.0	19º 43' 36"	40º 09' 51"	Precipitation and Temperature
	Automatic	From Jan/96				Precipitation, Wind Speed and Direction, Temperature, Relative Humidity, Global Radiation, PAR and Net Radiation
Viveiro	Conventional	Jan/68 - Dec/95	38.0	19º 48' 51"	40º 09' 26"	Precipitation and Temperature
	Automatic	From Jan/96				Precipitation, Wind Speed and Direction, Temperature, Relative Humidity, Global Radiation and PAR
Sede	Conventional	Jan/68 - Dec/95	66.0	19º 49' 29"	40º 15' 48"	Precipitation and Temperature
	Automatic	From Jan/96				Precipitation, Wind Speed and Direction, Temperature, Relative Humidity, Global Radiation and PAR
Microbacia	Conventional	Feb/94 - Jan/95	88.8	19º 51' 47"	40º 12' 52"	Precipitation and Temperature
	Automatic	From Feb/95				Precipitation, Wind Speed and Direction, Temperature, Relative Humidity, Global Radiation, PAR, Net Radiation and Water table level
Fabrica	Conventional	Jan/86 - Dec/95	11.4	19º 50' 29"	40º 04' 26"	Precipitation and Temperature
	Automatic	From Jan/96				Precipitation, Wind Speed and Direction, Temperature, Relative Humidity, Global Radiation, PAR, Barometric Pressure and Evaporation
Serra	Conventional	May/88 - Dec/95	90.5	20º 04' 51"	40º 15' 58"	Precipitation and Temperature
	Automatic	From Jan/96				Precipitation, Wind Speed and Direction, Temperature, Relative Humidity, Global Radiation and PAR

11.2. Appendix II Meteorological data

Table A II 1. Meteorological data from catchment area used in 3-PG simulation.

Parameter	Year	Month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature (ºC)	1994	25.9	34.4	32.7	29.8	29.5	26.4	27.2	27.2	28.8	30.6	31.6	32.2
	1995	26.1	27.2	25.9	24.0	23.2	21.9	21.7	22.2	22.2	23.2	23.4	24.3
	1996	26.0	26.7	26.3	24.1	22.1	21.4	20.8	20.5	21.6	22.9	23.1	25.1
	1997	25.6	25.1	24.1	23.8	22.1	21.9	21.4	21.3	23.0	23.5	25.4	25.8
	1998	26.4	27.0	26.4	25.4	23.6	21.0	21.5	22.9	23.1	22.9	22.7	25.4
	1999	26.2	26.4	25.4	24.2	22.3	21.7	21.2	20.6	21.9	21.5	22.0	24.4
	2000	25.0	25.5	24.7	23.6	21.9	21.3	20.3	20.8	21.2	24.0	23.9	24.9
	2001	25.5	26.5	26.0	25.2	23.0	22.0	21.5	21.0	21.3	22.0	23.9	24.5
	2002	25.2	25.1	25.7	24.7	23.5	22.2	21.9	22.1	22.9	23.8	24.5	25.8
Rain (mm)	1994	94.2	0.0	237.8	201.0	100.1	138.6	60.1	9.5	55.8	135.8	89.2	123.6
	1995	61.0	3.4	173.8	126.8	85.4	31.6	125.7	93.0	69.3	192.3	204.0	367.0
	1996	49.8	55.5	161.4	73.9	38.0	45.9	23.0	18.0	153.1	153.5	407.7	274.2
	1997	138.2	163.2	193.7	108.2	42.3	9.8	15.1	18.4	33.5	81.0	162.3	125.5
	1998	184.2	48.5	64.5	37.1	2.8	30.1	23.8	29.0	16.3	232.2	135.3	154.4
	1999	27.9	17.5	176.5	48.5	25.9	122.2	37.6	28.2	12.2	89.4	249.9	243.6
	2000	103.9	35.6	157.7	124.2	29.0	47.0	48.0	33.3	109.0	30.7	217.2	214.9
	2001	32.5	31.2	33.3	23.4	108.5	84.1	27.4	94.7	80.3	191.0	368.1	271.8
	2002	51.6	158.0	68.8	76.5	54.0	63.7	45.1	40.5	66.2	138.2	229.2	221.9
Radiation (MJ m^{-1} day^{-1})	1994	21.9	22.6	19.1	16.5	14.2	13.4	13.3	15.5	15.1	16.0	16.2	19.3
	1995	21.8	22.0	18.4	14.4	14.2	13.8	12.6	16.8	15.7	16.5	18.3	15.0
	1996	19.7	25.1	21.2	17.6	15.2	13.6	13.2	14.4	13.6	16.8	14.6	18.6
	1997	20.8	19.6	16.4	15.9	14.2	14.1	14.1	16.9	14.5	16.0	19.8	20.4
	1998	22.2	23.1	19.9	16.8	13.2	12.3	14.5	15.7	17.0	13.8	14.8	22.6
	1999	24.4	23.1	19.3	16.7	15.0	12.7	12.6	16.1	17.1	15.1	13.3	20.4
	2000	21.0	22.0	18.3	16.8	14.5	14.2	12.3	14.8	13.9	18.7	16.5	20.7
	2001	23.6	23.5	19.8	17.2	13.4	13.0	13.8	13.6	14.0	14.8	16.1	17.2
	2002	19.4	16.5	19.6	16.7	14.2	13.4	13.3	15.5	15.1	16.0	16.2	19.3
VPD (mB)	1994	7.6	9.5	7.8	7.2	7.3	6.6	5.9	7.0	6.3	6.4	5.1	5.8
	1995	7.6	14.5	11.6	7.9	7.6	9.1	5.9	8.7	8.1	7.8	7.4	5.6
	1996	10.0	12.2	9.3	7.6	8.6	7.3	7.5	7.8	5.5	6.8	4.8	6.8
	1997	7.0	5.7	5.6	6.2	7.3	8.3	6.7	8.3	7.8	7.3	8.4	7.2
	1998	7.1	8.9	8.8	8.6	8.7	7.3	7.0	7.9	7.5	5.3	3.8	7.1
	1999	9.2	10.5	6.7	7.0	7.5	4.5	4.0	6.8	7.2	6.6	3.4	4.7
	2000	5.6	5.7	4.8	4.6	5.2	5.0	4.2	5.7	3.4	7.5	4.4	4.7
	2001	6.8	9.2	7.8	8.2	6.0	4.4	6.0	3.9	4.4	3.6	3.4	4.1
	2002	4.8	5.3	5.5	5.0	7.3	6.6	5.9	7.0	6.3	6.4	5.1	5.8

11.3. Appendix III Conversion of plant area index (PAI) to leaf area index using LAI-2000

A calibration curve was established to convert plant area index for *Eucalyptus* plantations, measured with a Li-Cor LAI-2000, to leaf area index, LAI. The measurements were compared with the LAI obtained from destructive tree samples collected in MBE area. The Li-Cor LAI-2000 measurements underestimated LAI when PAI measured is above 1.2 as shown Figure AIII1.

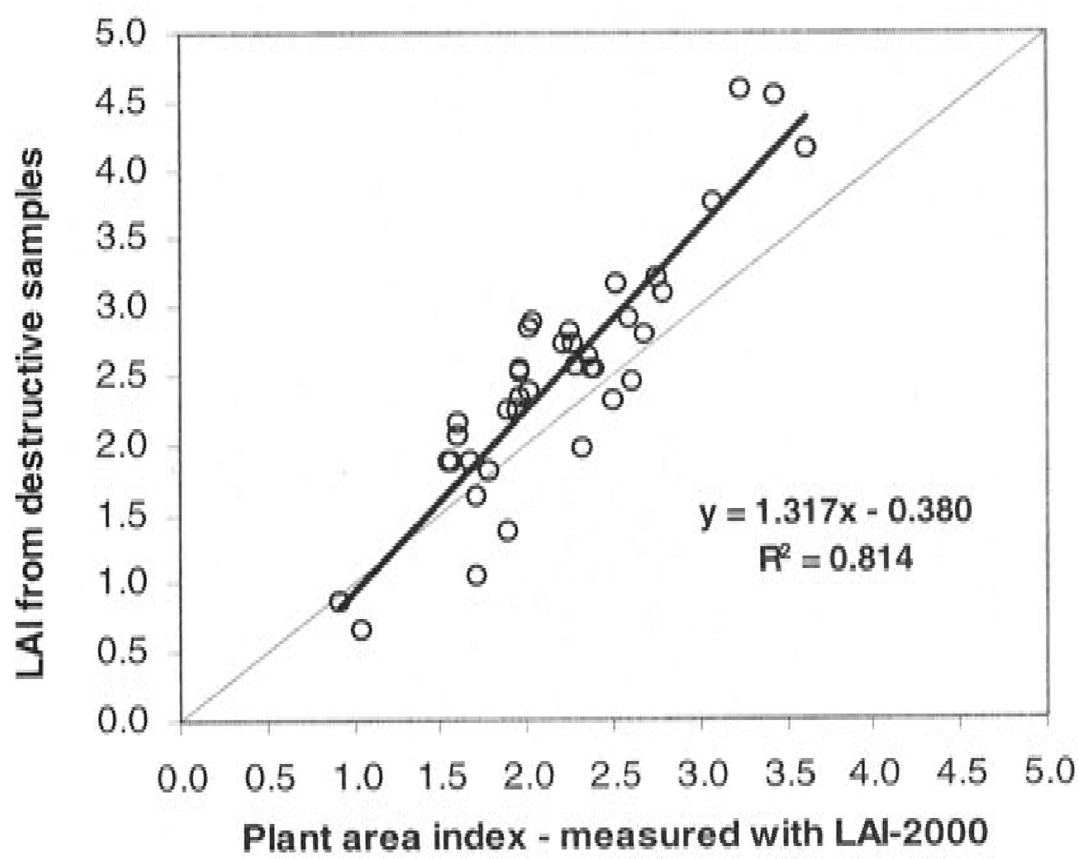


Figure A III 1. Comparison between Plant Area Index measured with the Plant canopy analyser (Li-Cor, LAI 2000) and leaf area index (L^*) obtained from destructive tree samples.

The regresion equation relating PAI (canopy analiser) to LAI (destructive samples) is presented:

$$LAI = 1.317\ PAI - 0.380 \quad r^2 = 0.814 \quad n = 38 \quad SE = 0.376 \qquad (A\ III\ 1)$$

Battaglia *et al.* (1998) also concluded that LAI 2000 underestimated LAI but they found a different relation.

$$LAI = 1.54\ PAI - 0.11,\ r^2 = 0.99 \qquad (A\ III2)$$

Figure A. III 2 shows a comparison between the Battaglia equation and equation A III1.

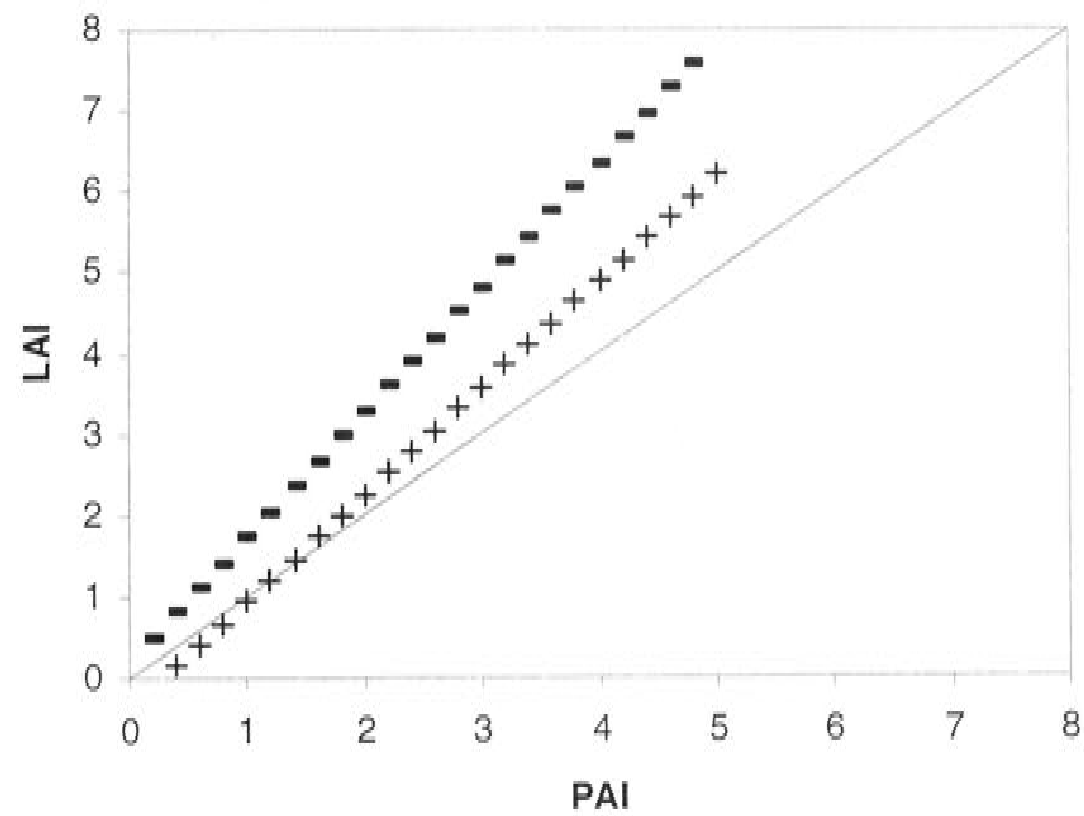


Figure A III 2. Comparison between PAI and LAI obtained from regression equations. The (-) symbols are from the equation by Battaglia *et al* (1998) and (+) symbols are from equation A III 1.

11.4. Appendix IV Neutron probe calibration

Neutron probe calibration curves obtained from soil samples and gravimetric analyses are presented. Calibration equations were obtained for each tube in the MBE area. The presented curves are applied to soil profile from 0.6 to 2.6 m. Equations A and B were the same for all genotypes. The parameters of Equation C for the subsoil differed between tubes (genotypes).

Table A IV 1 Regression equations obtained from neutron probe calibrations under five genotypes.

Soil moisture (mm) = a * (Neutron probe reading) - b

	Genotypes	a	b	r^2	n
Equation A (20 cm)	All genotypes	34.05	9.71	0.641	37
Equation B (40 cm)	All genotypes	44.79	2.40	0.754	34
	AR4	55.82	-7.47	0.807	21
	847	73.50	-15.27	0.846	23
Equation C (60-260 cm)	15	82.92	-24.04	0.802	41
	1248	92.08	-26.24	0.794	19
	22	91.53	-27.65	0.807	22

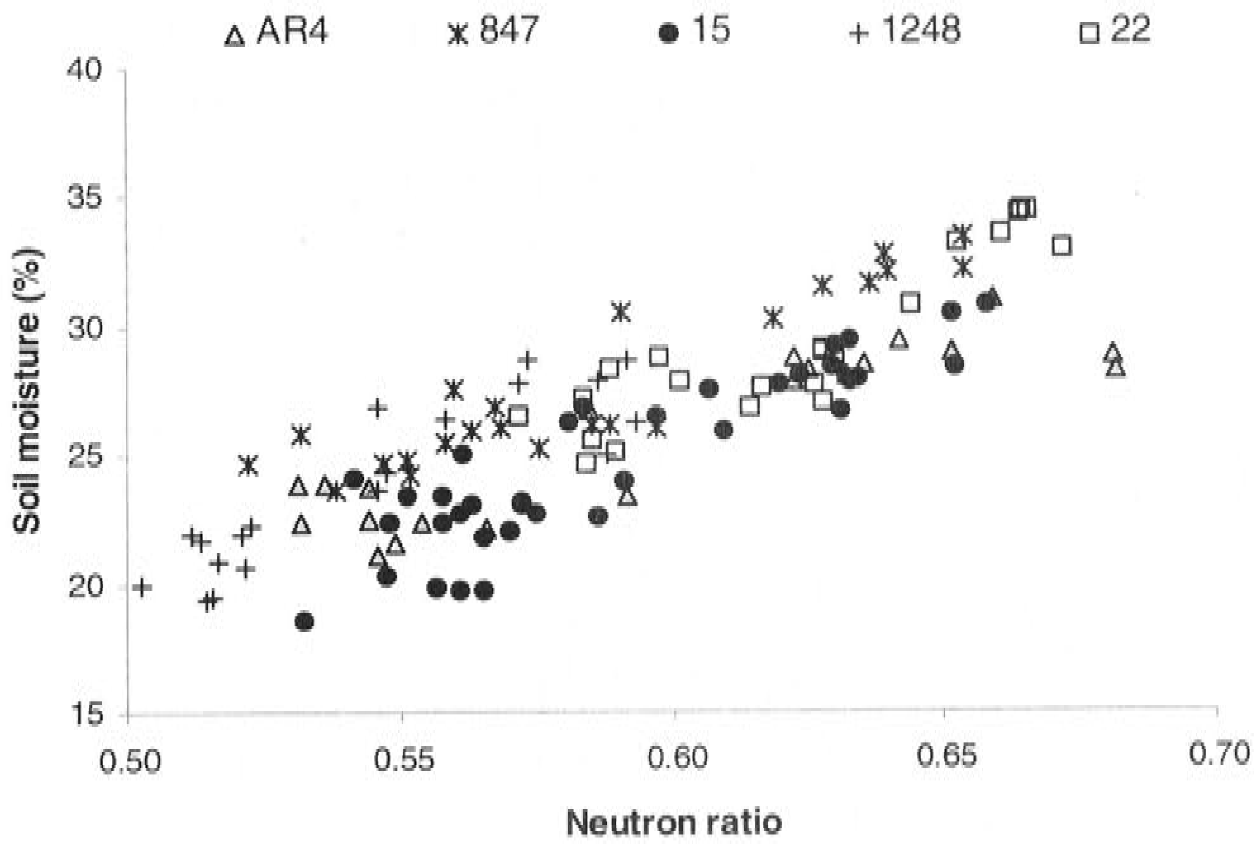


Figure A IV 1. Comparison between ratio of neutrons and soil moisture (%) obtained from laboratory analyses at depth from 60 to 260 cm.

11.5. Appendix V Comparison between parameter values of 3-PG applied to *E. grandis* in three different studies

Table A V 1. List and source of parameters used in the calibration 3-PG and values applied in Stape (2002) (used of fertilized and irrigated experiment), Williams (2002) (used the PEST software to estimate some parameters) and this study (based on local measurements).

3-PG Parameters

Meaning/comments	Symbol	Units	Stape 2002	Williams 2002	This study
Ratio of carbohydrate allocation to foliage and	p_{FS2}	-	0.096	0.75	0.70
stems at diameter at breast height = 2 and 20 cm	p_{FS20}	-	0.034	varying	0.10
Coefficients in stem allometric relationship with	a_s	-	0.065	varying	0.045
diameter at breast height	n_s	-	2.68	2.40	2.812
Maximum fraction of P_N to roots	η_{Rx}	-	0.8	0.6512	0.6
Minimum fraction of P_N to roots	η_{Rn}	-	0.2	varying	0.1
Minimum, optimum and maximum temperatures for growth	T_{min}, T_{opt}, T_{max}	ºC	8 / 25 / 40	11 / 21 / 31	8 / 25 / 36
Moisture ratio deficit for $f_\theta = 0.5$	c_θ		?	0.45	0.5
Power of moisture ratio deficit	n_θ		?	4	5
Power of (1-*FR*) in f_N	f_{Nn}		1	1	1
Value of f_N when *FR* = 0	f_{N0}	-	0.6	1	0.6
Maximum stand age used in age modifier f_{age}	-	years	?	50	9
Power of relative age in function for f_{age}	n_{age}	-	?	4	4
Relative age to give f_{age}= 0.5	r_{age}	-	?	0.95	0.95
Maximum litterfall rate	γ_{Fx}	1/month	0.07	0.042	0.13
Litterfall rate at t = 0	γ_{F0}	1/month	?	0.0001	0.00169
Age at which litterfall rate has median value	$t_{\gamma F}$	month	36	18	13
Average monthly root turnover rate	γ_R	month^{-1}	?	0.015	0.025
Maximum canopy conductance	g_{Cx}	m s^{-1}	0.02	0.02	0.021
Response of canopy to vapour pressure deficit	k_D	mbar^{-1}	0.324	0.05	0.048
*L** for maximum canopy conductance	L_{gcx}	-	?	varying	3
Canopy boundary layer conductance	g_B	m s^{-1}	0.2	0.2	0.2
Maximum stem mass per tree @ 1000 trees/hectare	w_{Sx1000}	kg tree^{-1}	?	300	180
Specific leaf area at stand age 0	σ	m^2 kg^{-1}	11	20	10.5
Specific leaf area for mature aged stand	σ	m^2 kg^{-1}	8.5	varying	8
Extinction coefficient for absorption of PAR by canopy	*k*	-	0.4	0.5	0.5

3-PG Parameters

Meaning/comments	Symbol	Units	Stape 2002	Williams 2002	This study
Maximum canopy quantum efficiency	α	mol C / mol PAR^{-1}	0.08	0.055	0.068
Ratio P_N/P_G	Y	-	0.50	0.47	0.47
Maximum proportion of rainfall evaporated from canopy	I_x	-	0.15	0.15	0.15
Leaf area index for maximum rainfall interception	L_{lx}	-	?	3	3
Branch and bark fraction at age 0	p_{BB0}	-	?	0.75	0.3
Branch and bark fraction for mature stands	p_{BB1}	-	?	0.15	0.12
Minimum basic density - for young trees	ρ_m	t m^{-3}	?	0.5	0.48
Maximum basic density - for older trees	ρ_x	t m^{-3}	?	0.5	0.52

11.6. Appendix VI Climate regions determined by weather stations

Appendix VI shows three maps containing the climate regions defined by the automatic weather station (ASW) network. The limits of each AWS were determined based on square of inverse distance from ASW (see Chapter 4).

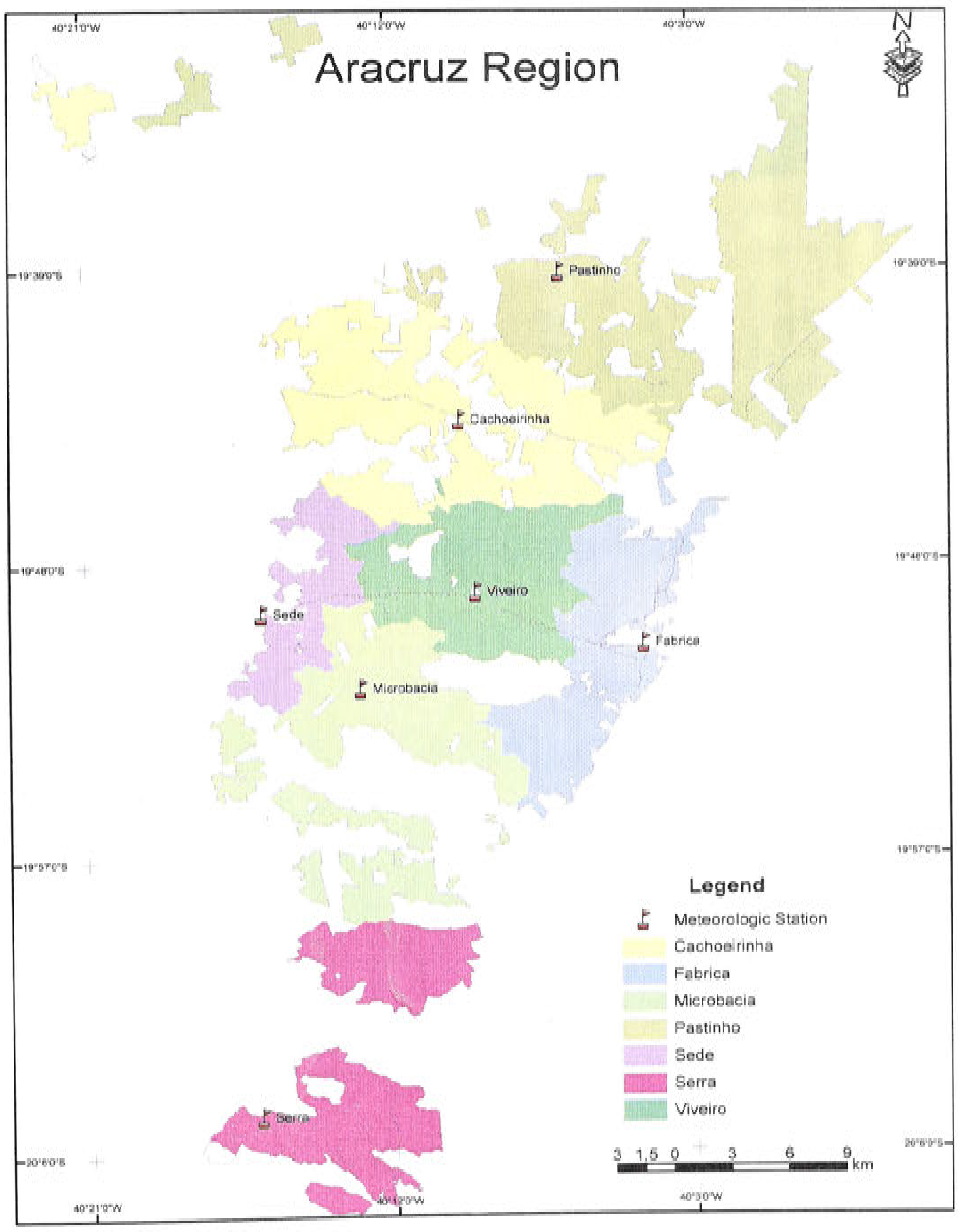


Figure A VI 1. Map of limits of automatic weather station in Aracruz region.

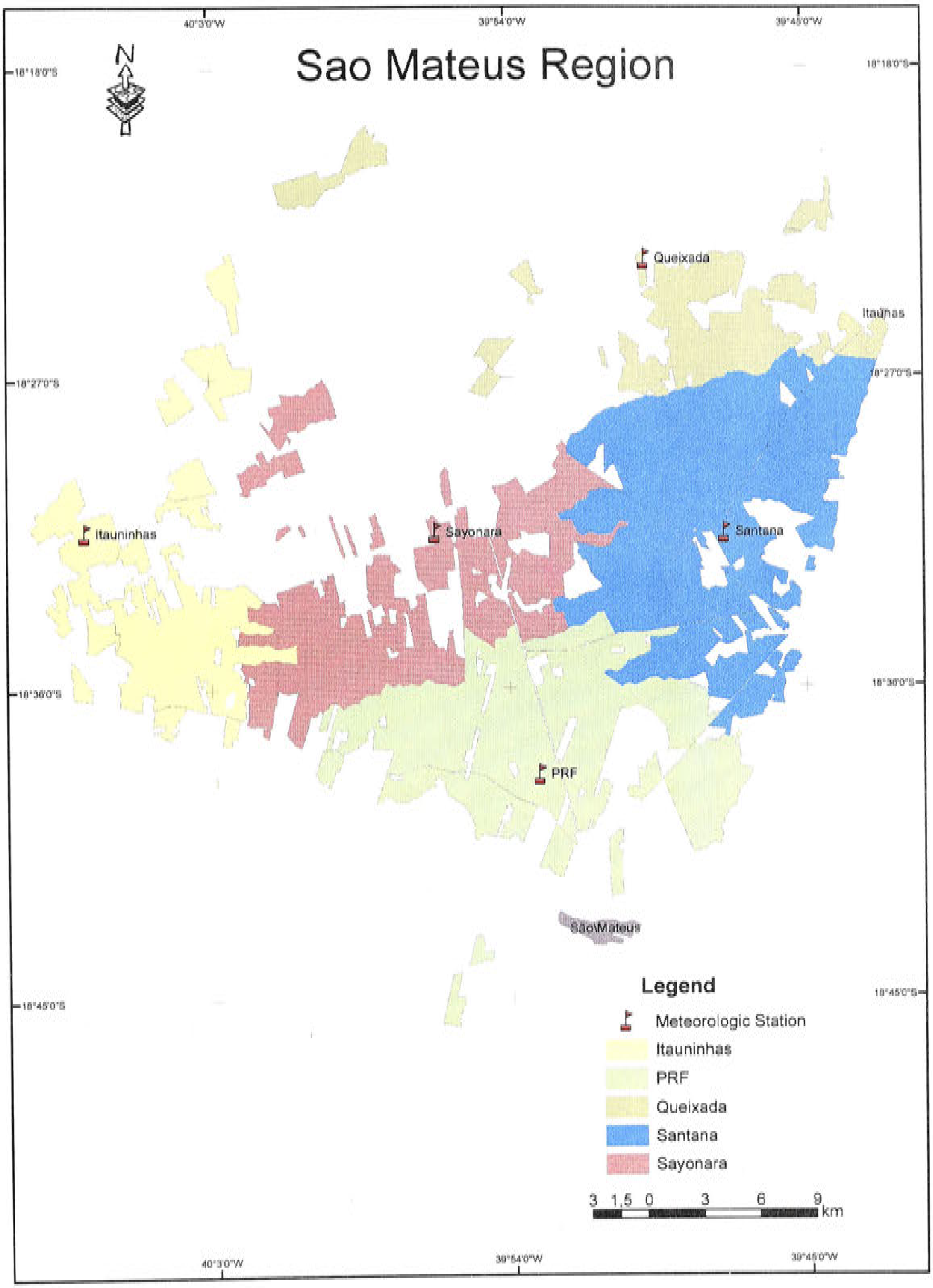


Figure A VI 2. Map of limits of automatic weather station in São Mateus region.

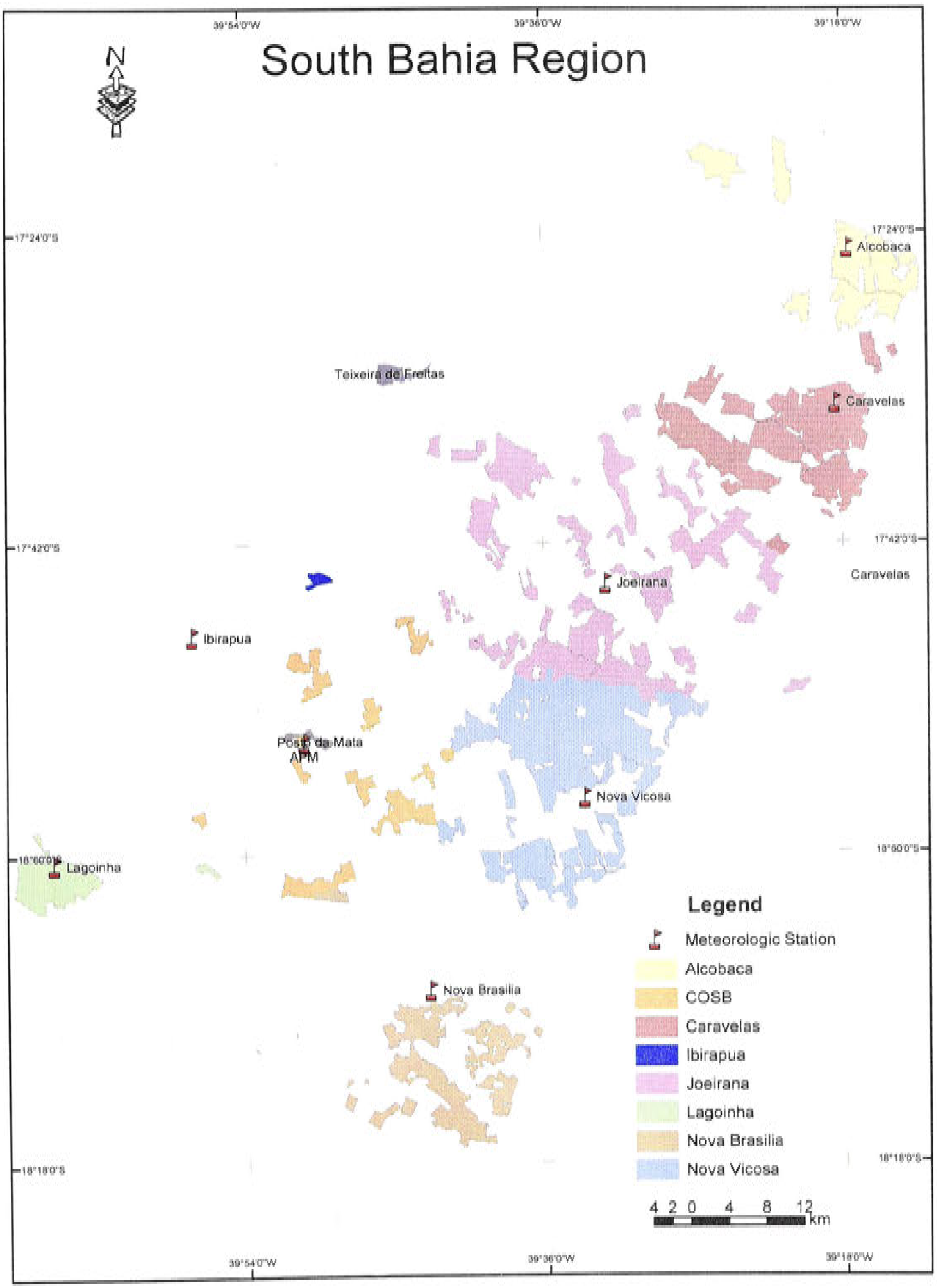


Figure A VI 3. Map of limits of automatic weather station in South Bahia region.

11.7. Appendix VII Distribution of soil type within each region

This appendix presents the maps of soil type in each one of the three main regions of ARCEL lands.

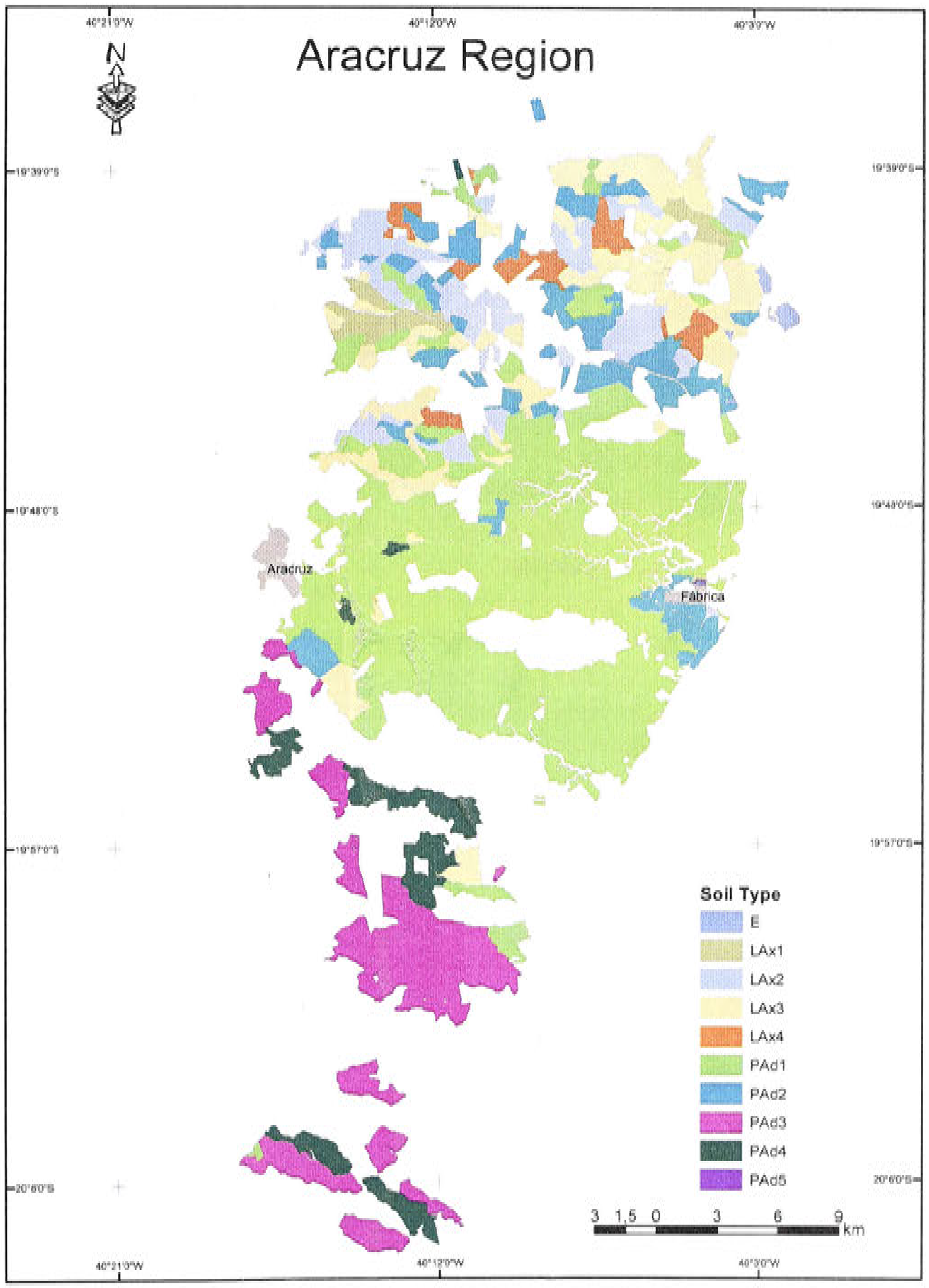


Figure A VII 1. Map of soil type in Aracruz region. The soil types and some of their characteristics are listed in Tables 5.7 and 5.8.

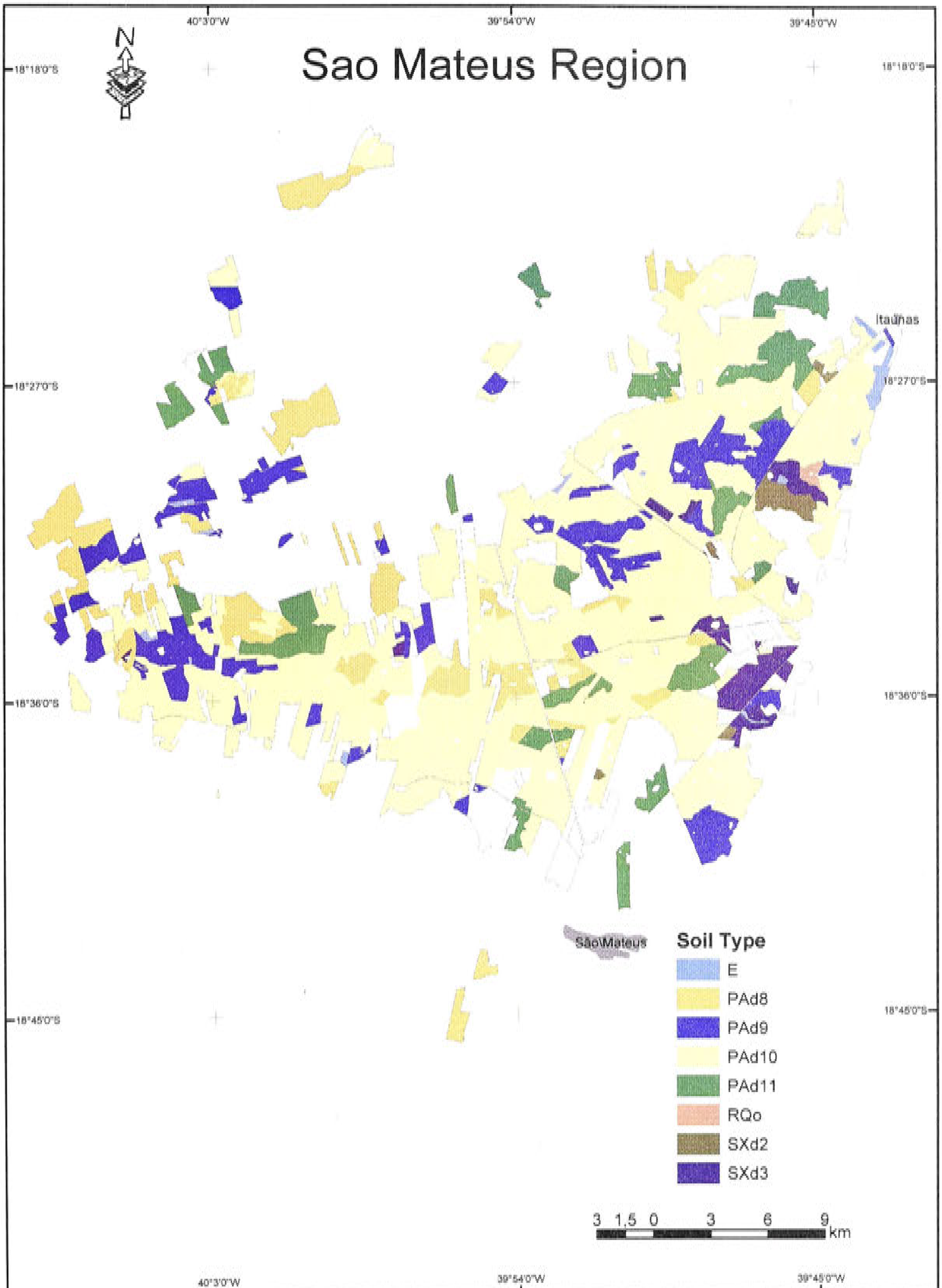


Figure A VII 2. Map of soil type in São Mateus region. The soil types and some of their characteristics are listed in Tables 5.7 and 5.8.

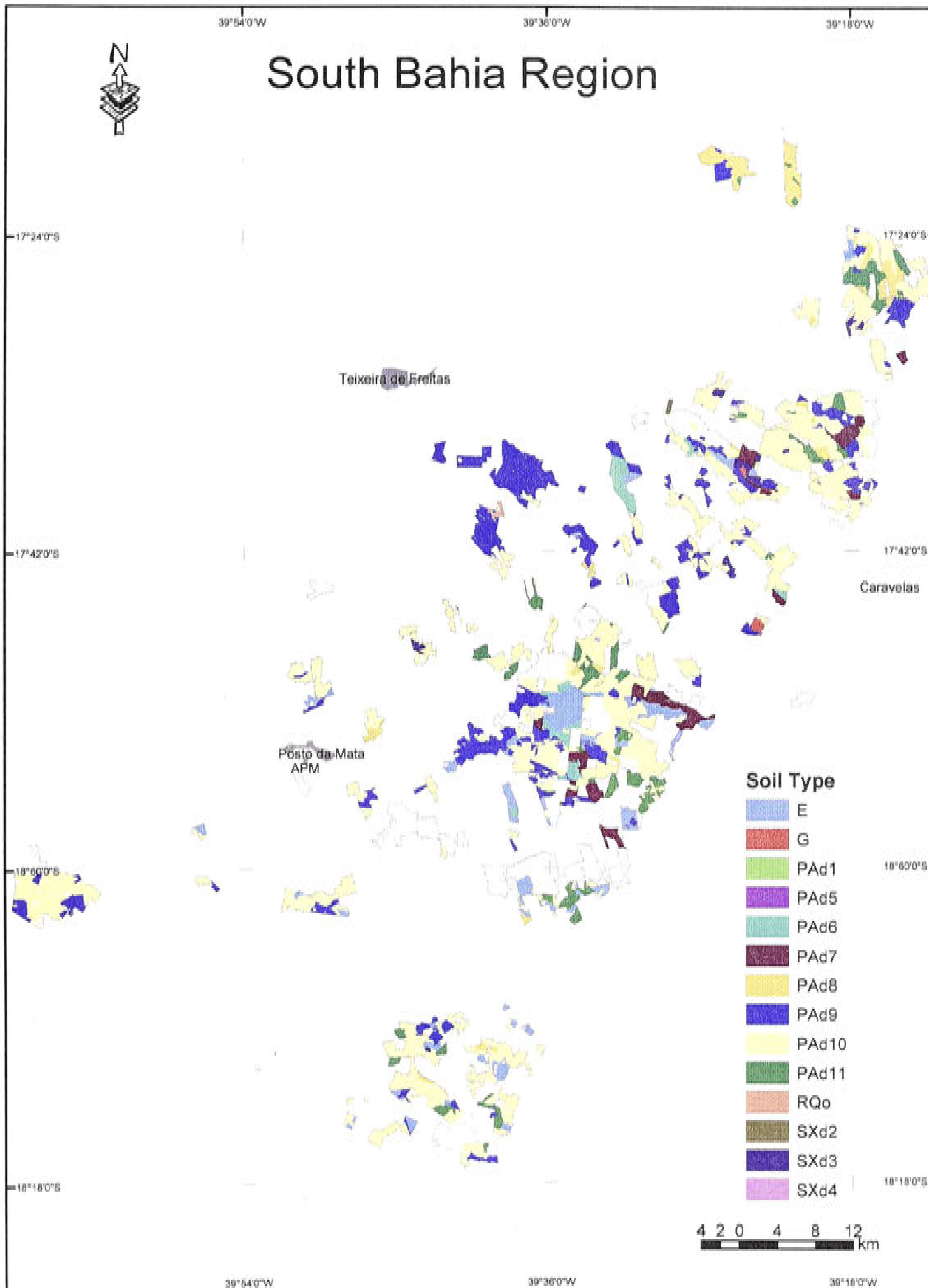
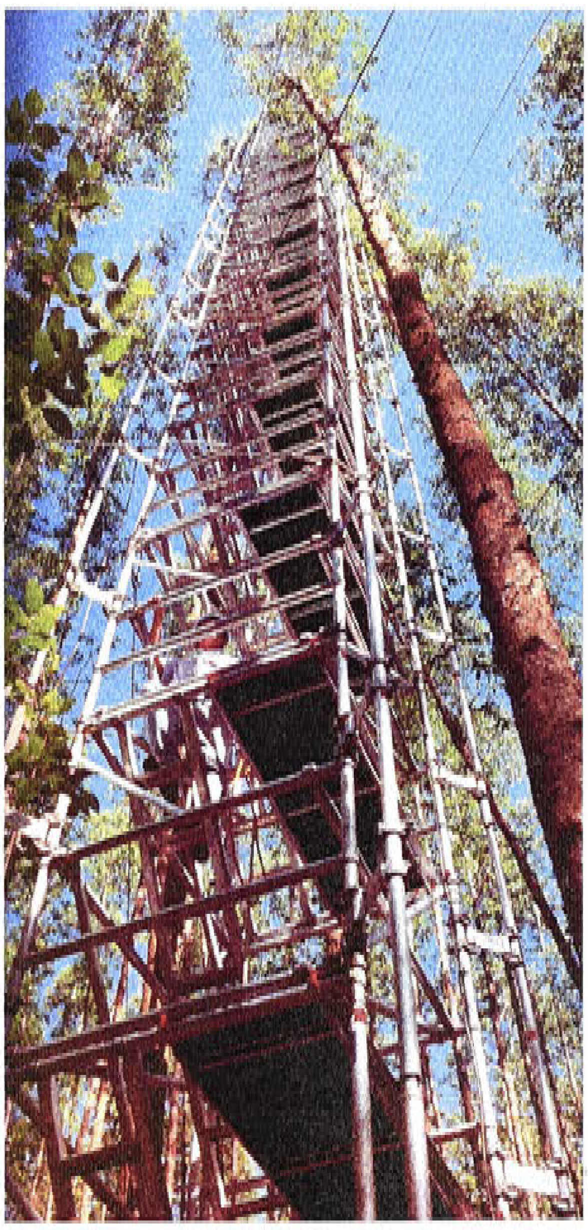


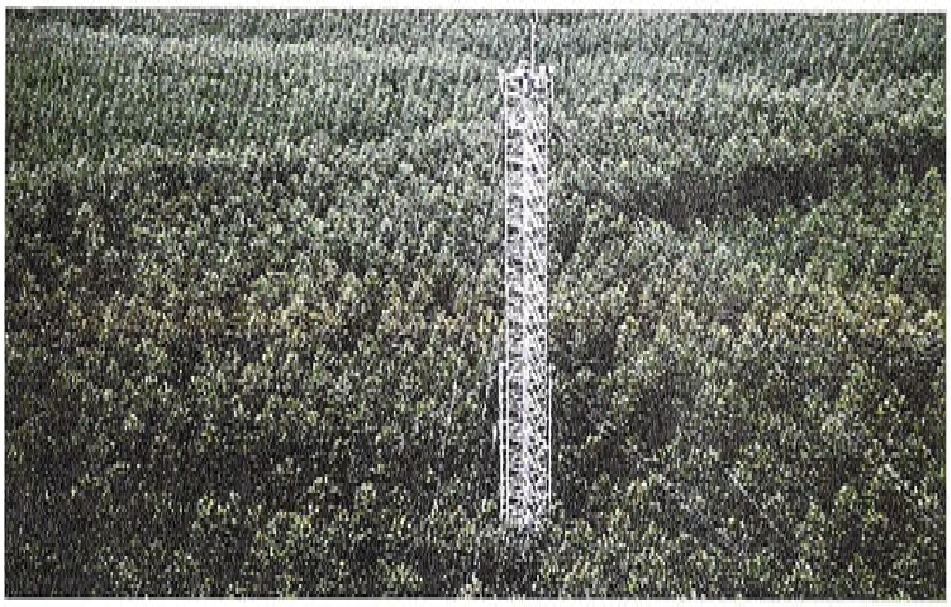
Figure A VII 3. Map of soil type in South Bahia region. The soil types and some of their characteristics are listed in Tables 5.7 and 5.8

11.8. Appendix VII Photographs of the study area and experiments

This appendix presents some photographs of the main experiments that generated the database used in this thesis.

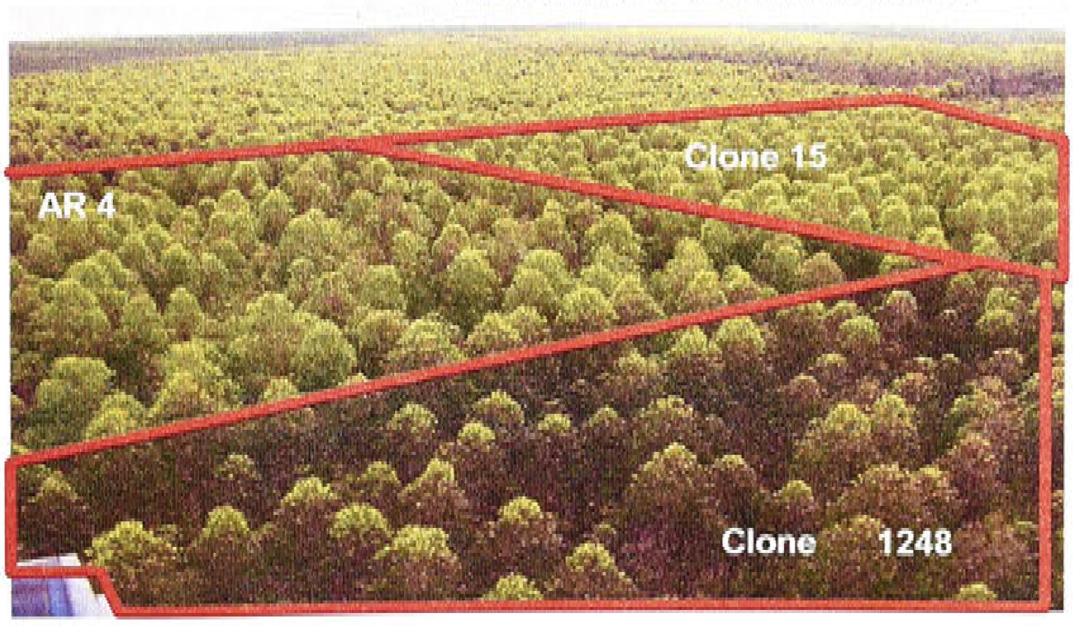


a) Tower used for ecophysiological and meteorological measurements



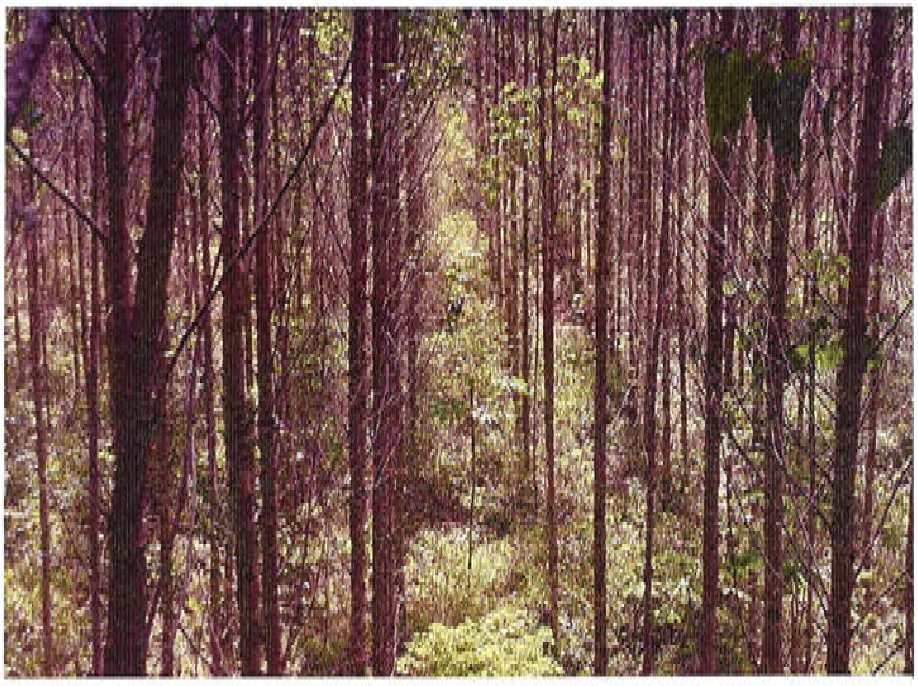
b) Location of the tower in the central area of the catchment with different clones plots

c) Overview of the catchment area



d) Genotypes plots

Figure A VIII 1. Overview of catchment experiment area (MBE)



a) *Eucalyptus grandis* plantation in the MBE area

b) Permanent sample plot in the MBE area

c) *Eucalyptus grandis* plantation in the fertilization and irrigation experiment

Figure A VIII 2. *Eucalyptus grandis* plantations stands in the study areas.

a) *Eucalyptus grandis* root system

b) Digging tree roots

c) Fine root weight

d) Coarse root weight

e) Tree root mass

Figure A VIII 3. Measurements of tree root biomass

a) Tree foliage mass measurement

b) Tree branches mass measurement

c) Litterfall trap

d) Overview of litterfall trap

e) Overview of litterfall trap

Figure A VIII 4. Foliage, branches and litterfall measurements in the MBE.

a) Microbacia weather station - sensors of wind direction and speed, net radiation, PAR, global radiation temperature and relative humidity, solar panel and antena for data transmission

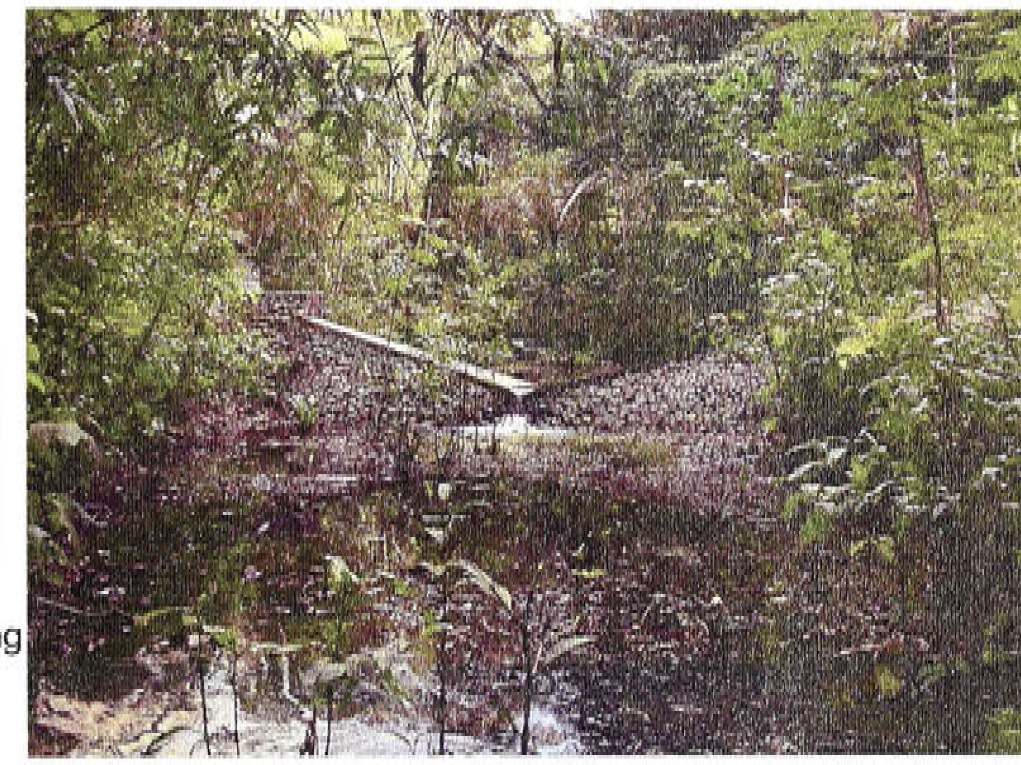
b) Net radiation sensor installed above the tree canopy

c) Raingauges above the tree canopy

d) Raingauges below the tree canopy to measure rainfall interception

Figure A VIII 5. Meteorological measurements in the MBE.

a) Measurement of soil moisture using neutron probe



b) Frontal view of the weir in MBE area used in the runoff measurements

c) Detailed view of the weir in MBE area used in the runoff measurements

Figure A VIII 6. Measurements of soil moisture and runoff in the MBE.

a) Sensor of plant canopy analyser LAI-2000 above the canopy

b) Sensor of plant canopy analyser LAI-2000 below the canopy

c) Measurement of stomatal conductance

Figure A VIII 7. Measurements of plant area index and stomatal conductance in the MBE.