ACIAR
AUSTRALIAN CENTRE FOR INTERNATIONAL AGRICULTURAL RESEARCH

Project Document

Partners in Agricultural Research

KFRI- 281/97

RR - 335

ACIAR PROJECT NO. FST/95/106

IMPROVING AND MAINTAINING PRODUCTIVITY OF EUCALYPT PLANTATIONS IN INDIA AND AUSTRALIA

SECTION 1 : PROJECT SUMMARY

1.1 Project Title — Improving and Maintaining Productivity of Eucalypt Plantations in India and Australia.

1.2 Project Number — FST/95/106

1.3 Category

(a) Program — Forestry

(b) Commodities/Countries (with proportion of expected project benefits)

	COUNTRIES					
COMMODITIES	AUST	INDIA				TOTAL
Pulpwood	35	45				80
Saw and veneer logs - non coniferous	5					5
Other industry roundwood		5				5
Fuelwood- non coniferous		10				10
TOTAL	40	60				100%

(c) Is there development expenditure associated with this project? If yes, show percentage — ..0.%

1.4 Geographic Region — South Asia

1.5 Related ACIAR Projects — 9414 Management of phosphorus for sustainable food crop production on acid upland soils in Australia, Philippines and Vietnam

9425 Ectomycorrhizal fungi for eucalypt plantations in China.

1.6 Commissioned Organisation — CSIRO Forestry and Forest Products

Director's signature (ACIAR) ....Sign-off Date: ....

1.7 Collaboration in Australia

University of Western Australia
Soil Science and Plant Nutrition
Nedlands
Western Australia 6907

Griffith University Queensland
School of Applied Science
Faculty of Engineering and Applied Science
PMB 50 Gold Coast Mail Centre
Queensland 4217

University of New South Wales
School of Biological Science
Sydney NSW 2052

Bunnings Treefarms
GPO Box R1276
Perth
Western Australia 6001

1.8 Developing Country Collaboration

Kerala Forest Research Institute
Peechi-680653
Thrissur Dist
Kerala State
India

Kerala Forest Department
Forest Head Quarters
Vazhuthacaud
Trivandrum - 695 014
Kerala State
India

Hindustan Newsprint Limited
Newsprint Nagar - 686 616
Kottayam Dist.
Kerala State
India

1.9 Collaboration with Other (Non-ACIAR) Projects

(a) AusAID/IDP Projects Nil

(b) External Agencies

1.10 Key Personnel

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(c) Administrator of Project in Commissioned Organisation

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Fax +61 6 281 8312

1.11 Proposed Duration of Project & Commencement date

Duration
Five years

Commencement date
1 July 1997

1.12

	YEAR 1 (1/7/97 30/6/98)	YEAR 2 (1/7/98 30/6/99)	YEAR 3 (1/7/99 30/6/00)	YEAR 4 (1/7/00 30/6/01)	YEAR 5 (1/7/01 30/6/02)	TOTAL
(a) Estimated Expenditure from ACIAR funds						
Personnel	123495	131952	192434	193372	194030	835283
Supplies and Services	184400	65000	45000	42000	40500	376900
Travel	48640	45140	47140	46940	50240	238100
Other	4492	3982	3350	3364	3397	18585
Total	361027	246074	287924	285676	288167	1468868
Of which development expenditure = (This is part of, not additional, to the above figures)						
(b) Other Support directly associated with this project						
(i) From Commissioned Organisation	220079	210079	210079	210079	210079	1060395
(ii) From Australian Collaborators	5400	21600	29700	29700	18900	105300
(iii) From Developing Country Partner	21395	21765	22141	22524	22914	110739
(iv) From Others						
Grand Total	607901	499518	549844	547979	540060	2745302

1.13 Abstract

Plantation forests are being increasingly utilized throughout the world to meet demands for wood products. Plantation are grown with minimal inputs and only rudimentary silvicultural management in short rotations (less than 10 years) to provide materials for pulp and paper production, fuel and construction purposes. The long-term sustainability of these systems is currently being questioned in many countries of the world. In the tropics more than 43 million ha of plantations have been established, about one quarter of this area being planted to species of eucalypts. In many areas (*eg* Brazil) production rates are high. However in India, which has the largest area of plantation eucalypts of any country in the world, growth rates in parts of the country are low due to the poor nutrient status of soils. Furthermore, sustainable production from plantations growing on some soil types is problematic as studies in some regions of India and elsewhere indicate soil fertility and tree productivity decline with successive tree rotations. In Australia, growth rates are high where plantations are established on ex-pasture sites. However, there is little information on how productivity will vary in second and subsequent rotations. In both India and Australia, nutrition of eucalypt plantations has been identified as a priority research area for maintenance of sustainable wood production.

The development of this proposal arose from linkages between Dr AM O'Connell of CSIRO and Dr KV Sankaran of Kerala Forest Research Institute (KFRI) who had previously collaborated in writing invited chapters for a book on tropical plantation forestry - a joint project between CSIRO, ACIAR and CIFOR. Discussions indicated a number of similarities (soils, seasonal climate, use of eucalypts etc) which are important in developing sustainable plantation systems in India and Australia. The heads of CSIRO Forestry and Forest Products and KFRI agreed that a collaborative research effort could greatly benefit sustainable plantation forestry in both countries. Subsequently, a Phase I research proposal focussing on management of forest nutrition as a critical factor in developing sustainable eucalypt plantation systems, was submitted to ACIAR and accepted in December 1995. Following this Dr O'Connell and Dr Fryer visited KFRI and other possible collaborators in India, and development of the full proposal was initiated.

The two primary research institutions will be CSIRO Forestry and Forest Products in Australia and Kerala Forest Research Institute (KFRI) in India. The project will be supported by 9 scientists and support staff from CSIRO and 10 scientists from KFRI plus associated technical and administrative personnel in both institutions. Senior academics and research scientists at the University of Western Australia (UWA), University of New South Wales (UNSW) and Griffith University (GU) will also collaborate with us in the research and in-kind contributions will be provided by Bunnings Tree Farms in Australia and Kerala Forests Department and Hindustan Newsprint Limited in India. In our research we will explore management options to optimize and sustain tree growth over successive rotations. The overall objective is to identify and develop practices for manipulating soil organic matter, site nutrients and soil and tree water status as a basis for implementing silvicultural regimes which optimise conservation and use of site resources and which will allow sustainable wood production from eucalypt plantations.

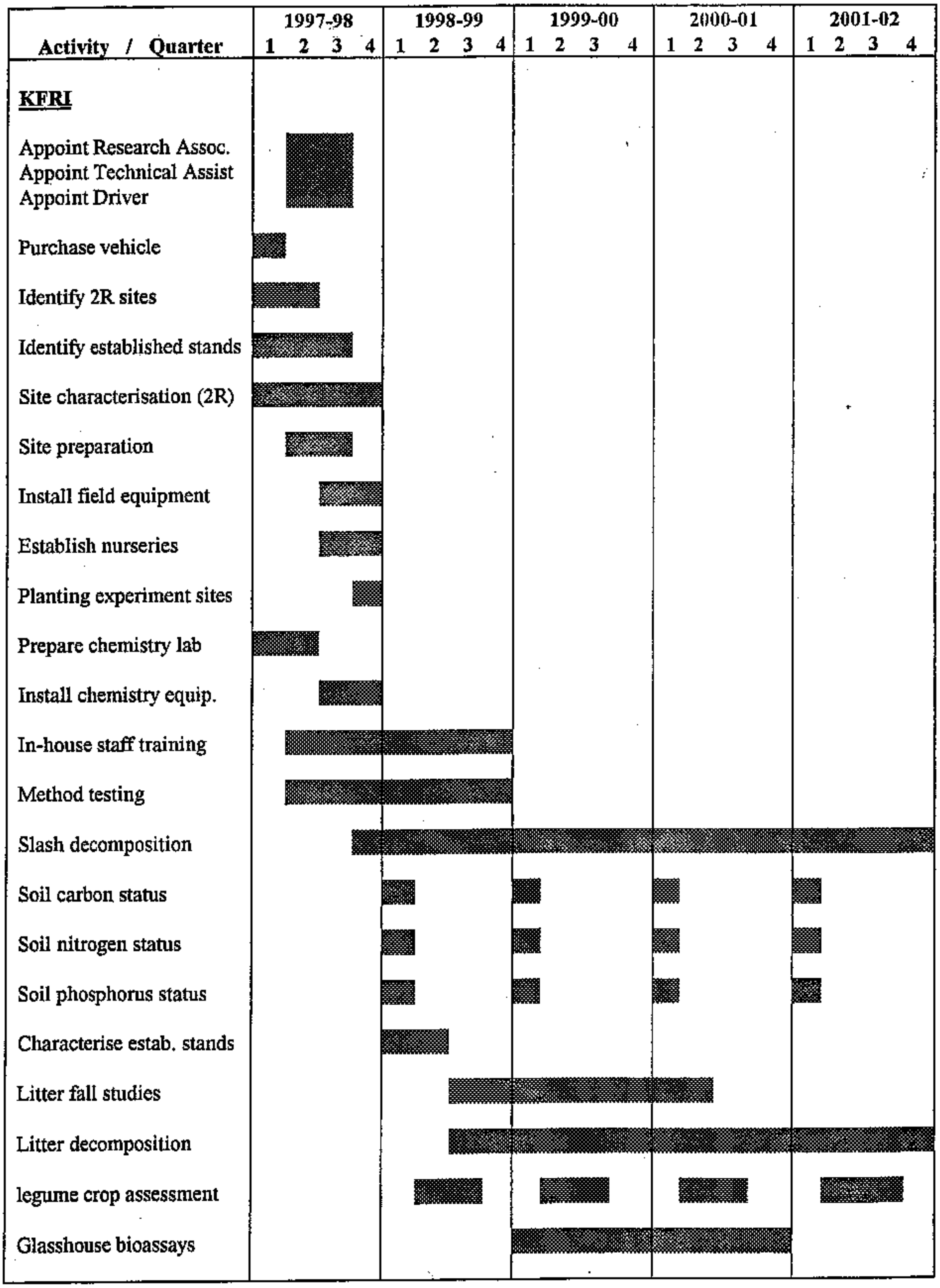
In India the research will be based on the two important eucalypt species used in Kerala (*Eucalyptus tereticornis* and *E. grandis*) and will be conducted at four different locations. At each, a series of six designed experiments will be initiated to investigate aspects of harvest residue management, nutrient application, use of legume undercrops to increase soil fertility and practical methods of water and soil conservation. The Australian component will use

E. globulus and will also investigate methods of organic matter conservation through management of harvest residues, nutrient applications and incorporation of agricultural legumes as undercrops. Within this experimental framework, research will focus on 4 inter-linked sub-projects, investigating the impact of silvicultural options in eucalypt plantations on - (i) nutrient status and nutrient cycling, (ii) plant physiology and water relations (iii) tree growth and nutrient uptake, and (iv) soil process and tree growth modelling. The modelling sub-project, conducted in collaboration with UNSW, will allow us to integrate experimental results from the other three sub-projects and provide the methodology for making long-term predictions of the consequences for productivity and sustainability of the silvicultural options investigated. We will also integrate parts of our research in Australia and India within a general framework proposed by CIFOR, which is to be applied to research on inter-rotation site management of plantations in a number of countries in the tropics. In this way the benefits of outcomes from our research project will flow to the forestry sectors in both countries as well as more widely in tropical countries where eucalypts are planted. Interaction with CIFOR will assist in establishing and maintaining links with researchers in other tropical countries and in disseminating research results within the region.

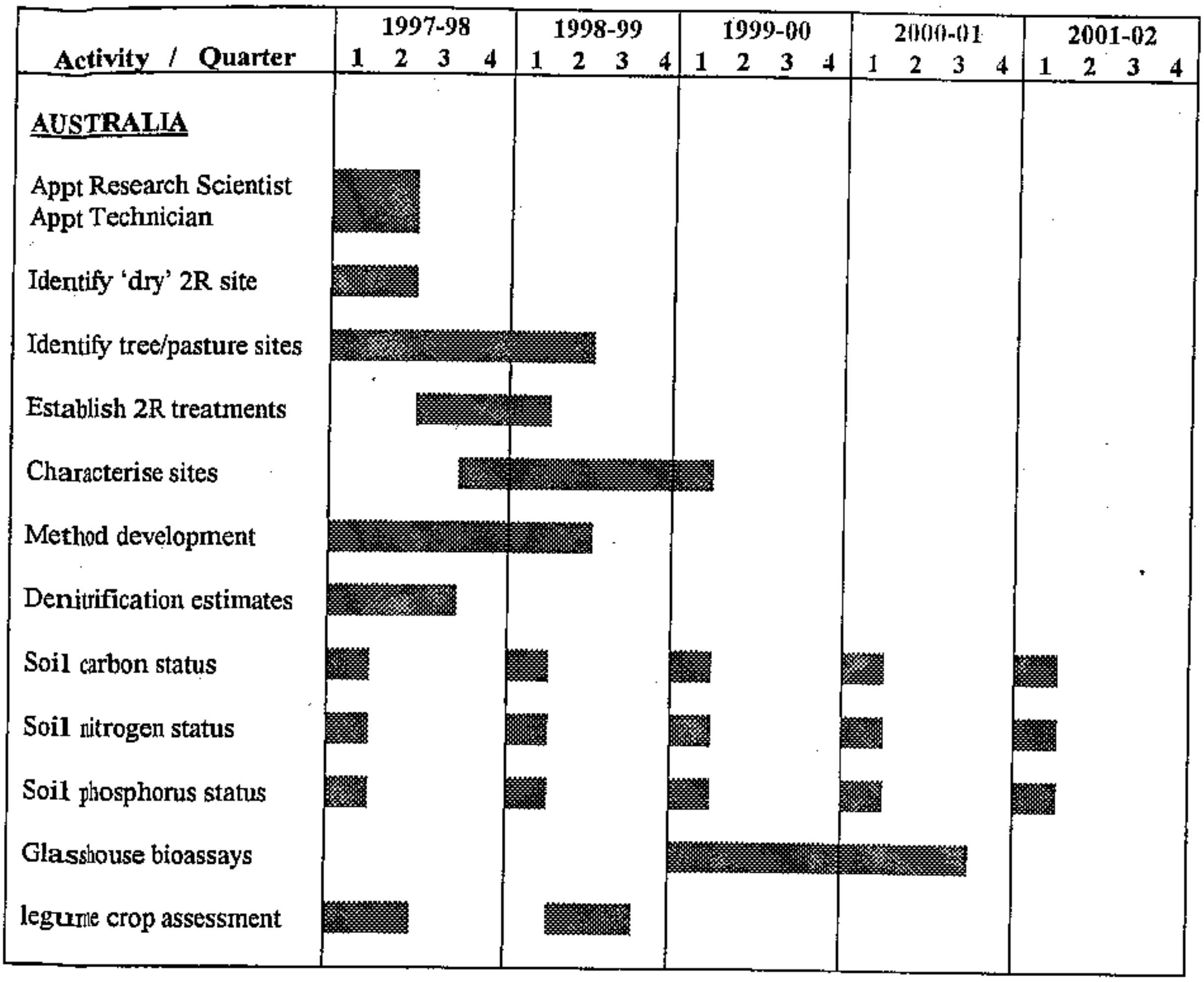
We have strong support from the Chief, CSIRO Forestry and Forest Products and the Director, KFRI. Both institutions have available a wide range of expertise in different aspects of forestry research. In addition to the direct participation of scientists from KFRI and CSIRO in the research program, we will also collaborate with Kerala Forest Department, Hindustan Newsprint Limited, Kerala Agricultural University, University of Western Australia, University of New South Wales and Griffith University. These linkages will facilitate rapid technology transfer as well as providing a network for training scientists and postgraduate students from India. Furthermore, we have established contacts with researchers working on related fields in agriculture where complimentary problems are being studied. This will allow us to utilize methodologies developed to evaluate the dynamics of soil carbon, phosphorus and nitrogen and to relate our research outcomes for plantation forests to management of crop systems more generally.

1.14 Flow Chart

Sub-project 1: **Nutrient status and nutrient cycling in eucalypt plantations**



Sub-project 1: **Nutrient status and nutrient cycling in eucalypt plantations**



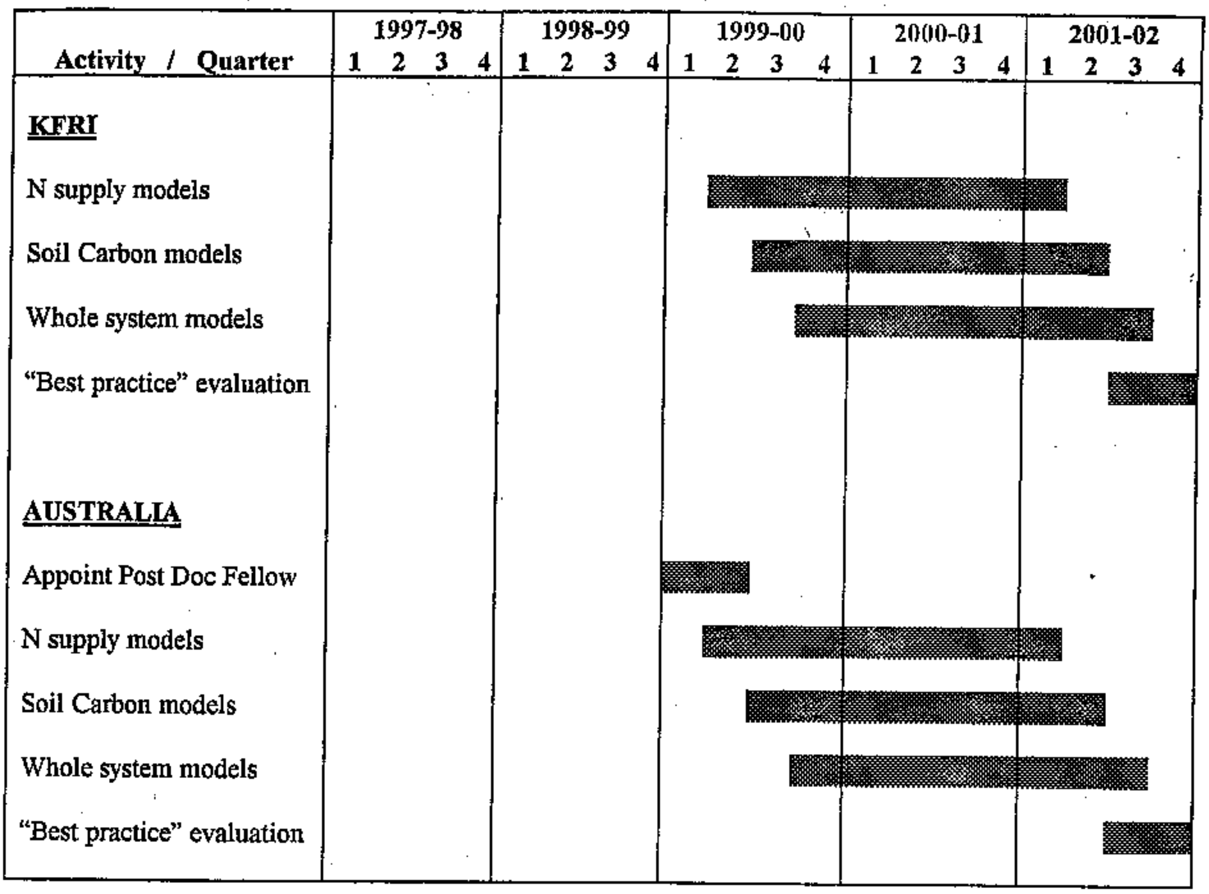
Sub-project 2 : Plant physiology and water relations

Activity / Quarter	1997-98				1998-99				1999-00				2000-01				2001-02			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
KFRI																				
Establish weather stations			X	X																
Micro-climate monitoring				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Leaf area index estimates					X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Litterfall													X	X	X	X	X	X	X	
Photosynthesis estimates							X		X	X	X		X	X	X		X	X	X	
Stomatal conductance							X	X	X	X	X	X	X	X	X	X	X	X	X	
Water potential							X	X	X	X	X	X	X	X	X	X	X	X	X	
Sap flow estimates													X	X	X	X	X	X	X	
Light requirements					X	X	X		X	X	X		X	X	X		X	X	X	
AUSTRALIA																				
Soil water status			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Leaf area index			X		X		X		X		X		X		X		X		X	

Sub-project 3 : Tree growth and nutrient uptake.

Activity / Quarter	1997-98				1998-99				1999-00				2000-01				2001-02			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
KFRI																				
Tree growth					■		■		■		■		■		■		■		■	
Allometric functions					■		■		■				■				■			
Nutrient uptake					■		■		■				■				■			
Indicator evaluation													■	■	■	■	■	■	■	■
Inter-row legume effects							■		■		■		■		■		■		■	
Economic analysis																	■	■	■	■
AUSTRALIA																				
Tree growth	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Allometric functions	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				
Nutrient uptake	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Indicator evaluation													■	■	■	■	■	■	■	■
Inter-row legume effects				■				■				■				■				
Economic analysis																	■	■	■	■

<u>Sub-project 4</u> : Modelling soil processes and tree growth



Project Management :

Activity / Quarter	1997-98				1998-99				1999-00				2000-01				2001-02			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
AUSTRALIA- CSIRO																				
Financial aquital ACIAR				■				■				■				■				■
Annual reports				■				■				■				■				■
Mid-term review												■								
Final report																				■
AUSTRALIA- GU																				
Financial aquital CSIRO								■				■				■				
Annual reports								■				■				■				
AUSTRALIA- UNSW																				
Financial aquital CSIRO												■				■				■
Annual reports												■				■				■
AUSTRALIA- UWA																				
Financial aquital CSIRO								■				■				■				■
Annual reports								■				■				■				■
KFRI																				
Financial aquital CSIRO				■				■				■				■				■
Reports to Project Leader			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Training programs		■				■	■			■	■			■					■	
Annual reports				■				■				■				■				■
Mid-term review												■								
Final review																				■

1.15 Outputs Table

Sub-Project	Scientific Outputs	Potential Applications
Sub-Project 1 Nutrient status and nutrient cycling in eucalypt plantations	1.1 *KFRI laboratory establishment* • Purchase major items of analytical chemistry equipment • Install in Perth laboratory • Train KFRI chemist • Transfer to equipment to India	This part of the project is crucial to the successful outcome of the research. The aim is to establish a modern analytical facility and train staff in its operation and maintenance. The equipment will be used for soil and plant nutrient analyses in all sub-projects.
	1.2 *Pre-harvest nutrient budgets in eucalypt plantations:* • Soil characteristics (description and classification) • Soil nutrient content to 1 metre depth by depth intervals (Total organic C, N, P, labile C, N, P, exchangeable cations and Al, pH, bulk density, particle size). • Stand biomass and nutrient content of trees before harvest • Understorey and forest floor biomass and nutrient content before harvest	A pre-harvest nutrient inventory of all the sites. will be established. This will supply crucial data in assessing the direct impact on nutrient stores of particular forms of plantation management. For example, options for harvest include bole only removal through to complete removal of all vegetative material. This is used for pulpwood, construction and fuel. Since nutrients are not homogeneously distributed in the different tissues, the intensity of harvest can markedly affect nutrient exports from the site.
	1.3 *Slash decomposition* • Decomposition (litter bag study of leaf and wood fractions of slash) • Nutrient release from decomposing slash residues • Annual estimate of remaining slash (quadrat measures after harvest and at 12 months intervals)	Harvest residues are a valuable nutrient resource for the next tree crop. They also provide some buffering against nutrient loss through leaching etc. Data on nutrient return from decaying residues will provide a quantitative measure of the likely nutritional consequences of practices such as rotational burning, residue harvesting, debarking on-site etc.
	1.4 *Litterfall+decomposition* • Litterfall rate in established stand and adjacent natural forest • Decomposition rate in established stand and adjacent natural forest • Nutrient dynamics in litter	A comparison of nutrient cycling in eucalypt plantations and the pre-existing land use is critical in evaluating the likely changes in soil fertility that may result from addition of relatively nutrient-poor eucalypt litter to soil.
	1.5 *Soil carbon status* (measured at 0,6, 12, 24, 36, 48 months after planting) • Total organic carbon • Microbial biomass carbon • Labile soil carbon	

1.6 *Soil nitrogen status*
(measured at 0,6,12,24,36, 48 months after planting)

- Total nitrogen
- Microbial biomass nitrogen
- Labile soil N (anaerobic N) N mineralization (lab incubations of intact cores)
- Denitrification potential
- Data logging of soil environmental parameters

1.7 Soil phosphorus status (measured at 0, 6,12, 24, 36, 48, months after planting)

- P forms estimated with a range of extractants to characterise P status and supplying power
- P sorption characteristics
- Microbial biomass P

1.8 Glasshouse bioassays

- Glasshouse studies to assess impact of changes in soil properties under eucalypt plantations on seedling growth and nutrient uptake
- Nutrient addition experiments to identify limitations induced by repeated tree cropping
- Complementary soil chemical analysis

Likewise, changes in the stores and cycling of carbon and nutrients will occur as a result of the alternative silvicultural treatments applied in our proposed experiments. We expect that some of these changes will be detectable within the time frame of the project. The measures of soil organic matter, nitrogen and phosphorus that we will make annually will be critical in evaluating any long term trends or changes in soil properties important to soil fertility and plantation productivity.

Specific treatments will provide quantitative scientific evidence of the value of practices such as residue retention, weed control, trenching, legume cover crops and fertilizer applications.

The glasshouse studies will indicate how soil fertility has changed following several rotations of eucalypt plantations and provide a measure of bio-availability of nutrients. Together with the field-based studies, this will provide part of the necessary information to (i) formulate management strategies to ameliorate nutrient declines and (ii) evaluate "sustainability indices" in intensively managed plantations.

Sub-Project 2

Plant physiology and water relations

2.1 *Weather+miroclimate data*
- Weather station installed at two of the experimental locations
- Microclimate measurements within and above the canopy
- Penman-Monteith estimates of stand water use

2.2 *Canopy dynamics*
- Leaf area index
- Litterfall

2.3 *Physiological parameters*
- Photosynthesis
- Stomatal conductance
- Porometer measure of transpiration
- Sap-flow measure of transpiration
- Leaf water potentials (pre-dawn and midday)
- Water stress integral evaluation

2.4 *Ground-level light availability*
- Assessment of impact on ground cover performance in terms of biomass productivity and nitrogen accretion in different ground cover species

A major application will be estimates of tree and stand water use. This will be determined by several different methods. Great concern exists about the environmental effects of eucalypts in India, especially excessive water use and lowering of water table. Our experiments will provide quantitative data on this.

The importance of water conservation methods (trenching, slash retention, weed control etc) will be evaluated.

Impact of treatments (eg. Fertilizer applications) on water use efficiency (dry matter produced/unit of water) will be determined.

Effect of silviculture on tree water status will be demonstrated. This will indicate whether optimum nutrition can reduce tree water stress as has been suggested (Brix 1972; Hillerdal-Hagstromer *et al.* 1972).

Role of light and water in success of under cover legume crops will be evaluated and will assist in selecting appropriate species.

Sub-Project 3

Tree growth and Nutrient uptake

3.1 *Tree Growth*

- Diameter measured at 0, 6, 12, 18,24, 30,36, 42,48, 54 months after planting
- Sampled trees used to develop allometric relationships between diameter and biomass of tree components

3.2 *Nutrient Uptake*

- Destructive sampling at 0, 6, 12, 24, 36, 48, months after planting
- 2 treatments in the N rate trial and 2 treatments in the P rate trial at each location
- Nutrient content of leaf, branches, stem and bark
- Wood properties (eg density)
- Relate nutrient uptake/supply

3.3 Fertility indices

- Evaluation of measures of tree N and P status and soil N and P supply rates which may be useful in formulating plantation nutrient management strategies

3.4 Economic analysis

- Economic and growth data to further develop cost and return analysis in relation to applied silviculture
- Identification of silvicultural options most beneficial from economic and sustainability viewpoints.

Potential for maximum growth and economic benefit will be established.

Effect of silviculture on growth and above-ground carbon partitioning will be determined. This will provide forest managers with the information needed to make informed decisions as to the consequences of different management options.

Allometric relationships will be transportable to forest operations to allow better prediction of biomass accretion and standing log volumes.

Nutrient requirements for maximum growth and their effects on properties important for wood utilization will be established. This will give managers the necessary information needed to make informed decisions on nutrient management and needs for fertilizer application.

If useful diagnostic indices of tree nutrient status can be identified, managers will be better placed to maximize production and minimize off site effects from nutrient management programs.

Determine economic viability of more intensive management of eucalypt plantations. Identify optimum "Best practice" management.

Sub-Project 4

Soil process and growth modelling

4.1 *Modelling N mineralization*

- Selected treatments
- Use and extend existing simulation model of N mineralization
- Seasonal patterns simulated
- Annual rates predicted from model simulations

4.2 *CENTURY Application*

- Collate data required to run model
- Apply CENTURY to selected treatments
- Predict effect of management treatments on soil carbon and N status

4.3 *Whole System Modelling*

- Apply G'DAY, N-BAL and SUSTAIN models to selected treatments.
- Long-term predictions of site nutrient balances and productivity

Predicting soil native nitrogen supply rates will allow better matching of nutrient supply to tree nutrient demand. This will also allow more effective reduction of deleterious site effects such as from leaching of nutrients into ground and stream water.

Long-term changes in soil due to establishment of eucalypt plantations is a controversial issue. Our data will provide predictions on the nature, direction and magnitude of these effects and what their consequences are for soil fertility.

Whole system modelling will indicate how productivity is likely to change over successive rotations under specific silvicultural operations. This will allow 'best practice' options to be identified and incorporated into plantation management.

SECTION 2 : PROJECT DESCRIPTION

2.1 Background

Project initiation

The development of this proposal arose from linkages between Dr AM O'Connell of CSIRO and Dr KV Sankaran of Kerala Forest Research Institute (KFRI) who had previously collaborated in writing invited chapters for a book on tropical plantation forestry - a joint project between CSIRO, ACIAR and CIFOR. Discussions indicated a number of similarities (soils, seasonal climate, use of eucalypts etc) which are important in developing sustainable plantations in India and Australia. At this time, CSIRO Centre for Mediterranean Agricultural Research (CCMAR) obtained special funding from the Federal Government to begin new initiatives in agricultural research in southern Australia. As a consequence, research was initiated in 1995 on the sustainable management of eucalypt plantations established on farm land in the south west region. These studies are focussing on silvicultural options available to managers at the critical inter-rotation period of plantation harvest and re-establishment. Many of the issues being researched are equally applicable in Australia and India and the heads of CSIRO Forestry and Forest Products and KFRI agreed that a collaborative research effort could greatly progress this work and benefit sustainable plantation forestry in both countries. Subsequently, a Phase I research proposal, focussing on management of forest nutrition as a critical factor in developing sustainable eucalypt plantation systems, was submitted to ACIAR and accepted in December 1995. Following this Dr O'Connell and Dr Fryer visited KFRI and other possible collaborators in India, and development of the full proposal was initiated.

The problem

Many soils of tropical forest ecosystems are poor in nutrients. Nevertheless, undisturbed natural forests do not usually display symptoms of nutrient disorders, probably because nutrient cycles are in a state of dynamic equilibrium where inputs and outputs of nutrients are in balance and plant demand for nutrients is met by efficient recycling systems - the so-called "closed nutrient cycle" (Zech and Drechsel 1995). Where natural forests are replaced by short-rotation plantations we can expect changes in nutrient storage and cycling processes due to factors such as harvest exports, changed organic matter quality, altered patterns of nutrient inputs and outputs (fertilization, erosion, leaching, volatile losses etc) and modified patterns of organic matter turnover (rates of accession and decomposition of litter and nutrient dynamics in the decomposition sub-system). All of these factors can impact on storage and supply of soil nutrients for plant growth and consequently the sustainability of plantation systems. A number of studies have investigated the effect of monoculture plantations on organic matter dynamics and nutrient cycling (eg Kadeba and Aduayi 1985, 1986; Singh 1982; Sanchez *et al.* 1985). These have usually found changed patterns of organic matter and nutrient storage which in turn result in altered nutrient flux rates. Some studies have suggested that short rotations of some species in plantations will not be sustainable in the long-term (eg Bargali and Singh 1991). Nevertheless, there is clear evidence from research in some temperate plantation forests that prudent management systems, especially those directed at conservation and enhancement of soil organic matter and nutrient status, can not only result in sustainable ecosystems, but that site quality and wood production can be improved over successive crop rotations (Nambiar 1995).

Only limited attention has been directed to devising sustainable plantation systems in the tropics. Additionally, in many regions the high potential for wood production has not been realized. For example, growth rates of eucalypts in parts of India are often low - in the order of 5-10 m^3 ha^{-1} yr^{-1} in tropical SW India. This compares with rates of 30 m^3 ha^{-1} yr^{-1} or more in SW Australia. Improved nutrition has been identified as a critical factor in increasing the productivity of plantations in Kerala to meet the demands of the local pulp industry. Consequently, management of soil organic matter for improved forest nutrition and nutrient cycling are priority areas for research at KFRI. Likewise, continued high growth currently obtained from eucalypt plantations in south-western Australia is dependent on maintenance of soil fertility on ex-pasture sites. This topic has been identified as a key area for research in the CSIRO Centre for Mediterranean Agricultural Research at Floreat Park, Western Australia.

In both regions, rainfall distribution is highly seasonal. Kerala, located between latitudes 8.2-12.8^0 N latitude, has a tropical warm humid monsoonal climate (Menon and Rajan 1989 - Fig. 1). There are two main monsoons. The south-west monsoon, which corresponds with the principal rainy season, starts in early June and extends till November. At the main KFRI research centre at Peechi annual rainfall is 2500 mm, the majority of which falls during June, July and August. This is also the coolest period of the year. The north-east monsoon is relatively dry with only occasional rains and lasts from December to February. The summer season begins in March and continues up to May. The average rainfall for the whole state is 3000 mm (range 2200-3600 mm) spread over a period of about 120 rainy days. Mean atmospheric temperature is 27^0 C (range 20 - 42^0 C) and relative humidity ranges between 64% (Feb-March) and 93% (June-July). Eucalypt plantations in Kerala are located in two broad geographic regions. At lower elevations on the undulating coastal plains *Eucalyptus tereticornis* dominates and accounts for about 60% of the State's eucalypt resource. At higher elevations, on the ranges of the Western Ghats, *E. grandis* is the principal species. We propose to focus our research on these two species, with two sites in the lower elevation regions utilizing *E. tereticornis* plantations and two sites in the high ranges based on *E. grandis*.

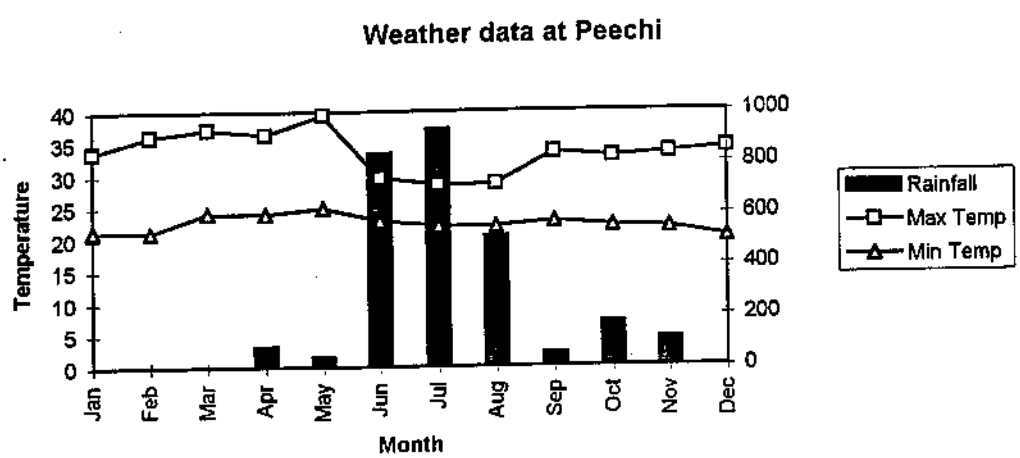


Figure 1. Seasonal variation in temperature and rainfall at the main KFRI research station at Peechi, Kerala.

The climate of the south-western region of Australia is conventionally described as Mediterranean (Gentilli 1989 - Fig. 2). There is a marked seasonality of monthly rainfall and mean maximum and minimum temperatures. The winter months are cool and moist while the summers are hot and dry. About 70 - 80% of annual rainfall occurs in the period May to September. There is a strong rainfall gradient from south-west to north-east from the southern coast and from west to east along the western coast. Maximum annual rainfall of about 1500 mm occurs near the south coast and on the Darling escarpment just south of Perth. Mean monthly temperatures increase from south to north and summer evaporation increases two-fold from the southern coast to the northern extent of jarrah forest near Perth. The extreme seasonal climate of the region exerts a strong influence on the soil microclimate, on biological processes occurring in the soil, and on plant growth (O'Connell 1987; O'Connell and Grove 1987; O'Connell and Rance 1995). Annual rainfall is one of the main factors delineating the area in which production hardwood plantations are established. The principal eucalypt plantation species grown in this region is *E. globulus*. Our experimental framework will include plantations established on different soil types and in areas with high and low annual rainfalls.

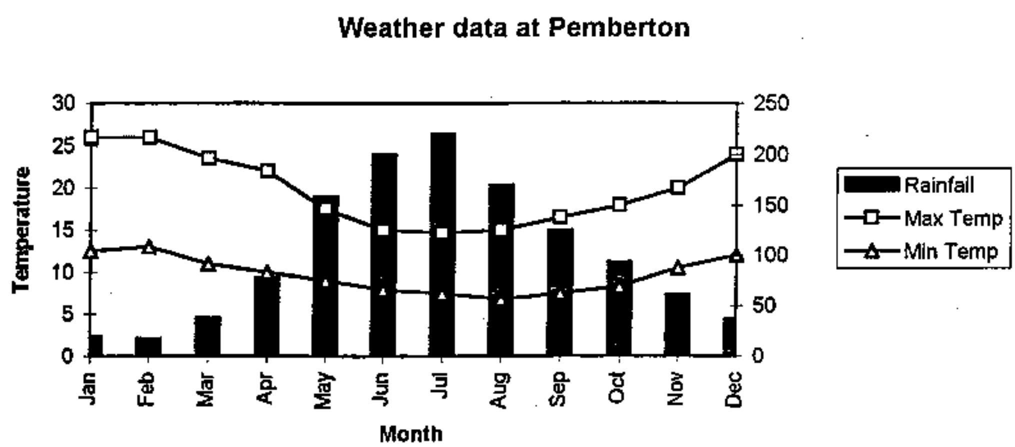


Figure 2. Seasonal variation in temperature and rainfall at Pemberton, within the main *Eucalyptus globulus* plantation region of south western Australia.

At the proposed experimental areas in both India and Australia, availability of soil water will markedly influence the processes which regulate organic matter turnover, nutrient mineralization, nutrient uptake and utilization by trees. Some of the experimental treatments we propose to apply will effect soil water storage and/or tree water use. Consequently, although the primary focus of the research will be nutrition, important aspects of the proposed program will be to investigate the temporal and spatial variation in soil water supply and tree water status and their effect on growth, and to quantify interactions between nutrient cycling processes and soil moisture availability. We intend to link research in the two participating Institutions (CSIRO and KFRI) with the aim of developing methodologies for increasing and sustaining productivity from hardwood plantations in India and Australia.

Significance and priority

More than 43 million ha of plantation forests have been established in the tropics. Eucalypts are the most important species used throughout the region, accounting for about one quarter of the planted area (Brown 1996). Planting of eucalypts has doubled each decade since 1960 and is predicted to reach 16 million ha by the year 2000 (Davidson 1995). Eucalypt plantations are predominantly utilized for short rotation, high volume production of wood products. However, without sound scientific evidence there should be no assumption that this form of land use can continue for long periods without adverse impact on soils and water. Critics, admittedly without much scientific support, are already vocal in condemning eucalypt plantations for environmental and social damage throughout South and South-east Asia. ACIAR, through its forestry research program, has been active in the introduction and domestication of eucalypts in a number of countries, with limited attention to the question of long-term impacts. Research in this field will assist in understanding the processes that limit sustainable production from these plantations, and in designing management systems for optimal production with minimum or no environmental impacts in the long term.

Kerala State has a high population density (750 people/sq.km) and there is an acute shortage of pulpwood and also fuelwood. Consequently, pressures put on the forest resource for wood products are causing severe degradation of the natural forest ecosystems. The government is committed to providing pulpwood for several major industries in the State and hence it is necessary to retain the existing area under eucalypts. This, coupled with the limited land base available for plantation forestry, has resulted in a high priority being attached to increasing productivity of existing plantations. The aim is to maintain the existing pulpwood industries and consequently ensure the security of the jobs of several thousand people. Furthermore, eucalypts and other introduced species may provide the means of rehabilitating large areas of degraded lands, especially if it can be conclusively demonstrated that with appropriate management there are no deleterious effects on soil fertility and that sustained high forest growth rates can be maintained in the long term.

In both India and Australia, plantation forestry is becoming increasingly important for supply of forest products. Rotation times for hardwood pulpwood plantations are similar in both countries - frequently 10 years or less. In India, in particular, there are constraints to increasing the area under plantation forests so that maximizing productivity from existing eucalypt forests and sustaining productivity in subsequent rotations is a priority for research. In Australia, growing eucalypts in plantations is a relatively new undertaking. Developing the methodology to maximize and sustain productivity to enhance the economic benefits of short rotation eucalypt crops is a major challenge for forest managers and researchers.

Current relevant research in Australia and India

A considerable body of research exists in Australia on the interaction between forest management and the functioning of native eucalypt forests (see O'Connell and Grove 1991,1996 for reviews of these studies in jarrah and karri forests of south-western Australia and Attiwill 1991, 1994a,b for general reviews of disturbance and conservative management of eucalypt forests). Likewise, much research has been undertaken on silviculture of softwood plantations, especially relating to management of *Pinus radiata* in the south eastern region of Australia (see Cellier *et al.* 1985; Farrell *et al.* 1986; Smethurst and Nambiar 1990; Bekunda *et al.* 1990; Nambiar 1995). Paradoxically, little attention has been applied to studies of sustainable management of eucalypt plantations in Australia until very recently. In part this reflects the youth of the hardwood plantation industry in Australia. The research initiated in Western Australia during the last year or so (Grove and O'Connell 1995) is currently the most comprehensive study of sustainability issues in eucalypt plantations in Australia. It seeks to quantify the impact of a wide range of silvicultural options on soil and plant functional processes as a basis for defining "best practice" management leading to sustainable wood production. Parts of this work will be incorporated into the proposed ACIAR research.

In India, research on eucalypt plantations has tended to be somewhat fragmentary. At KFRI, research projects have investigated changes in soil under eucalypts (Balagopalan and Alexander 1983; Alexander *et al.* 1981), litter dynamics (Mary and Sankaran 1991), foliar analysis (Sankar *et al.* 1986) and water use (Kallacrackal 1993). However, there have been no integrated studies incorporating a range of plantation management options and no attempts to establish experimental programs that seek to manipulate key factors important to long-term sustainability. Some studies have been conducted in other parts of India, especially Dehra Dun, on effects of organic additions such as hare droppings, rice husks and farmyard manure (Anonymous 1994), but generally these experiments have been conducted in pot culture. Only tree growth was measured and no information is available on how the treatments may have affected soil processes important to sustainable production. The application of these procedures to practical field-based silviculture is also somewhat problematic. We believe the approach outlined in this proposal, in which a range of designed field experiments is used as a framework for integrated interdisciplinary research, provides the best option for understanding at the process level the effects of alternative silvicultural practices. This information then forms the basis, through application and development of existing simulation modelling techniques, for evaluating plantation management in relation to sustained productivity.

Soil nutrient supply and water storage are two site characteristics important in determining long term productivity of plantation forests and they are the primary focus of this proposal. However, other factors such as pathogens and degree of infection with growth-enhancing mycorrhizal fungi will also be critical for survival and growth of short rotation eucalypt tree crops. These topics are the subject of ongoing research in India and Australia. Fungal diseases are particularly important for eucalypts in India. Cylindrocladium leaf blight (CBL - causal agent *Cylindrocladium quinqueseptatum*) and Pink disease (causal agent *Corticium salmonicolor*) have devastated many eucalypts in India, particularly in the nursery establishment stage and the early phase of stand development following outplanting (Sharma *et al.* 1985). Since the mid 1980's an intensive research program has been undertaken at KFRI to overcome these two serious pathogens. Systematic multi-location species/provenance trials of the commonly used eucalypts has led to identification of resistant provenances with more favourable growth rates than previously used seed lots (Sharma 1996). We will utilize these superior disease resistant provenances in our proposed experiments. Extensive research on nursery practices at KFRI has also resulted in specification of disease control protocols for use in nursery establishment and management, with marked improvement in planting stocks (KFRI 1984). These practices will be implemented in our experimental program.

Root infection with mycorrhizal fungi is important to nutrient uptake (principally phosphorus) and growth of eucalypts. Extensive research programs are seeking methods of selecting and managing growth-enhancing mycorrhizal fungi in plantation forests (eg ACIAR Project 9425). In our research we will not apply treatments involving different types of mycorrhizas. However, we will monitor root status especially in nursery plants, to ensure adequate infection of planted seedlings. This approach will be facilitated by two scientists in our research team, both of whom have extensive experience in mycorrhizal research (Dr Grove in Australia and

Dr Sankaran in India). Additionally, we have in our laboratory in Perth one of the world's foremost mycorrhizal research groups, led by Dr Nick Malajczuk, with whom we shall consult regularly. Dr Grove has worked for many years with Dr Malajczuk and has published extensively on the interaction of nutrition and mycorrhizas in plantation forests (see Grove and Le Tacon 1993).

Economic impact

Despite the fact that India has a larger area of planted eucalypts than any other country, the productivity of these stands is often low. In Kerala State annual growth increments range from 5 to 10 m^3 ha^{-1} yr^{-1} . As a consequence, contracts entered into by the Government to supply feedstock to several pulping industries cannot be fulfilled. Furthermore, costs of production significantly exceed returns from harvested wood. We estimate the average negative gross margin on wood production from eucalypt plantations in Kerala to be Rs10,038 ha^{-1}. Increased productivity is the only mechanism to reverse the wood production shortfall and establish a viable economic industry. Increases in production from 43 to 73 t ha^{-1} over a complete rotation are required if supply and demand for pulpwood are to be approximately in balance. Based on this scenario, and using realistic assumptions about costs of silvicultural treatments to improve production, current losses of Rs 53.67 million annually for the whole plantation estate will be reversed to give a small positive margin of Rs 1.08 million $year^{-1}$

Beneficiaries

There is a range of potential beneficiaries in India. Eucalypt plantations are owned by government, private industry, individual land holders or are under communal ownership. Traditionally, forest products have come primarily from natural forest areas. In 1988 the Central Government announced the National Forest Policy which required industrial forest companies to seek a greater proportion of raw materials from farm forest areas rather than from natural forests or state owned plantations. In many areas eucalypts are the major species grown by farmers. Eucalypts are increasingly being grown by farmers in the states of Punjab, Haryana, Gujarat, Maharashtra, Andhra Pradesh, Uttar Pradesh, Karnataka and Kerala (Kumar 1991). Small land holders rely on eucalypts for fuelwood, building materials packing crates and as a cash crop, often pulpwood. Nevertheless, larger government owned plantations still supply the majority feedstock for the three pulp milling industries in the State. If the productivity of these industrial eucalypt plantations can be increased, it will create more employment opportunities for the local people in the pulp industries and in maintenance of plantations. Establishment of nurseries, raising of seedlings, planting, weeding and harvesting operations will provide additional employment and an increase in income for the general population.

Framework for research

In the Asia-Pacific region the extent of closed natural forests decreased from 325 million ha in 1980 to about half this value by the mid 1990's and is projected to decline further to 30-35 million ha in another decade (Nambiar and Brown 1995). Concomitant with this trend, growth in population and rapid economic expansion in the region have resulted in an escalation in demand for industrial wood products and fuelwood. Increased supply of wood from plantation forests has the potential to reduce pressure on natural forest resources as well as contributing to environmental care and economic advancement for landholders in the tropics. As a consequence the area of tropical plantations has increased from about 1 million ha during the 1950's to more than 40 million ha currently. Recognition of the growing importance of plantations forests for wood production in the tropics has led to the Centre for International Forestry Research (CIFOR) initiating a partnership research project *Site Management and Productivity in Tropical Plantations* (SMPTP). This project proposes establishment of at least five experimental sites throughout the tropics. The common goal of research at these locations is to evaluate impact of soil and site management practices on productivity of successive rotations of plantations with the aim of developing management strategies for maintaining or increasing productivity.

The CIFOR proposal focuses on site and soil impacts during harvesting and the inter-rotation phase of plantation management for a number of tropical tree species. Collaboration with CIFOR in research into sustainability of plantations gives a logical balance to the ACIAR forestry program by addressing this obvious and important question. Our intention is to utilize the CIFOR framework to investigate inter-rotation site management options in eucalypt plantations for part of the research program we propose. This, and associated experiments on established stands, will form the basis for collaborative research between CSIRO Forestry and Forest Products and Kerala Forest Research Institute on sustainability of eucalypt plantations. The project would utilize expertise available in both institutions. In particular it will draw on research currently being supported by the CSIRO Centre for Mediterranean Agricultural Research (CCMAR) on *Maximizing sustainable production from eucalypt plantations in south-western Australia*. This research priority has recently been recognised through allocation of Industry Statement Funds by the Australian Government to CCMAR. KFRI also has a strong commitment to research aimed at understanding impact of plantations on site properties and has four senior soil scientists working on this and related topics.

Commitment to implement research outcomes

Kerala Forest Department has the responsibility for establishing and maintaining the majority of the State's eucalypt plantations. Officers of the Department would have a primary role in application of research outcomes. We have held discussions with the Chief Principal Conservator, Kerala Forest Department, on the prospects for improving plantation productivity through a collaborative effort between CSIRO and KFRI. The Conservator has confirmed to us his support for the project, the need for the research and the fact that implementation of outcomes would be given a high priority by his Department (letter of support attached). We have also held discussions with the Managing Director of Hindustan Newsprint Limited, the largest eucalypt pulpwood manufacturer in the State, and received similar expressions of support.

CSIRO - experience and advantages

CSIRO Forestry and Forest Products has its headquarters in Canberra and regional stations in Perth, Hobart, Mount Gambier and Melbourne. The research group in Perth is attached to the Hardwood Plantations Program and its scientists have extensive expertise in a wide range of nutritional aspects of forestry including soil science, nutrient cycling, plant nutrition, plant symbiotic relationships and growth modelling and water use. The group possesses a unique skills base, especially in the area of process-based studies, which can be applied to solving problems of plant nutrition common to plantation forestry in both India and Australia. During the past 15 years the Division has conducted ground-breaking research on site improvement and productivity enhancement of *Pinus radiata* plantations. Much of this work has involved strategies for conservation of soil organic matter through silvicultural practices applied at the inter-rotation period. More recently, the Division has initiated the first integrated approach to second rotation site management of eucalypt plantations in Australia. We will incorporate parts of this research conducted in Western Australia into the proposed ACIAR project.

The Division has had a long standing collaboration with ACIAR and has participated in many research projects in South Asia, South East Asia and Africa.

2.2 Economic Significance

In the face of a rapidly escalating world population, increasing pressure on land resources and a declining area of natural forests, sustainability of production systems is becoming an increasingly relevant issue globally. In the tropical Asia-Pacific region alone, the area of closed forest has declined by almost 50% during the last 15 years and the rate of exploitation of these resources continues at a rapid rate (Nambiar and Brown 1995). This comes at a time when there is growing public pressure to limit harvesting of natural forests in many parts of the world. Sustainable plantation systems provide an attractive alternative for supplementing long-term supply of forest products in both tropical and temperate regions of the globe. Devising silvicultural systems which allow sustainable production from intensively managed man-made forest ecosystems is one of the most pressing issues facing landholders, plantation managers and land management authorities in the 1990's. Our proposal seeks to address this problem through development of a scientifically based package of inter-rotation forest management practices aimed at increasing and sustaining productivity of eucalypt plantations in India and Australia.

India is the world's largest grower of eucalypt plantations in terms of land-base. About 25% of the country's plantation estate is devoted to eucalypts. The total area planted to eucalypts is 4.8 million ha (Davidson 1995). Comparative figures for other countries are Brazil 3.6 million ha, China 0.67 million ha, South Africa 0.54 million ha, Vietnam 0.25 million ha, Argentina 0.24 million ha, Morocco 0.2 million ha and Australia 0.14 million ha.

Kerala Forests Department and Kerala Forest Research Institute have identified nutrition as a primary factor limiting eucalypt growth in the region. Studies have indicated that both macro and micro nutrient status of soils limit growth of eucalypts in Kerala (Singh *et al.* 1988; Madhaven Nair *et al.* 1986). Furthermore, soil fertility has been shown to decline with successive rotations of eucalypts (Balagopalan 1992; Balagopalan and Jose 1983). Existing information suggests that there is a great potential for enhancing plantation productivity through appropriate management of site nutrients. Although some exploratory fertilizer experiments have been conducted in various parts of India, there is a dearth of detailed scientific studies at the process level which allow results to be generalized and few procedures have been advanced to ameliorate soil fertility decline under plantation forests. Realization of this objective requires a detailed understanding of practices affecting conservation and utilization of plant nutrients, including management of native nutrients via soil organic matter, use of ground vegetation and cover crops to enhance soil organic matter characteristics and reduce erosion losses, and the role of nutrient applications. Improved silvicultural practices based on this knowledge provide the means for enhancing productivity and economic returns from eucalypt plantation forestry.

A major positive contribution of eucalypts is in reducing exploitation of indigenous species for firewood and construction, thus preventing denudation of natural forests. For example, in Karnataka State, eucalypts constitute more than 50% of firewood burnt (Venugopal 1988). In

Gujarat State, 27 million poles are used annually for construction and repair of houses (Sunder 1995). In Kerala, demand for wood is about 15 million t yr^{-1}, about 20% of which is for industrial requirements (Krishnankutty 1990). There is a shortfall of about 2 million t yr^{-1} of production relative to demand. For the whole of India, total annual demand for fuel wood is 306 million m^3 yr^{-1} and for industrial wood 32 million m^3 yr^{-1} compared with production of only 40 million m^3 ha^{-1} yr^{-1} and 12 million m^3 ha^{-1} yr^{-1}, respectively (Kumar 1991). Increasing production from eucalypt plantations and greater use of eucalypts on small land holdings are avenues for redressing this imbalance. Growing eucalypts on farmlands also enhances employment opportunities, improves living standards for the local people and reduces adverse impacts on natural forest ecosystems.

The other major user of eucalypt wood is the paper industry. The Indian paper industry currently has an installed capacity of 2.7 million t yr^{-1} and this is expected to rise to 3.6 million t yr^{-1} by the year 2000. Supply of bamboo, a common feedstock for paper mills, is dwindling and availability of other raw materials such as eucalypt wood will be critical for future requirements of the industry (Maheswari and Jivandra 1988). However in many areas the productivity of eucalypts is low and declining and plantations are unable to meet demands of industry for mill feedstocks (Sunder 1995). In Kerala, demand for wood pulp is currently about 0.3 million t yr^{-1} , only about one third of which can be met by eucalypt wood production. Increased productivity from eucalypt plantations will help the Government reduce this shortfall. Although the majority of the plantation estate is still owned by the government we anticipate that benefits from our research will also flow to the private sector and small land holders. All research outcomes will be made freely available through rural extension and other means and thus will provide benefits to a broad cross section of community interests. If it is possible to demonstrate that growing eucalypts is profitable and that it does not lead to adverse effects on soil, farmers as well as private industry will be encouraged to establish plantations and small wood lots for pulpwood as well as for fuel and other forest products.

In India, eucalypts are grown in a wide variety of edaphic and climatic conditions. Our trial sites will be chosen to represent areas of the tropics and sub-tropics where high seasonal rainfall occurs and where warm and humid climatic conditions prevail (Fig 1). Outcomes from research in Kerala will be directly applicable to other areas in India such as in the States of Karnataka; Tamil Nadu, Andhra Pradesh and Maharashtra (Fig. 3) as well as more widely in areas having tropical warm and humid climates such as Sri Lanka, Malaysia, Indonesia, Philippines, Thailand and Vietnam. Additionally, we will link with similar research being proposed under the CIFOR network. Currently it seems likely that complementary studies will be undertaken in China, the Congo, Sabah, Sumatra, Queensland and possibly Brazil. Furthermore, although our experiments will be undertaken in eucalypt plantations, the general principals of our research will be applicable to other species grown in short rotations tree cropping systems.

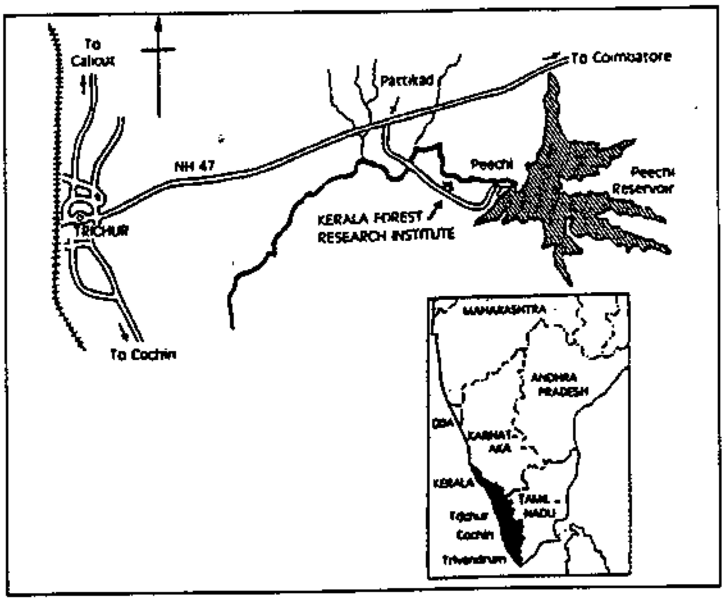


Figure 3. Kerala Forest Research Institute and surrounding regions and Kerala State in relation to adjacent areas in India (inset).

Australia has a large trade deficit in forest products (more than $1 billion annually), a substantial part of which results from import of pulp and paper products. Production of pulpwood from eucalypt plantations has the potential to redress this position through import replacement and possible enhanced export earnings. Plantation eucalypt forestry is a relatively new industry in Australia, and south-western Australia and Tasmania appear to be the regions best suited to this enterprise (Fig. 4). Eucalypt plantations are primarily developed in Australia by industrial companies with associated wood, pulp and paper processing interests and by individual landholders who supply raw materials for these industries. Additionally, trees are increasingly being planted by farmers for multi-purpose values, including restoration of degraded land and to prevent future environmental problems resulting from wind erosion, salinisation and waterlogging. Eucalypt plantations in south western Australia currently cover more than 50,000 ha and account for about 35% of the total area of hardwood plantations in Australia. This proportion is expected to rise by the year 2000 and consequently the region will be a major national focal point for intensive forestry. By this time about 100,000 ha of predominantly *E. globulus* will be planted in the south-west for production of export woodchips. This is expected to make a substantial contribution to the local economy, boost export earnings, provide new job opportunities and assist in ameliorating land degradation problems. Sustainable plantation production is a key factor in capturing these benefits.

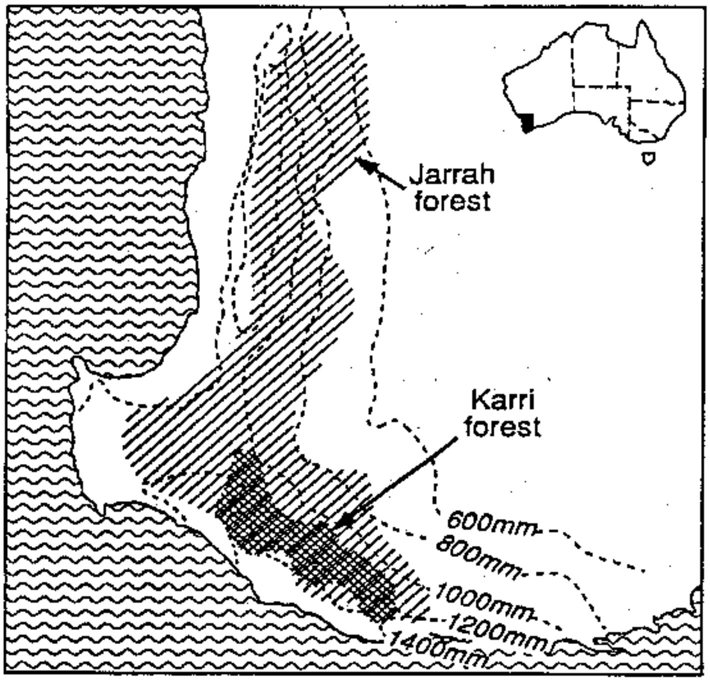


Figure 4. South western Australia showing the forested areas and rainfall isohyets. Eucalypt plantations are mainly located on agricultural land with annual rainfall exceeding 700 mm.

2.3 Literature Review

Eucalypts as plantation species

Tropical plantations cover approximately 43 million ha (Brown 1996). They are dominated by species of *Eucalyptus* which account for about one quarter of the area of tropical plantations. Other species such as *Pinus* spp., *Albizia falcataria, Acacia auriculiformis, Acacia mangium, Gmelina arborea, Casuarina equisetifolia* etc. occupy comparatively smaller areas. India is the world's largest grower of eucalypt plantations in terms of land-base (see Fig. 5 and section 2.2, *Economic Significance*, for comparitive land areas in the major eucalypt-growing countries of the world). Significant plantations of eucalypts have existed in India for more than 150 years. Despite this, productivity from these stands is often low and there have been many vocal critics of eucalypts as plantation species.

In Kerala, large scale planting of eucalypts commenced in the 1960's. Initially eucalypts were grown on marginal lands and in degraded areas. However when the demand for eucalypt wood increased, the Government of Kerala increased the extent of plantations by clear felling natural forests or by growing eucalypts in naturally occurring grasslands at higher altitudes. Clear-felling of natural forests was banned by the Central Government of India in 1982 and thereafter new plantations could only be raised after harvesting existing plantations. Productivity of these plantations is often low (<10 m^3 ha^{-1} yr^{-1}) and declines further in successive rotations. This appears to be to due to low nutrient status of soils and poor plantation management practices (Madhavan Nair *et al.* 1986; Prasad *et al.* 1984 a,b).

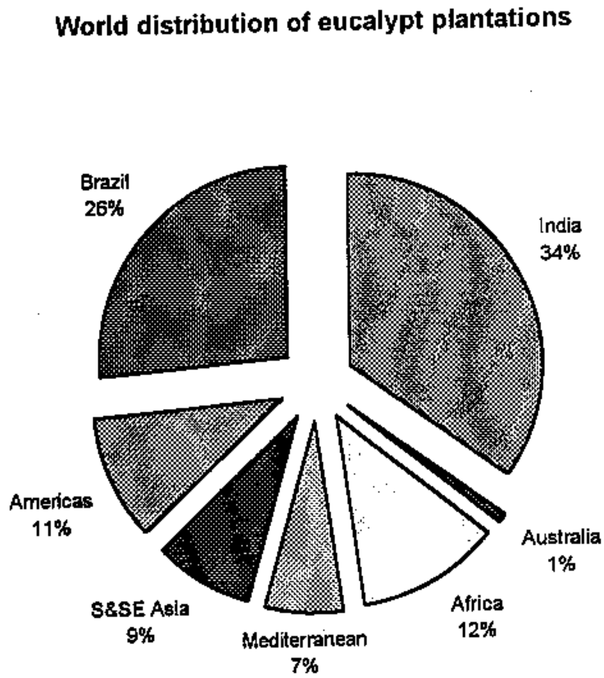


Figure 5. World distribution of eucalypt plantations by area (Davidson 1995). The Americas include North and South America (excluding Brazil). Other countries apart from India in South and South East Asia with significant areas of eucalypts include China, Thailand, Sri Lanka, Vietnam and Indonesia.

In Australia, wood products have traditionally been derived from native forests. More recently, plantations , principally of softwoods such as *Pinus radiata* and subtropical pine species, have become the major source of Australia's manufactured wood products (65% from plantations and 35% from native forests in 1994 - Clark 1995). Use of eucalypts in plantations is a relatively new venture in Australia and there are currently about 140,000 ha established. Tasmania and Western Australia are the main regions and account for 75% of the area planted to eucalypts. However, hardwood plantation forestry is now expanding in all the southern states (Western Australia, Tasmania, Victoria, South Australia) and more recently new initiatives have commenced in NSW and Queensland. Because of the high production rates achieved in eucalypt plantations in Western Australia this region is expected to become a focal point for intensive forestry in the future.

Sustainable plantation production

There is an increasing information base on nutrient cycling in tropical plantations which suggests long-term sustainable production will rely on management practices which maintain soil organic matter, conserve nutrient stores and minimize direct nutrient export and loss by other mechanisms. Reduction in the stores of soil organic matter commonly follows conversion of natural forest to other forms of land use, including plantation establishment (Sanchez *et al.* 1985). Pulpwood, a common product of eucalypt plantations in India and Australia, is a low value, high volume product and the industry is characterised by large areas under short rotation, high volume tree crops. It is this type of plantation management that is most likely to exert excessive demand on the site, and hence it is highly appropriate for studies addressing issues of sustainability. There is critical need for designed experiments which investigate silvicultural options, especially at the inter-rotation phase, in terms of ecosystem functional processes. These studies will provide the scientific basis for quantitative evaluation of plantation management practices. The challenge for researchers is to develop the scientific information base that enables managers to devise silvicultural systems for plantations which enhance soil properties important to sustainable production and minimize deleterious effects associated with short rotation tree crops.

In evaluating the functional aspects of nutrient cycling in tropical plantation forests and in attempting to predict the impact of plantations on the soil environment, it is common to compare the attributes of these man-made ecosystems with those of forests that naturally occur in the same region. Ideally this is best done by following changing land management at the same site over time. An alternative is to make comparisons at one time between adjacent or similar plantation and natural forest areas (Sanchez *et al.* 1985). Studies of the first type are clearly long-term and results for only a few ecosystems are available (Nandi *et al.* 1991; Richter *et al.* 1994). Most comparisons between plantations and natural forests are made by attempting to select comparable plantation and natural forest areas with similar site and soil attributes. In part this may help explain the conflicting views of the impact of exotic species on soil fertility and the differing assessments of the long-term sustainability of short rotation plantations in the tropics.

Declining soil fertility has been identified as the main factor leading to decreased productivity between rotations in temperate plantation forests (eg. Keeves 1966; Morris 1986; Farrell *et al.* 1986; Zen and do Couto 1991). Reduced productivity of second rotation plantations of *Pinus radiata* in South Australia (Keeves, 1966) led to a large research effort to understand and ameliorate the problem. New silvicultural practices with increased rates and frequency of fertiliser application were initially adopted to correct the decline which was largely attributed to loss of N and organic matter (Woods, 1976, 1980). Research over the past decade has shown that retention of logging residues and litter, together with fertiliser application and other silvicultural practices, are the most appropriate methods to maintain organic matter and nutrients in soil and to avoid a decline in productivity in the second and subsequent rotations (eg. Cellier *et al.*, 1985; Farrell *et al.*, 1986; Smethurst and Nambiar, 1990; Bekunda *et al.*, 1990).

Management of site nutrients through organic matter manipulation as discussed above, and other practices such as intercropping of legumes, application of fertilizers and adoption of appropriate silvicultural practices during harvest and the inter-rotation period, are the main options for increasing the productivity of tropical plantations. Herbert, & Schonau, (1989, 1990) have demonstrated that in South Africa, fertilizer application at planting promotes the development of a vigorous root system, providing growth enhancement of up to 11 m^3 ha^{-1}. There have been some studies on the influence of fertilizers on growth of eucalypts in Kerala (Alexander and Mary, 1984; Prasad *et al* 1984ab) although there has been no systematic approach that allows generalizations to be made from research. Consequently, there is little application of fertilizers on a routine basis, either at initial planting of after coppice regeneration following harvest. Likewise, although, it is known that the retention of harvest residues in the forest will enhance nutrient status of soils, no information is available in India on the impact of these practices on productivity of eucalypt plantations. Rather, the common silvicultural management in use in the region includes burning of residues following harvest, a practice which will cause serious decline in soil organic matter levels and the loss of soil stores of plant nutrients.

In south-western Australia, *Eucalyptus globulus* plantations are being grown primarily on soils derived from the erosion of an ancient plateau mantled by laterite soils and the profiles are deep and highly leached (McArthur and Clifton 1975; McArthur, 1991). Consequently, they are inherently low in nutrients and organic matter, and generally contain high levels of iron and aluminium oxides which are strongly reactive with applied phosphorus (Turton *et al.*, 1962; McArthur, 1991; Tennant *et al.*, 1992). Large responses in plant growth have been observed following application of phosphorus and other major and minor nutrients to these soils (Robson and Gilkes, 1980). Despite these factors, high growth rates (often >30 $m^3 ha^{-1} yr^{-1}$) are being obtained in eucalypt plantations established on ex-farm sites. This is largely due to the enhanced fertility of the soils which has resulted from a long history of applications of phosphate fertilisers (McArthur, 1991) together with the accumulation of organic residues from improved legume pastures and crops (Rowland *et al.*, 1988; Mason and Rowland, 1990, 1992). Agricultural research has shown that where fertiliser applications cease, or become less frequent, the fertility of these soils declines markedly within a period of several years (Fig. 6). This is especially so where high-surface area soils react with applied phosphate to reduce concentrations of labile soil P (Barrow, 1980). Likewise, where legumes have been replaced by cropping systems, reductions in productivity have ensued (Fig. 7) due to a reduction in soil nitrogen supply (Tuohey and Robson, 1980; Rowland *et al.*, 1984; see Rovira, 1992). Losses of N by denitrification and leaching (Fillery and McInnes, 1992) and changes in the nature of organic matter pools due to a decrease in nutrient-rich legume residues and an increase in lignified litter from the plantation eucalypts are important processes affecting soil fertility. Sustaining the growth of plantations in future will depend on implementing silvicultural measures to cope with the declining availability of soil nutrients. The period during harvesting and stand re-establishment is a time when significant opportunities exist for site nutrient manipulations as outlined below.

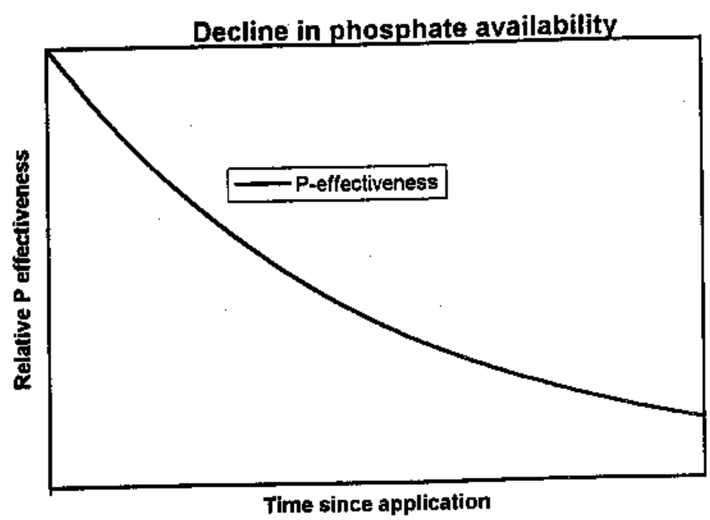


Figure 6. Decline in relative effectiveness of applied phosphate with time since application. Based on data from Bolland and Bowden (1986) for yields of pasture and wheat in different years following fertilizer application.

Options for plantation silviculture

Maintaining and enhancing site fertility is crucial for sustaining long-term productivity of short rotation plantation forests. A minimum requirement on all sites is that nutrients removed in wood during harvesting or lost as a consequence of other silvicultural practices should be replaced either through accessions from natural inputs, as inputs from fertilizers or by other means such as through inter-row legume cropping or application of mulches. Removal of harvest residues either manually or by fire is a common practice in many plantations in India and burning is also used in Australia for site preparation prior to planting. Both residue removal and fire have the potential to accelerate site fertility decline through soil organic matter and nutrient loss. Fire causes immediate volatile losses of some nutrients, especially N, and can create conditions where further loss may result through run-off, leaching and erosion. In some temperate forests regular fire has also been shown to reduce biological mineralization rates of elements such as N (Raison *et al.* 1993). Application of inorganic fertilizers will be necessary to maintain sustainable production from many tropical plantations. These practices can influence the nutrient flux rates, especially in litterfall and mineralization through organic matter turnover (O'Connell and Grove 1993; O'Connell 1994). However, the impact of fertilizer additions on nutrient cycling processes in tropical plantations has been little studied.

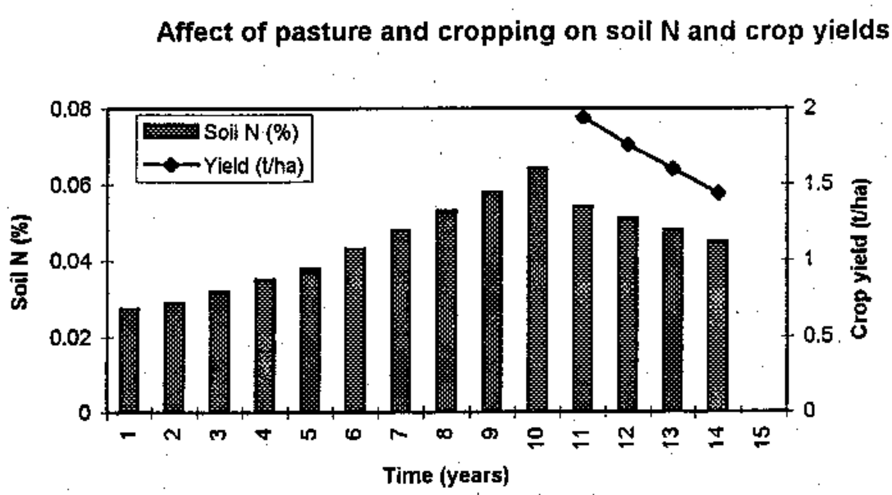


Figure 7. Changes in soil N content after 10 years pasture and 4 years cropping and declines in crop yield with continuous cropping (based on Rowlands *et al.* 1984).

A range of options is available to forest managers to conserve soil organic matter and reduce nutrient drain and perturbations to nutrient cycling processes especially during the inter-rotation period. Harvesting practices which are designed to retain nutrient-rich components of slash residues and the accumulated litter on the site following wood removal will assist nutrient conservation. This can be achieved through debarking of wood in the field and retaining the leaves and small branches at the felling site, minimizing soil disturbance, restricting use of fire in site preparation, protecting accumulated forest floor litter and harvest residues and encouraging rapid revegetation of the site to reduce erosion and leaching losses. Impacts of these and related management practices on soil nutrient stores, nutrient cycling processes and tree nutrient supply have been investigated in temperate forest plantation systems such as *Pinus radiata* (Smethurst and Nambiar 1990) and similar experiments have recently been established in *Eucalyptus globulus* plantations (Grove and O'Connell 1995). However no comprehensive research of this type has been reported for tropical eucalypt plantations.

Inter-row cropping with leguminous species provides an option for maintaining soil organic matter, soil nitrogen and enhancing tree growth. For example Nambiar and Nethercott (1987) found an increase in stem growth of *Pinus radiata* when lupins were grown as an intercrop in plantations. Leguminous cover crops are capable of fixing atmospheric nitrogen and enriching the nitrogen content of the soil through root exudates, while decomposition of nitrogen rich litter increases the nitrogen content of soil (O'Connell, 1986). Cover crops also improve the microclimate in the plantation, acting as a mulch capable of retaining moisture and provide a more conducive environment for litter breakdown and nutrient turnover (Wilson & Ludlow, 1991; Wilson and Wild 1991). Cover crops suppress weed growth which in turn can help in reducing pest and disease problems in the plantation. The main environmental limitation to growth of cover crops in plantations is the reduction in photosynthetically active radiation (PAR) incident to the understorey canopy. Competition for water between the trees and cover crops may also induce tree water stress and limit plantation growth (Nambiar and Sands 1993). Identifying suitable ground cover species for use in tropical plantations and quantifying their impact on soil fertility, soil water storage, tree water status and tree growth is a priority area for research.

From recent unpublished research in Western Australia we have found that it is possible to establish annual legumes (faba bean, lupin, field pea, vetch and latherus) in eucalypt plantations. The extent of reseeding and persistence into further rotations is as yet unknown but there is some expectation of continued restablishment in the early years of stand development.

Weed control has been found to be one of the most critical issues for tree survival and early growth in plantations in Australia, primarily because weeds compete with trees for nutrients, PAR and water. In India, experiences from the horticultural and rubber plantations also indicates that weeding can greatly enhance yield. However there have been no studies in India on the effects of weeds in eucalypt plantations. *Chromalaena odorata, Lantana camara, Mikania micrantha* and grasses are the most common weeds in eucalypt plantations, and they compete for light and suppress seedling growth during the juvenile stage of a plantation. All these species, especially *Mikania micrantha* - a gregarious climber, pose a threat to plantations. *Mikania,* in particular, is now widespread in India (Choudhury, 1972). *Chromalaena* is another noxious weed long established in various parts of India in open land, plantations and natural forests (Biswas, 1934). Evaluation of the impact of various strategies for weed control is likely to lead to significant gains in survival and early growth in eucalypt plantations in India.

Water stress has been identified as one of the factors limiting growth of eucalypts in Kerala (Kallarackal & Soman 1996). In part this is caused by the marked seasonal climate (Fig. 1) and the hilly terrain which can result in surface run off between 40 and 80% of incident rainfall (James and Mohan 1986). Contour trenching, in which trenches are spaced according to the slope of land, is a relatively inexpensive method of increasing infiltration rates and soil water recharge. Trenching has been used in rubber plantations and in these systems has been shown to raise the level of the ground water table (Mathew, 1987). However, it has not been evaluated in eucalypt plantations in India or elsewhere. It is expected that this method will reduce the water stress presently suffered by eucalypt plantations and it may also assist in conserving soil and nutrients by reducing overland flow during periods of heavy monsoonal rain and thus enhance productivity of plantations. Other treatments such as inter-row cropping, retention or removal of harvest residues and fertilizer applications (especially nitrogen additions), will also affect soil moisture storage and tree water relations. Response of growth to these treatments provides the ultimate measure of their effectiveness. However detailed knowledge of the underlying mechanisms is also valuable and provides the understanding necessary for extrapolating research results more widely. A range of plant physiological parameters such as tree water relations, photosynthesis, stomatal conductance and leaf area index development are available and have been used in the study of water use by eucalypts in Kerala (Kallarackal 1993). Coupled with responses in soil water storage, these methods provide a powerful set of tools to evaluate response of trees to imposed silvicultural treatments.

Each of the silvicultural options mentioned above has the potential to affect the stores and flux rates of plant available nutrients in eucalypt plantations. This will be especially so when combined with nutrient management through fertilizer additions. Some silvicultural practices will also impact on soil water storage and plant water status. Both nutrient status and supply rates and soil and tree water status will be critical for tree growth and, in the longer term, the sustainability of plantation systems. In Kerala and south-western Australia, the major nutrients limiting growth are nitrogen and phosphorus. Management of the stores and flux rates of these nutrients and soil organic matter is the focus of this proposal. Below we review some of the critical processes relating to soil organic matter status and cycling of nitrogen and phosphorus as they relate to intensively managed eucalypt plantations in India and Australia. We also outline plant physiological measures important in evaluating responses of soil and plant water status to applied silvicultural treatments.

Nutrition and nutrient cycling

The primary factors controlling forest productivity are energy, water and nutrient supply. In natural forests, nutrient requirements for growth and maintenance are met through nutrient cycling. Switzer and Nelson (1972) identified three processes of nutrient cycling, namely (i) geochemical cycling in which nutrients are supplied from weathering of soil minerals and through input from the atmosphere or are lost in volatile forms or through drainage; (ii) biochemical cycling where nutrients are redistributed within the plant to meet demands for growth; and (iii) biogeochemical cycling in which nutrients released from plant residues or through canopy leaching or stemflow enter the soil and then are taken up by the plant roots. Each of these processes can be affected when current land use is replaced by short rotation tree cropping. In most natural forests and plantations, biogeochemical nutrient cycling is dominated by litter production and decomposition. Litter from both above and below ground sources is important in these processes.

Plant residues accumulating on the forest floor disappear as a result of various processes. Soil fauna consume and fragment the litter and incorporate it in the surface layers of the soil. Water soluble compounds are leached from the residues and carbon is mineralized and respired as CO_2 through the action of micro-organisms. The importance of each process depends on the nature of the plant residues, on the micro-environment at the soil surface and on the qualitative and quantitative composition of the decomposer organisms (Swift *et al.* 1979). During litter breakdown, release of plant nutrients occurs principally through microbially-mediated biochemical reactions. Mineralized nutrients are available for uptake and re-use by the plant community. Nutrients may also be immobilised in the microbial biomass or by reactions with soil minerals or be lost from the ecosystem through leaching or in volatile forms.

Many native tropical forests grow on sites with highly weathered soils having low nutrient status. The fact that these forests can attain such stature has been attributed in part to mechanisms they have evolved to acquire and conserve nutrients (Golley 1983a,b). Nutrient cycling in many undisturbed ecosystems, exemplified by rates of annual nutrient uptake and retranslocation, return in litterfall, litter accumulation and decay and nutrient mineralization in the litter layer and surface soil, is in a state of dynamic equilibrium. Functioning of short rotation plantations (eg. 8-10 year pulpwood systems) differs in two important respects from that of natural forest ecosystems. Firstly, rates of nutrient cycling often do not reach dynamic equilibrium during the lifetime of the plantation and secondly, nutrient cycling in plantations is markedly affected by intensive management practices. These two factors will be critical in determining rates of biomass productivity and the long-term sustainability of the plantations. Furthermore, in areas of high rainfall where native tropical forests are cleared and replaced by other land uses, immediate and severe losses of plant nutrients and soil organic matter are likely (Nye and Greenland 1964; Herrera and Jordan 1981; Tiessen *et al.* 1994). Similar processes can occur when successive rotations of plantations are harvested.

In terms of nutrition and nutrient cycling, the focus on eucalypts in tropical plantations is important, because species of this genus often have higher nutrient use efficiencies (NPP per unit of nutrient uptake - Bargali and Singh 1991; Binkley 1992; Binkley *et al.* 1992) and litter that is poorer in nutrients (Lugo *et al.* 1990a,b; Wang *et al.* 1991) than other plantation species and natural tropical forests. These characteristics in turn affect the quality of detrital plant residues, rates of residue decay, accumulation of forest floor biomass, the quantity and quality of soil organic matter and the rates of nutrient cycling through biochemical and biogeochemical pathways. The consequences for sustainable production of these changes in ecosystem characteristics and functional processes remain largely unexplored in both tropical and temperate climatic regions.

Litter turnover

Rates of forest floor accumulation in plantation forests can differ markedly between species planted on the same site. In general, species of eucalypt, pine and casuarina accumulate more litter compared to many other plantation species and many natural tropical forest species. Large accumulations under eucalypt plantations have been found in several countries eg in Australia (Bradstock 1981), the Congo region (Bernhard-Reversat 1993) and India (Singh *et al* 1993; Toky and Singh 1993). Amounts of accumulated forest floor litter are determined by the balance between rates of litterfall accessions and rates of litter decomposition. Rate of litterfall in plantations depends on species, stand age and growth rate and can be similar to, greater than or smaller than in native tropical forests. Accumulation of large amounts of litter under some eucalypt plantations appears to be due primarily to slow rates of decomposition of the eucalypt residues.

Decomposition plays a critical role in stand nutrition through its contribution to nutrient cycling and formation of soil organic matter. As decomposition proceeds, part of the carbon content of the residue is respired as CO_2 and some may be leached from the soil. Secondary products of decomposition form the source material for soil organic matter. Following decomposition of surface litter, remaining organic compounds may be incorporated in humus and contribute to the exchange complex of the soil. The rate at which nutrients are released during decomposition can differ markedly between different elements and is influenced by physical and biochemical characteristics of the residues and the heterotrophic demand of the decomposer organisms. As indicated above, decay rates of litter from plantation species have often been found to be slower than for litter from native tropical forests, especially where introduced species such as eucalypts, pines and casuarina are used in plantation establishment (Bargali and Singh 1991; Bargali *et al.* 1993; Kadeba and Aduayi 1985; Swamy 1989; Spain and Le Feuvre 1987; Singh *et al.* 1993; Sankaran, 1993, Sankaran *et al.* 1993). Decomposition rates of litter from endemic species used in plantations are also often slower than for litter in native forests within the same region (Brasell and Sinclair 1983; Holt and Spain 1986). Consequently, replacement of natural vegetation with plantations of both native or introduced species can affect litter decomposition and forest floor accumulation and modify soil organic matter formation and the rate of biogeochemical nutrient cycling.

Patterns and rates of decomposition of slash residues produced during harvesting differ from those of naturally occurring litterfall (O'Connell and McCaw 1995, 1996; O'Connell 1996). This is primarily due to differences in the composition of harvest residues, which consist of fresh plant material, and litterfall which is derived largely from senescent materials. Slash residues normally contain higher nutrient concentrations, especially of mobile plant nutrients such as nitrogen and phosphorus, decay more rapidly and release nutrients faster than normal litterfall (O'Connell and Menage 1983). Thus, large inputs of nutrients to the soil from decaying slash residues can be expected soon after plantations are thinned or harvested. Rapid revegetation of harvested sites will be important in retaining nutrients on the site. This will be especially important for mobile ions such as nitrate, which can accumulate rapidly in soils following clearfelling (see following sections).

Soil organic matter

Organic matter plays a crucial role in plant growth through its effect on the physical, chemical and biological properties of soils (Syers and Craswell 1995). These factors in turn influence soil structure, infiltration rates, water holding capacity, pools of plant available nutrients in soil and the rates of mineralization of organically bound nutrients. Replacement of one vegetation type with a new species, as occurs when plantations are initially established, leads to changes in the nature and level of soil organic matter and other soil properties and processes important to sustainable plant growth. Likewise, within a single vegetation type such as a forest plantation, opportunities exist to manipulate soil organic matter through silvicultural practices. This is especially so where stands are subjected to intensive management over short rotation periods.

Establishment of plantations on land previously utilized for other purposes (natural forest, agriculture, grasslands etc) may affect carbon allocation, the partitioning of organic matter within ecosystem compartments such as to litter, roots, and above-ground biomass and biogeochemical nutrient cycling. In some plantations the amounts of nutrients accumulated in forest floor litter are a significant proportion of the biotically active nutrient pool. Lugo *et al.* (1990a) suggest that the greater amounts of litter and the greater ratio of litter to above ground biomass in plantations relative to natural forests is a fundamental difference between these two forest types in the tropics. In some circumstances the accumulation of substantial quantities of nutrients in the litter layer of plantations can act as a storage buffer against nutrient loss. At many sites, conservation of the litter layer during forest management operations, including stand harvesting, will be critically important for maintenance of soil organic matter stores and for meeting the nutritional demands of subsequent rotations (Lugo *et al.* 1990b; Mailly and Margolis 1992).

Although maintenance of soil organic matter (SOM) is widely regarded as being critical for sustainable agricultural and forest systems, few specific measures of SOM that are easily linked to sustainability. Many analytic methods are available to determine physical, chemical and biological properties of the soil organic fraction. Estimates of total soil organic carbon are not very sensitive to short term changes in fluxes of carbon or quality of SOM. Likewise, the numerous separation techniques (chemical, physical) used to fractionate SOM have not been used widely to identify specific organic components as indicators of sustainability. Instrumental methods being developed to characterize SOM provide possibilities for the future, but probably require more fundamental research before results can be widely applied to issues of sustainabilty. Of the various techniques for assessing changes in SOM two approaches appear to be the most attractive of those currently available. Firstly, fractionation of organic carbon based on susceptibility to oxidation by permanganate solutions of various concentrations has been proposed as a method for identifying labile soil carbon (Loginow *et al.* 1987). Recently, these procedures have been extended to provide indirect estimates of organic carbon turnover and indicators of sustainability of agricultural cropping systems (Lefroy and Blair 1994). We will apply these methods to plantation forests to assess the impact of short rotation eucalypt systems on the quality and quantity of soil organic matter. Secondly, soil microbial biomass represents the active pool of soil carbon and has been proposed as an early indicator of changes in soil organic matter and mineralizable nutrients (Powlson *et al.* 1987; Sparling 1992). Mineralization of organically bound nutrients results largely through biochemical reactions mediated by enzymes produced by soil microbes. The microbial biomass thus provides a measure of the active pool of soil carbon. Consequently, we propose to use this and associated assays (microbial-N, microbial-P and ninhydrin reactive N) as measures of changes in SOM.

Nutrient dynamics during residue decay

Three sequential phases occur during mineralization of nutrients from decomposing plant residues: (i) an initial phase when leaching and nutrient release predominates, (ii) a net immobilization phase during which nutrients are imported into the residues by microbes and (iii) a net release phase when the nutrient mass decreases (Swift *et al.* 1979; Staaf and Berg 1980, 1981). However, not all these phases occur for every nutrient and each litter type. Potassium is one of the most mobile elements and a large proportion leaches out during initial phase without immobilization (Lousier and Parkinson 1978, Maclean and Wein 1978, Toky and Singh 1993). Among other nutrients, Ca and Mg are usually more mobile than N and P (Attiwill 1968, Baker and Attiwill 1985) and because they are often associated with cell structures, their release parallels loss in dry weight of the litters. Some Ca and Mg is also mobilized through leaching during the initial phase of decomposition (Ward *et al.* 1991; Maheswaran and Gunatilleke 1988), whereas immobilization of Ca during later stages of decay can occur (Upadhyay 1982, Upadhyay and Singh 1989). Initial release of N and P is followed by an immobilization phase in many types of litters in tropical, temperate and boreal forests (Toky and Singh 1993, Lisanework and Michelsen 1994, Wood 1974, Vitousek and Sanford 1986). The relative increase in N and P in decomposing litters is caused by non-symbiotic N-fixation (Granhall and Lindberg 1977), uptake from surroundings by fungal hyphae growing in litter (Berg and Soderstrom 1979), atmospheric precipitation or deposition of insect frass and plant material from the canopy. Different patterns of mobility and mineralization of nutrient elements during decay are due to variations in carbon to nutrient ratios, nutrient requirements of decomposer organisms, resource quality, availability of nutrients from soil, the physical environment and its effect on decomposer organisms.

Studies of nutrient dynamics during decomposition in temperate forests have focussed on release of N and its relationship to chemical characteristics of the decaying plant residue (Aber and Melillo 1982; Berg and Staaf 1980; Gholz *et al.* 1985; O'Connell 1988; Aber *et al.* 1990). Litter properties most useful in predicting nutrient dynamics are initial N concentrations and biochemical properties such as lignin and polyphenol content. Less data are available for tropical plantations and these are mostly based on incubation experiments. Palm and Sanchez (1991) compared N release from leaf materials of tropical legumes and concluded that polyphenol content of the plant residues was a better predictor of N dynamics than lignin or N content. In a greenhouse experiment (lignin+polyphenol):N ratio was the best predictor of N mineralization from 6 types of legume residues (Fox *et al.* 1990). Using a wider range of residues from legumes and non-legumes, Constantinides and Fownes (1994) reported that initial N content of the materials was the variable which best predicted release or accumulation of N. Other properties such as lignin:N ratio and (lignin+polyphenol):N ratio were also significantly related to N dynamics. These studies differ in their conclusions regarding the factors controlling immobilization and mineralization of N, probably because of the differing chemical composition of the residues and the differing experimental procedures used.

The interaction of litter quality and nutrient mineralization, as described above, can influence synchrony of supply and tree demand of nutrients in managed ecosystems. Marked pulses in amounts of nutrient available for plant uptake (Lodge 1987; Lodge *et al.* 1994) can occur in seasonal climates where moisture becomes an important factor regulating litterfall and decomposition. This phenomenon commonly occurs in seasonally dry tropical and temperate climates as found in Kerala and the Mediterranean regions of southern Australia. It is due to the interaction of factors affecting rates of litter accession, decomposition and nutrient mineralization. During periods of water stress, litterfall rates can be high and decomposition low. The onset of the wet season accelerates decomposition and releases available nutrients (Swift *et al* 1981). Furthermore, wetting and drying cycles can accelerate the mineralization of labile nutrients such as those stored in microbial biomass, and also increase turnover rate of more recalcitrant and protected organic pools of litter and surface soil (Cabrera 1993; Van Veen *et al.* 1984). Myers *et al.* (1994) suggest that manipulation of mineralization rates through mixtures of plant residue with varying qualities could form the basis of practical management systems for efficient use of nutrients and for minimizing losses. Undercover crops of legumes provide one option for manipulating organic residue quality. These management practices are used routinely in many rubber plantations (Myers *et al.* 1994) and have also been applied in temperate conifer plantations (Gadgil *et al.* 1984; Nambiar and Nethercott 1987). We propose to incorporate experiments to test the impact of legume cover crops on organic residue quality, soil nutrient supply rates and tree growth rates in eucalypt plantations in both India and Australia.

Soil nitrogen supply

Growth of many natural and plantation forests is limited by nitrogen supply. In natural systems, and in most man-made forests also, the majority of N available for plant growth is derived from mineralization of organic residues through biochemical reactions mediated by the soil microbial population. In managed forest systems a knowledge of N supply rates in relation to tree requirement for N is critical for maintenance of maximum tree growth through appropriate fertilizer regimes. The ability to predict N supply rate and relate this to tree requirements for optimum wood production will also allow more conservative approaches to fertilizer management which avoid nutrient loss and adverse environmental effects. Three general schemes are available for assessing the N status of sites, namely (i) soil index of N such as the pool of mineral N in soil at a specific time of year or the amount of potentially available N derived through laboratory incubation (Maimone *et al.* 1991; Keeney and Bremner 1966), (ii) a direct field measure of N mineralization using *in situ* sequential incubations over an extended time period (Binkley and Matson 1983; Raison *et al.* 1987), and (iii) model simulations of rates of N mineralization (Van Veen *et al.* 1984; Goncalves and Carlyle 1994; O'Connell and Rance 1995). The first method is relatively simple but provides only an index of N status rather than a quantitative estimate of the annual supply rate of N for tree growth. The second method does provide a measure of N flux rates which can be related to seasonal requirements for plant uptake. However, these procedures are often impractical for normal forest management purposes because they require intensive soil sampling over an extended period. Simulation modelling is an attractive alternative to direct measurement of N mineralization provided the input data required for the model can be obtained readily.

Rate of mineralization of organically bound nitrogen depends on soil environmental factors, principally soil moisture and soil temperature, and soil chemical and physical factors which determine the potential supply rate of mineralizable nitrogen. Rates of N mineralization increase exponentially with temperature and logistically with soil moisture (O'Connell and Rance 1995 - Fig 8). Environmental data can be measured directly in the field, derived from historical meteorological records or predicted by simulation models. Soil chemical and physical parameters important in determining potential rate of mineralization are organic matter content and quality, total nitrogen store, particle size distribution and soil water holding properties. Various other measures of the available soil nitrogen pool have also been utilized, including the nitrogen content of the microbial biomass, and mineral nitrogen produced during laboratory incubation, by chemical extraction or following autoclaving of soil. These state variables can be combined with soil environmental data in model simulations to predict seasonal patterns of nitrogen mineralization and annual nitrogen supply rates. (Fig. 9). We will use these procedures to assess the nitrogen supplying capacity of soils and to provide a measure of the impact of the experimentally applied treatments on nitrogen flux rates.

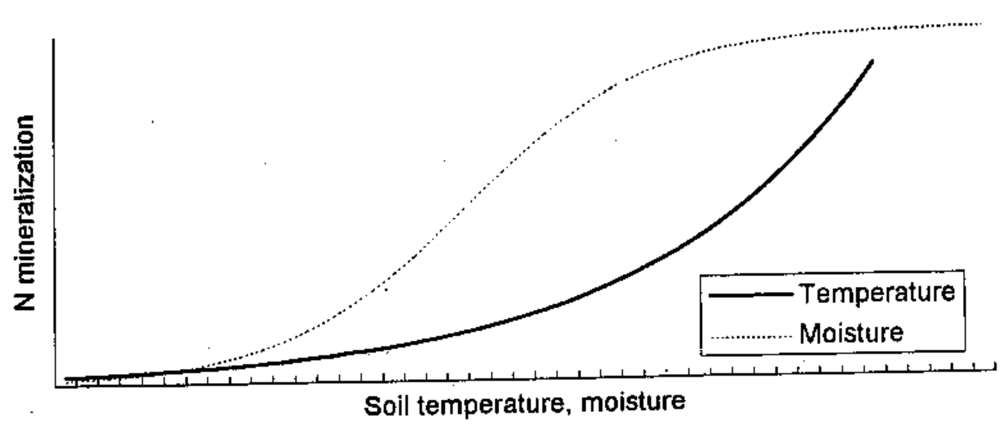


Figure 8. Response of rate of soil nitrogen mineralization to variation in soil temperature and soil moisture (from O'Connell and Rance 1995).

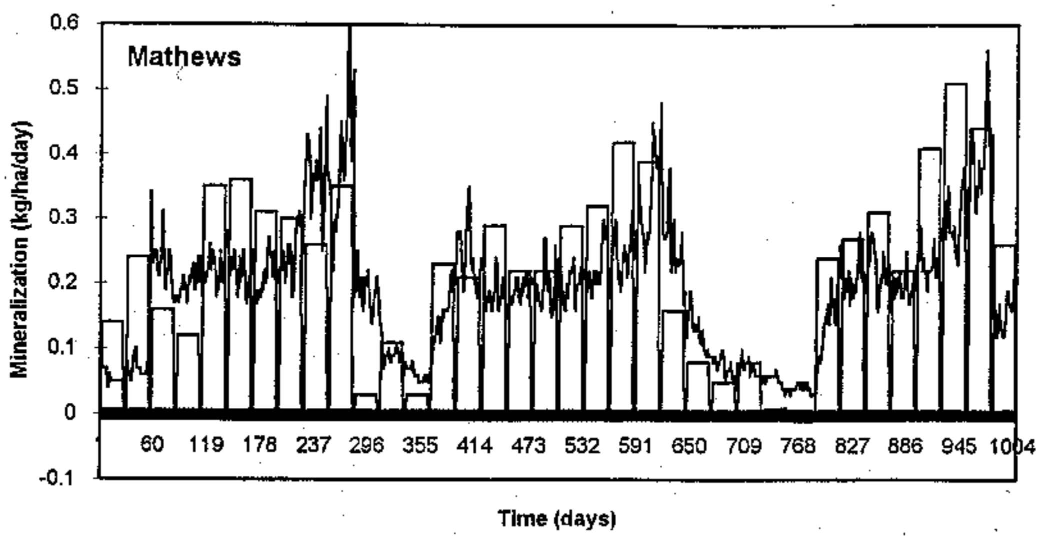


Figure 9. Simulation of seasonal pattern of nitrogen mineralization over three years in a *Eucalyptus globulus* plantation growing in the Mediterranean environment of south western Australia (O'Connell and Rance 1995). Histograms show observed rates of N mineralization, continuous line shows daily model-predicted rates of mineralization.

In many natural eucalypt forests, soil mineral nitrogen occurs predominantly in the ammonium form with only small amounts of soil nitrate present (Hingston *et al.* 1989). In part this may be due to relatively high C:N ratios of eucalypt litter and low mineralization rates. Our data (Aggangan and O'Connell - unpublished) also suggest that soluble extracts from eucalypt litter may directly affect mineralization processes. In laboratory incubation experiments in which *Eucalyptus globulus* leaf litter was added to a highly nitrifying pasture soil, N mineralization rates were reduced and nitrification was almost completely inhibited (Fig. 10). Microbial immobilization, bacteriostatic effects or denitrification are probable mechanisms for these effects. Thus, where land use change occurs, such as when eucalypt plantations are established in areas previously utilized for agriculture or for natural forests, soil processes important in regulating nutrient supply rates are also likely to be affected. Depending on the time scale of these changes, productivity of the current or future rotations of tree crops may be influenced.

Following harvesting of plantations, N mineralization rates usually increase and the patterns of mineralization and nitrification also change. Mineralization rates are also markedly affected by the management practices used to treat harvest residues (Smethurst and Nambiar 1990). Nitrification usually increases, probably because of changes in soil microclimate and accumulation of ammonium due to reduced plant uptake. These effects increase the potential for nutrient loss through leaching and denitrification. Elevated levels of labile soil carbon, probably derived from leaching of harvest residues, increases the possibility of denitrification losses. Our studies in *E. globulus* plantations show large accumulations of nitrate following harvesting of the first rotation of trees (Grove and O'Connell 1995 - Fig 11). Nitrate levels decline following the onset of winter rains and the rate of decrease varies with the method of harvest residue treatment. Significantly, greatest rate of decline in nitrate is associated with the highest level of slash residue accumulation suggesting denitrification may be an important process for N loss in the initial period following harvest. We intend to investigate potential for denitrification in relation to harvest management practices using stable isotope techniques recently developed at Griffith University (Avalakki *et al.* 1995a,b).

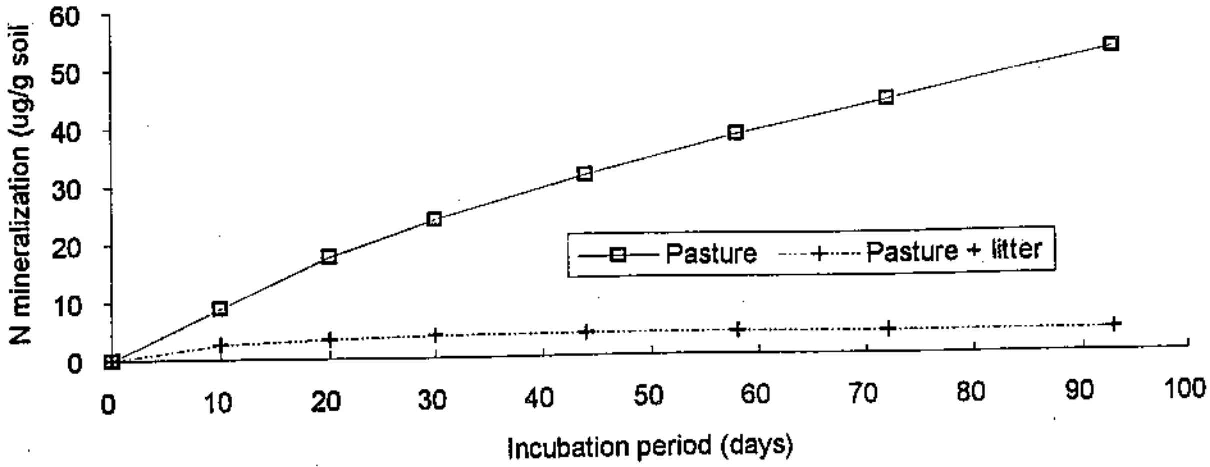


Figure 10. Cumulative net nitrogen mineralization during laboratory incubation of pasture soil and pasture soil to which eucalypt litter has been added. Data from Aggangan and O'Connell - unpublished.

Soil phosphorus supply

Measurement of soil phosphorus status and the flux rates of inorganic soil P available for plant uptake is much more problematic than similar measures for nitrogen. Consequently, a different approach is required in determining the longer-term impact of eucalypt plantations and silvicultural practices on soil phosphorus supply and the phosphorus nutrition of stands. In addition to biological processes (mineralisation, immobilisation), soil P supply is strongly moderated by reactions of inorganic P with mineral surfaces (Barrow 1980) and by effects of the rhizosphere and mycorrhizal fungi on these reactions and P uptake. Furthermore, the proportions of different forms of P in soil (inorganic, organic: labile, non-labile) vary between forest and soil types and can change markedly with forest operations (eg burning). It is not currently feasible to determine stores and flux rates of soil P as a direct estimate of P uptake by the tree, as is being attempted with N mineralisation studies. Greater emphasis will therefore be given to identifying measures of soil phosphorus which relate to P uptake and to P limitations to tree growth and which can be used as sensitive indicators of changes in soil P supply. The retention of P by soil is also greatly dependent on soil mineralogy, and other soil properties such as pH, so that a major thrust of this work will be to relate P supply to site characteristics. The approach will be to measure soil P availability in terms of capacity and rate factors (Dalal and Hallsworth 1976). This will involve investigating methodologies for fractionation of soil P using of a range of extractants (Romanya *et al.* 1994), resin exchange (Abrams and Jarrell 1992), iron oxide sorption techniques (Menon *et al.* 1990), quantification of soil P fractions (Hedley *et al.* 1982) and P sorption characteristics (Mead 1981; Bolland *et al.* 1996). We propose that part of the ACIAR funding be applied to employment of a Research Officer whose duties will include investigation of soil P status in relation to P supply for plant growth and the interaction of these factors with applied silvicultural treatments. We will work collaboratively with the University of Western Australia Department of Soil Science and Plant Nutrition (Professor R.J. Gilkes) in exploring appropriate methodologies to establish the impact of plantation silviculture on soil phosphorus status in eucalypt plantations. Additionally, we have established links with Dr Pax Blamey (ACIAR Project 9414), who has recently commenced work on his project *Phosphorus for Sustainable Food Crops in Acid Upland Soils*. In the first phase of this work Dr Blamey will explore methodologies for relating soil and plant tissue tests to various pools of P in the soil and plant. He has agreed to make available to us outcomes of his research on establishing methodologies to measure soil and plant P status.

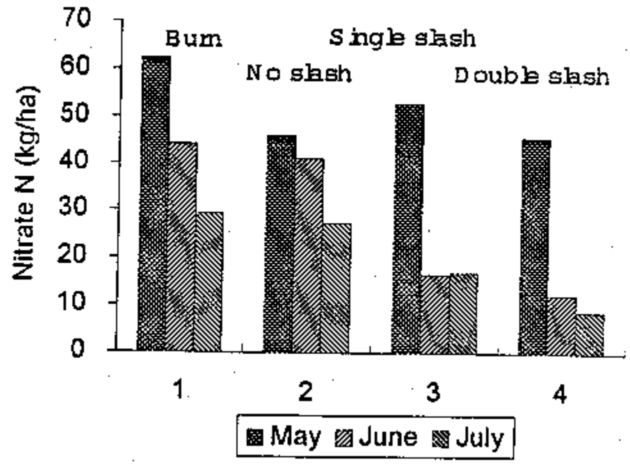


Figure 11. Nitrate accumulation in relation to four different methods of harvest residue treatment at a site in south western Australia at which 9-year-old *Eucalyptus globulus* was logged approximately 9 months previously.

Growth and nutrient uptake

Partitioning of Net Primary Production (NPP) to various growth processes changes with stage of development of the stand. Three definable stages of growth and nutrient cycling have been identified (Attiwill 1979). Initially the majority of NPP is directed at growth of the living biomass, especially development of the tree canopy, and nutrient cycling is dominated by uptake and accumulation in the tree. This is followed by a period when photosynthate is directed primarily to growth of woody tissues, heartwood formation is initiated and internal redistribution of nutrients becomes important for meeting nutrient requirements for growth. Finally, during the stage of stand maintenance, the majority of NPP is discarded as litterfall and biogeochemical nutrient cycling through decomposition of plant residues becomes increasingly important for tree nutrient supply. During this phase, rates of litter production provide a measure of annual NPP and the amounts of nutrients in annual litterfall approximate annual rates of nutrient uptake from soil. The allocation of nutrients in different tissues also changes as stands develop. For nutrients such as nitrogen and phosphorus, accumulation is generally most rapid during the early stages of stand development when leaf area is expanding. Declining rates of nutrient accumulation in older stands may reflect either a reduced 'demand' after full leaf area is developed, or declining nutrient supplies in the soil; these alternative explanations remain largely unexamined.

How does pattern of growth, carbon partitioning and nutrient uptake, nutrient cycling and the efficiency of utilization of nutrients affect productivity and long-term sustainability of plantations? Clearly, nutrient cost of harvesting is one factor which affects the pool of sites nutrients and this varies markedly between plantation species (Wang *et al.* 1991). Species of *Eucalyptus* generally exhibit high efficiency of nutrient use (NPP per unit of nutrient taken up - Vitousek 1982) compared with more nutrient demanding species and nutrient removals in wood are concomitantly lower. However, plantation species which utilize nutrients efficiently also produce plant litter with low nutrient contents and high carbon to nutrient ratios. Residues of this type decompose more slowly, immobilize more nutrients during decomposition and have slower rates of net nutrient mineralization than nutrient-rich litter (Vitousek 1982). Changes in these processes can act as a buffer against nutrient loss from the site, but they may also reduce nutrient supply rates and necessitate greater fertilizer inputs to meet growth requirements of trees in subsequent rotations. The literature on impacts of plantation species on soil fertility and growth of future rotations is conflicting and is a topic needing further soundly based studies utilizing statistically valid experimental designs.

Matching of soil nutrient supply to plant nutrient requirement is particularly important in young fast-growing plantations where nutrient demand for growth is high and internal stores of nutrients available for transformation to actively growing tissues are relatively low. An essential part of the project will therefore involve estimation of variations in nutrient uptake and allocation within eucalypt stands in relation to the measures of soil nutrient fluxes. In the strongly seasonal climate of southern India and SW Australia, transient nutrient limitations to growth may occur where the seasonal period of most active canopy growth and high nutrient demand is not in synchrony with the period of high soil nutrient supply and nutrient uptake.

Plant studies will also provide the basis to assess plant indices of the N and P status of eucalypt stands. Most studies of eucalypts have focussed on foliar analysis and this has generally not been found to be a sensitive indicator of nutrient status (Khanna 1994). This may be due to homeostatic mechanisms regulating concentrations in this key functional tissue to a greater extent than in other storage tissues. Therefore, in addition to foliar analysis, our approach will be to investigate other tissues (bark, twigs, fine roots) which appear to be more sensitive to changes in nutrient supply but which have not yet been extensively investigated (Grove 1990; O'Connell and Grove 1985; Khanna 1994). Alternative approaches which include the analysis of storage tissues, gradients of mobile nutrients from old to developing tissues (Grove 1990), analysis of specific nutrient forms (Polglase *et al.* 1992) and biochemical assays (O'Connell and Grove 1985) will also be evaluated. Plant indices combined with soil indices may ultimately provide the best prediction of nutrient limitations to growth, and form the basis for nutrition indicators to evaluate the sustainability of intensively managed short rotation eucalypt plantations.

Interpretation and integration

The previous discussion has focussed on individual processes such as litter accession, decomposition and accumulation, soil organic matter formation and nutrient mineralization from organic residues, growth and nutrient uptake and the interaction of these factors with stand management. Integration of these processes and interpreting their interaction is often difficult especially in field-based experiments where confounding effects can occur. Models provide one method for integrating process-based knowledge and for predicting the effects of factors important to long-term sustainable production from plantations. The type and complexity of models ranges from simple empirical relationships to mechanistic models which seek to describe important biological processes in detail. In general, as the complexity of the model increases, so does the need for improved understanding and description of the functional processes and also the amount of input data needed to run the model. Here we outline some of the modelling approaches that are applicable for integrating knowledge of organic matter turnover, nutrient mineralization rates, tree growth and sustainable plantation production.

Litter decomposition is most often described by simple exponential models (Olson 1963) of the form

$$X_t = X_o \, e^{-kt} \quad .... (1)$$

where X_o and X_t represent the amount of decaying residue present initially and at time t and k is the decay constant. More complex double exponential decay models (Bunnell and Tate 1974; Lousier and Parkinson 1976), have also been found to provide good descriptions of the breakdown of a wide range of plant residues in temperate eucalypt forests (O'Connell 1987, 1994). This type of model is likely to also be applicable to tropical forests, especially those forest types which occur in seasonal rainfall regions and where the plant residues contain substantial amounts of labile components as often occurs with eucalypt species. As well as providing better descriptions of the time course of litter decay the coefficients of these models also allow for prediction of residence times and accumulation rates of individual litter components (O'Connell 1987).

Simple empirical nutrient mineralization models of the type described above (O'Connell and Rance 1995) provide useful practical tools for predicting the short term response of nutrient supply to silvicultural practices. There have been only limited attempts to model longer-term nutrient and soil organic matter dynamics in tropical forests using more process-based models. Models of soil organic matter and nitrogen dynamics such as CENTURY (Parton *et al.* 1988), which have been developed for temperate agricultural systems, hold prospects for evaluating longer-term consequences for soil fertility of particular land uses in the tropics. This approach, which nominally separates organic matter into a range of separate pools, balances simplicity with enough detail to provide an understanding of system behaviour (Fig. 12).

Parton *et al.* (1994) evaluated CENTURY for a range of twelve tropical ecosystems, including two plantation forests, and reasonable correlations were obtained between observed and simulated productivity, soil organic carbon and soil nitrogen. Models of this type may be particularly useful in evaluating the long-term effects on soil fertility of land use such as short rotation tree cropping. The challenge for researchers is to adequately characterize tropical forest soil and plant systems to run the model and to evaluate the model assumptions and outputs under tropical climatic conditions (Motavalli *et al.* 1994). Establishment of well designed long-term experiments as proposed for this project are crucial for this purpose.

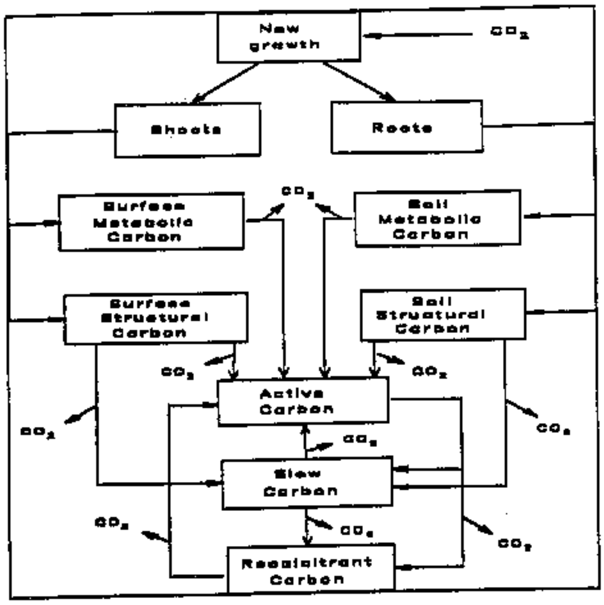


Figure 12. CENTURY carbon flow model (Kirschbaum 1995).

There have been few attempts to model whole stand carbon and nutrient dynamics at the process level in tropical plantations. A budgeting approach to the stores and transfers of organic matter and nutrients has been used to describe the differences in nutrient cycles of cacao plantations with different species of shade trees (Fassbender *et al.* 1988) and plantation eucalypts of different age (Bargali *et al.* 1992a,b). Bormann and Gordon (1989) used a similar procedure to evaluate the impact of intensive management on nitrogen sufficiency of forests. This is a useful approach to look at the impact of harvesting on nutrient stores. However, it does not provide insight into the underlying nutrient cycling processes which is necessary for understanding the impact of different plantation species on sites or the way nutrient cycling and plantation nutrient status may vary over time and with the intensity of forest management. A more detailed mechanistic approach incorporating models of tree growth, organic matter turnover and soil nitrogen dynamics has been proposed for plantation forests (Thornley and Cannell 1992). Similar procedures have been applied in only a limited number of studies at tropical forest sites (*eg.* Vitousek *et al.* 1994). For temperate forests, Comins and McMurtrie (1993) have combined a physiologically-based plant growth model with a modified version of CENTURY. They have used this in developing an ecosystem model G'DAY (Generic Decomposition And Yield) which predicts temporal changes in forest productivity over a rotation. Simpler, more empirical modelling approaches have also been used to evaluate the combined effects of harvesting, regeneration and fire on site nitrogen balances and yield within and between rotations of temperate forests (Dewar and McMurtrie 1996a,b). Simple graphical analyses developed by Dewar and McMurtrie (1996b) provide a quantitative basis for evaluating sustainable forest productivity under specified harvesting and management practices. In their model (SUSTAIN), sustainable yield is defined explicitly as the steady-state productivity obtained after many rotations if management practices are continued indefinitely. These various models provide a sound theoretical framework for evaluating both the short and long-term consequences of silvicultural practices for sustainable forest production. We propose to use this framework to evaluate and interpret the experimental results obtained from our studies of the effects of silvicultural options on sustainability of short rotation eucalypt plantations in Kerala and south western Australia.

2.4 Research Objectives, Hypotheses and Expected Outputs

Development of sustainable managed ecosystems is critically dependent on the protection and enhancement of the quality of the soil resource. Soil fertility, moderated by the quantity and nature of soil organic matter, is one of the key factors determining site quality and consequently the sustainability of land management systems.

The objective of this project is to identify and develop practices for manipulating soil organic matter, and soil and tree nutrient and water status as a basis for implementing silvicultural regimes which optimise conservation and use of site resources and which will allow sustainable wood production from eucalypt plantations.

We hypothesise that silvicultural practices can be developed which maintain the quantity and quality of soil organic matter and soil fertility so that long-term productivity of eucalypt plantations can be sustained and enhanced in tropical and temperate environments.

Part of the research will be directed at the critical inter-rotation phase of harvesting, site preparation and stand establishment (the CIFOR framework) and part towards established eucalypt stands.

Firstly, site organic matter, nutrient status and soil water status will be manipulated during the inter-rotation period in designed experiments through :

- management of soil organic matter by efficient utilization of plantation harvest residues,
- utilizing inter-row planting of N-fixing cover crops,
- efficient weed management
- water, soil and nutrient conservation with contour trenching, and
- efficient use of applied nutrients.

Secondly, impact of land use on soil fertility will be examined by comparing established eucalypt plantations to adjacent sites with pre-existing vegetation. Through these comparisons, we will :

- quantify changes to fertility of soils on land which has grown several rotations of eucalypts.
- evaluate the consequences of these changes for future plantation productivity.

The project will require a detailed understanding of the effect of the different management treatments on soil organic matter quantity and quality, plant uptake and nutrient cycling processes, tree growth and site water status. Key elements of the project will include studies of organic matter turnover, rates of mineralization of organically bound nutrients, dynamics of plant nutrient uptake, storage and utilization, competition from weeds, soil and plant water status and the way these various factors affect growth. Key processes will be integrated through application of simulation modelling techniques.

The outcome from this research will be scientifically-based methodologies to better match sustainable nutrient and water supply with tree requirement.

The project will be subdivided into four discrete but inter-linked sub-projects as follows :

Sub-project 1 : Nutrient status and nutrient cycling in eucalypt plantations.

The objectives of this sub-project are to :

- Acquire analytical equipment to establish soil and plant chemistry facility at KFRI.
- Train KFRI scientists in use and maintenance of analytical equipment and in standard methodologies to be used in the project in India and Australia.
- Quantify nutrient budgets for soil, litter and vegetation at all experimental sites.
- Quantify decay rates and nutrient dynamics in harvest residues and their likely contribution to nutrient demands of the new tree crop.
- Quantify nutrient cycling in litterfall as a basis for evaluating differences between eucalypt plantations and the pre-existing land use (natural forest, grassland, agriculture).
- Determine impact of applied silvicultural treatments on soil carbon, nitrogen and phosphorus status and supply rates through regular annual soil sampling.
- Quantify effect of changed land use on soil nutrient status using glasshouse studies and bioassay techniques.

Sub-project 2 : Plant physiology and water relations

The objectives of this sub-project are to :

- Quantify monthly variation in leaf water potential (pre-dawn, midday) to assess seasonal effect of selected treatments on water availability to trees and maximum tree water stress. Use water stress integral (Myers 1988) to evaluate treatment effects on long-term tree and site water status.
- Quantify stomatal conductance seasonally (pre- and post- monsoon period) to assess effect of treatments on stomatal functioning.
- Determine transpiration (porometer, sap flow gauge) to assess treatment effects on tree water use.
- Investigate impact of treatments on carbon assimilation using regular measures of leaf photosynthesis (portable IRGA - LI-COR-6200) and Leaf Area Index (LI-COR 2000).
- At two sites quantify stand microclimate parameters (atmospheric temperature, relative humidity, vapour pressure deficit, wind velocity, solar radiation, rainfall) as a basis for determining stand water use by the Penman-Monteith equation.
- Monitor ground-level light availability seasonally as a basis for evaluating effect of shading on performance (growth, survival, N-fixation) of cover crops in eucalypt plantations.

Sub-project 3 : Tree growth and nutrient uptake

The objectives of this sub-project are to :

- Determine the annual pattern of tree growth and the partitioning of biomass between tree components (foliage, wood, bark etc) in relation to the applied silvicultural treatments.
- Develop quantitative allometric relationships to predict biomass and nutrient content of tree components from easily collected tree dimensional data (tree diameter/height)
- Quantify the annual pattern of nutrient uptake and the distribution of nutrients within different plant tissues to relate to measures of nutrient supply and applied silvicultural treatments.
- Quantify effects of legume cover crops on carbon and nitrogen status of soils and determine impact on tree growth.
- Evaluate measures which may be useful predictors of plant nutrient status that could be used as practical tools for implementing nutrient management strategies.
- Utililize growth data in evaluating economic returns and input costs to (i) develop cost-benefit return analysis in relation to applied silviculture and (ii) identify most economic "Best practice" management options.

Sub-project 4 : Modelling soil processes and tree growth

The objectives of this sub-project are to :

- Apply an existing simulation model (NMIN) and measures of soil environmental data and nitrogen status to simulate rates of nitrogen supply in relation to applied silvicultural treatments.
- Use CENTURY model of soil organic carbon and nitrogen turnover to evaluate the long-term impact of establishing eucalypt plantations on sites previously covered with natural forest or grassland or which were utilized for agriculture.
- Use whole-system models developed at University of New South Wales (G'DAY, N-BAL, SFP, SUSTAIN) to predict how plantation productivity will change over successive rotations in relation to the various applied silvicultural practices.
- Based on model simulations, identify the "Best practice" options for managing eucalypt plantations for long-term sustainable productivity.

2.5 Research Method

1. Experimental framework

As indicated above, the study will incorporate experiments within two basic frameworks :

- designed experiments at the inter-rotation period when plantations are harvested and re-established (Inter-rotation sites).
- comparisons between established plantations and adjacent areas representing prior land use (Established stand sites).

1.1 Inter-rotation sites

Experimental design

The framework for this part of the experimental program will include a sub-set of the common treatments as specified in the core CIFOR research program SMPTP. The rationale for this approach is that management practices applied during and following harvest operations can determine whether organic matter and nutrients are conserved or depleted and whether other soil properties are degraded. Previous studies have demonstrated the impact of harvest practices on subsequent productivity (Kneeves 1966; Sim and Nykvist 1991). Furthermore, in temperate plantations systems it has been shown that good management practices can not only prevent soil fertility decline but that future productivity can be enhanced (Nambiar 1995). Designs in India and Australia will differ somewhat, reflecting the importance of different issues to plantation silviculture in the two regions. However the core treatments of organic matter manipulation and nutrient additions will be similar in both countries.

1.1.1 India

Experiments at four locations with two sets of replicate sites in each of two eucalypt species, ie

- two low altitude sites based on *E. tereticornis*, and
- two high elevation sites utilizing *E. grandis*.

Five discrete experiments will be established at each location. The design of each will be a randomized block with 4 replicates. Plot size will be 24 x 24 m, planting spacing 2 x 2 m, with 144 seedlings per plot (64 measurement trees after allocating buffer rows). At each sites the following experiments will be established after the existing stand has been harvested :

⇒ Organic matter manipulation

- No slash - all harvest material removed
- single slash - harvest material retained and spread evenly on each plot
- Double slash - slash added
- Leaf slash only - all wood residue removed (simulates firewood removal)
- All organic matter removed (litter, understorey, slash)
- Burn - all residues burnt (current practice)

⇒ *Inter-row legumes*

- 3 legumes plus control. The legumes to be used are :
  - *Peuraria phaseoloides* (shade intolerant)
  - *Stylosanthes guianensis* (shade intolerant)
  - *Mucuna* sp. (shade tolerant).

⇒ *Soil trenching*

- 2 levels of trenching plus control.
  - The trenches will be located on the contour and at two different spacings. The spacings will depend on topography and will be determined for each site following consultation with the Kerala Forest Department.

⇒ *Ground vegetation management*

- Weeds retained (with normal tree clearance)
- Strip weed control (1m wide)
- Total weed control.

⇒ *Nutrient additions*

- 6 levels of added P plus basal major and minor nutrients
- 6 levels of N plus basal major and minor nutrients

1.1.2 Australia

The studies in Australia will be located across the rainfall gradient utilized for *E. globulus* plantation production and will include :

- high rainfall sites (1000-1100 mm) on contrasting soil types (high and low fertility), and
- a site at which moisture limitations will affect tree growth (650- 800 mm).

There will be three discrete experiments at each location. The designs of each are randomized block with 4 replicates, plot size will be 18 x 18 m, planting spacing 4 x 2 m, with 40 seedlings per plot (18 measurement trees after allocating buffer rows) for the organic matter and nutrient experiments. Legume experiments are single row tree plots 18 x 6 m. At each site, experiments established following harvest will include :

⇒ *Organic matter manipulation*

- No slash - all harvest material removed
- single slash - harvest material retained and spread evenly on each plot
- Double slash - slash added
- Burn - all residues burnt
- Single slash with legume undercrop (vetch) and added P fertilizer
- Single slash and added P fertilizer (control for previous treatment)

⇒ *Inter-row legumes*

- 5 agricultural legumes plus control. The legumes to be used are :
  - Lupin
  - Faba bean
  - Field pea.
  - Vetch
  - Lathyrus

⇒ *Nutrient additions*

- 6 levels of added P plus basal major and minor nutrients
- 6 levels of N plus basal major and minor nutrients

1.2 Established stand sites

Experimental design

The influence of plantations on soil properties will also be measured on replicated established stands which are paired with adjacent sites where previous land use has been maintained. The purpose of these experiments will be to establish the extent to which establishment of eucalypt plantations has modified soil properties with respect to the pre-existing land use. Again, the designs will differ slightly between the two countries, reflecting the different environments in the two regions. In India pre-existing land use will be either natural forest or grassland, whereas in Australia pre-existing land use will always be agriculture.

1.2.1 India

The studies in India will be conducted at the four locations where the main inter-rotation designed experiments are located. Parts of the existing stand will be retained and these sites will be paired with adjacent sites representing previous land use.

1.2.2 Australia

The studies in Australia will use paired plantation/pasture sites. Effects of trees on soil properties will be evaluated in established stands which are paired with adjacent pasture land, where the paired sites have an identical history of land use prior to tree planting. This will utilise both alley farming and plantation systems. Between 15 and 20 paired sites will be selected to be representative of contrasting soil types and climatic zones.

2.5.1 Experimental methodologies

In India, the research will be conducted within the experimental framework outlined above. The four research projects will link with the six experiments at each of the four locations as detailed in the following Table. Numbers within each module refer to the tasks undertaken and outcomes as detailed in the legends following the table :

Experiment	*Sub-project 1* Nutrient status & Nutrient cycling	*Sub-project 2* Plant physiology & Water relations	*Sub-project 3* Tree growth & Nutrient uptake	*Sub-project 4* Soil process & Growth modelling
Organic matter manipulation	1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8	2.1 2.2 2.3	3.1 3.3 3.4	4.1 4.2 4.3
Nutrient Additions	1.2 1.5 1.6 1.7	2.1 2.2 2.3	3.1 3.2 3.3 3.4	4.3
Inter-row legume crops	1.2 1.5 1.6	2.1 2.3 2.4	3.1 3.4	4.1 4.2 4.3
Soil trenching	1.2	2.1 2.3	3.1 3.4	4.3
Ground vegetation control	1.2	2.1 2.3	3.1 3.4	4.3
Established stand experiments	1.2 1.4 1.8			4.2

Sub-project 1 **: Nutrient status and nutrient cycling**

1.1 Establish analytical laboratory

The chemistry laboratory at KFRI currently uses mostly manual methods and wet chemistry for soil and plant analysis. We propose to purchase laboratory analytical instruments to update this facility. This will include an Atomic Absorption Spectrometer, an Auto analyser and other basic sample preparation equipment. The equipment will initially be set up and tested in Perth. The Chief Soil Chemist from KFRI will work in the Perth laboratory during this phase and will be trained in maintenance of the equipment and the appropriate analytical methodologies. The instruments will then be transferred to KFRI. Ms Tuyen Pham, Laboratory Manager CSIRO Forestry and Forest Products WA, will assist in coordinating equipment commissioning and method development in Perth and at KFRI.

1.2 Site characterization

An important aspect in setting up the experimental sites will be to characterise the soil and vegetation at each experimental site. This will include soil descriptions and soil nutrient content to 1 metre depth by depth intervals (total organic C, N, P, labile C, N, P, exchangeable cations and Al, pH, bulk density, particle size). Stand biomass and nutrient content of trees, understorey and litter before harvest will be determined. This will provide the basic nutrient budgeting data necessary to evaluate the impact of silvicultural operations such as harvesting, firewood collection and site preparation burning.

1.3 Slash quantity and decomposition

Conservation of soil organic matter is a central theme of this proposal. We will quantify amounts and type of residues present after harvest. Rates of breakdown and nutrient cycling in harvest residues will be determined using litter bag methods for leaf and wood fractions of slash. We will also make annual quadrat measurements of remaining slash to obtain independent measures of decomposition rates and nutrient content of unconfined residues. These data will provide direct estimates of the contribution of harvest residues to nutrient cycling and indicate their importance in nutrient supply and as a buffer against losses through leaching or by volatilization in sites preparation fires.

1.4 Litterfall and litter decomposition

Comparisons of nutrient cycling in litter between established eucalypt plantations and the pre-existing land use (usually natural forest) will be made by preserving parts of the eucalypt stand at time of harvest. Litterfall rate, decomposition and nutrient dynamics in decaying litter in the retained established stands and adjacent natural forest will be measured (litterfall traps, mesh bag decomposition method) to establish the differences between these processes in the natural and introduced species. This will provide information for understanding the differences in nutrient and tree nutrition between the two vegetation types and will provide data for understanding how eucalypts impact on soil processes.

1.5 Soil carbon status

A critical issue will be the impact of the applied silvicultural treatments on soil organic carbon. We will conduct regular soil sampling at 0, 12, 24, 36, 48, months after planting to determine changes in soil carbon storage. Although total organic carbon is the most usual parameter measured to assess soil carbon status, this property may not be very sensitive to changes likely to be induced by silviculture. The reason for this is that soil contains very large stores of carbon and much of this is in relatively inactive pools. More labile measures such as soil microbial biomass (Sparling 1992) and readily oxidizable carbon (Lefroy and Blair 1994) will be tested as alternatives to better measure system response to applied treatment. Together with our collaborators at Griffith University, we will also explore the possibility of using instrumental techniques such as ^{13}C NMR spectoscopy to investigate management-induced changes in soil carbon characteristics (Kinchesh *et al.* 1995a,b; Trofymow *et al.* 1995).

1.6 Soil nitrogen status

As with soil carbon, N response to silvicultural treatments will be assessed through regular sampling at 0, 12, 24, 36, 48, months after planting. A range of measures of soil N status will be evaluated to indicate impact of treatments. These will include total soil N, microbial biomass N, labile soil N (anaerobic N), N mineralization (lab incubations of intact cores) and denitrification potential measured using stable isotope methods.

1.7 Soil phosphorus status

Changes in soil phosphorus status will be measured at 0, 12, 24, 36, 48, months after planting using a range of extraction and fractionation techniques. An initial phase of this work will be identification and development of the analytical methodologies to be used. This will be a major primary task of the research scientist appointed on ACIAR funds to the Perth laboratory and will be achieved by collaboration with Professor RJ Gilkes of UWA and Dr P Blamey of Queensland University.

1.8 Glasshouse bioassays

In assessing the impact of eucalypt plantations on soil properties we will conduct a series of bioassay studies using soil from plantation and adjacent pre-existing land use sites (established stands framework). Impact of land use on seedling growth and nutrient uptake will be quantified and nutrient addition experiments will be used to identify limitations induced by repeated tree cropping. These experiments will be complemented by soil chemical analyses as a basis for understanding possible amelioration procedures for soils under successive rotations of plantations.

Sub-project 2 **: Plant physiology and water relations**

2.1 Weather and microclimate data

Climatic data will be collected by automatic weather stations. Microclimate measurements within the canopy and above the canopy will be used to calculate transpiration by the Penman-Monteith method. This will provide data on the effects of different silvicultural treatments on stand water use and changes in the efficiency of water use. In Australia we will monitor soil water storage through monthly neutron probe measurements to assess impact of silviculture on plantation water status.

2.2 Plant development

Plant growth and development will be evaluated monthly by measuring leaf area index (LAI). This will be done by measuring light interception through the canopy with a Canopy Analyser (LI-CORR 2000). Destructive sampling will be used to calibrate the instrument and results compared with those predicted by allometric relationships from tree diameter. Litterfall will be measured monthly starting when seedlings are 2 years old.

2.3 Physiological parameters

A range of measures will be used to determine photosynthesis (portable IRGA) and tree water status to evaluate the effect of treatments on plant physiological function. Pre-dawn and midday water potentials will provide monthly measures of water availability and tree water stress in relation to treatments. Myer's (1988) water stress integral will be used to assess cumulative plant water status. As well as Penman-Monteith estimates of stand water use, transpiration will be monitored on a leaf and stem basis using porometer and sap flow methods. We will also explore the possibility of using ^{13}C isotope discrimination techniques as a measure of tree water use efficiency.

2.4 Ground level light availability.

The study of effects of different legume ground cover species will incorporate species with a range of tolerances to shade. We will quantify light availability at ground level and use this information in evaluating ground cover performance in relation to survival, growth and biomass nitrogen accumulation.

Sub-project 3 **: Tree growth & Nutrient uptake**

3.1 Tree growth

Regular estimates of tree growth (diameter measured at 6,12,18,30,42,54 months after planting) will be made on all plots at each location. We will sample trees with a range of growth rates from the nutrient addition experiments, separate them into various components (foliage, stem, bark etc) and use these data to develop predictive allometric functions based on easily measured tree characteristics such as diameter at breast height. These relationships will subsequently be used to estimate biomass production on all plots and relate growth rates to silvicultural treatments. Biomass of legume cover crops will be estimated.

3.2 Nutrient uptake by destructive sampling

Sampled trees collected for biomass estimation will be used to provide regular estimates of the time course of nutrient uptake by analysing samples for major nutrients. These data will also provide information on allocation of nutrients to different tree components. Two treatments within each of the nutrient addition experiments will be selected to provide detailed information on tree nutrient uptake in relation to nutrient supply. Nitrogen accretion in legume cover crops will be estimated.

3.3 Fertility indices.

Several measures of plant and soil N and P status will be evaluated to test their usefulness as indicators of likely responses to nutrient management.

3.4 Economic analysis.

The growth data will be used to evaluate growth responses in relation to cost of applying the silvicultural treatments as a basis for analysing the economics of each option. This will provide the information necessary for detailed cost/return analysis.

Sub-project 4 : Soil process and growth modelling

Modelling soil and plant response to land use and silvicultural practices will be a central theme of this sub-project. This will be facilitated by collaboration with Assoc. Professor McMurtrie and Dr Dewar (UNSW) and our current work on development of models to simulate N supply rates in plantation forests. A Post-doctoral Fellow will be appointed to the Perth laboratory of CSIRO in year 3 of the program to conduct these studies.

4.1 Modelling N mineralization

To facilitate evaluation of soil nitrogen status, we have developed a computer simulation model for predicting soil nitrogen supply rates under trees (O'Connell and Rance 1995). This model is based on an understanding of how environmental factors (temperature, moisture) and soil properties (organic nitrogen quality, soil physical factors) affect nitrogen mineralization processes. We will adapt this model to predict rates of nitrogen supply in relation to silviculture on selected treatments.

4.2 Application of CENTURY

The ability to predict changes in soil fertility resulting from changes in land use is critical for devising sustainable management systems. CENTURY is a soil simulation model which predicts changes in soil carbon levels and nitrogen status and mineralization. We will test CENTURY and evaluate its performance in simulating changes in soil properties as a result of establishment of eucalypt plantations.

4.3 Whole system modelling

Several whole system models have been developed by Associate Professor Ross McMurtrie, Dr Roddy Dewar and colleagues at UNSW to evaluate the response of forest ecosystems to disturbance. We will collaborate with Associate Professor McMurtrie and Dr Dewar to apply these models to simulate long-term productivity of eucalypt plantations in relation to site management. We will use these model predictions to evaluate sustainable productivity in relation to nutrient inputs and losses under various silvicultural treatments and to identify "best practice" management options

Project management and training

This is a large multi-disciplinary project, planned to extend for a period of five years. This time scale is essential to evaluate the experimental application of silvicultural options and to capture the benefits of outcomes from the project. Management, training and coordination will be critical to the success of the project and will be achieved through a range of processes :

- The project leader and Research Scientists from CSIRO will make regular visits to KFRI to monitor progress and advise on experimental procedures and analysis of results. A preliminary program for these visits is outlined in Table 1.
- Scientists from KFRI will visit Australia for (i) training in specific areas of expertise, (ii) collaboration with Australian colleagues and (iii) gaining first hand knowledge of practical silvicultural options applied in Australian eucalypt plantations. The contacts and collaborative arrangements between CSIRO and private and public land management

agencies involved in forestry in Australia will facilitate this process. A preliminary program and identified scientists participating in these visits is outlined in Table 2.

- Dr Sankaran, project coordinator in Kerala, will hold regular monthly meetings with the KFRI research team to review progress. He will submit a formal written report each three months to Dr O'Connell on the outcomes of these meetings and more generally on the progress of the project. These reports will be submitted within the month following the end of each quarter (reports submitted in January, April, July, October of each calander year). Dr O'Connell will formally respond to the reports.
- Training and reporting workshops will be held on three occasions during the project :
  - Following the initiation of the project in 1997, a two day workshop will be held at KFRI. This workshop will be timed to coincide with the site evaluation and selection process. Participants from Australia will be Dr O'Connell, Dr Grove, Professor Gilkes and Ms Tuyen Pham. Senior colleagues from KFRI will lead some sessions during the workshop. Ms Pham will also use this time to assist the Soils Division at KFRI in setting up the analytical equipment and establishing the main methodologies required in the project. Dr O'Connell, Dr Grove and Professor Gilkes will spend approximately 8 days in the field to advise on site selection and to assist in site and soil evaluation. This workshop is planned for January-February 1997.
  - A workshop will be held in December 1999 at the time of the mid-term review. The purpose of this meeting will be to (i) facilitate further training as required, (ii) report on current progress and (iii) evaluate the research program for the final half of the project.
  - A workshop will be held to correspond with the final review of the project in December 2001. This will evaluate outcomes from the project and assess priorities for future research.
- We will seek support for postgraduate students from India to undertake PhD studies at UWA under the joint supervision of Professor RJ Gilkes and CSIRO team members. Several potential students from Kerala Agricultural University have been identified by Dr Sankaran. PhD projects will be based on the experiments established in Western Australia and will address one of the main sub-project areas listed above. The overall project will not be dependent on the results of PhD studies, but rather these studies will enhance the outcomes that are achieved and provide training opportunities for Indian students.

Table 1. Proposed time table of visits by Australian scientists to Kerala.

Date	Personnel	Duration (days)	Purpose
Dec.1997	Dr. O'Connell Dr. Grove Ms. Pham Prof. Gilkes	14	Initial workshop and training program. Soil evaluation and site selection Chemistry laboratory establishment Analytical methodology training
Mar.1998	Dr. O'Connell	14.	Project evaluation
Jun.1998	Dr. O'Connell Dr. Grove	14	Planting of sites
Dec.1998	Dr. O'Connell Dr. Grove	14	First measurements of trees on experimental plots and tree sampling for biomass and nutrient uptake
Jun.1999	Dr. O'Connell RS	14	Project evaluation Transfer of phosphorus and carbon methodologies
Dec.1999	Dr. O'Connell Dr. Grove	14	Measurements of trees on experimental plots and tree sampling for biomass and nutrient uptake
Jun. 2000	Dr. O'Connell RS	14	Project evaluation
Dec.2000	Dr. O'Connell Dr. Grove	14	Mid term review Training workshop Tree measurements and biomass sampling
Jun.2001	Dr. O'Connell PDF AP. Mc Murtrie	14	Project evaluation Evaluation of application of models to KFRI data
Dec.2001	Dr. O'Connell Dr. Grove	14	Measurements of trees on experimental plots and tree sampling for biomass and nutrient uptake
Jun.2002	Dr. O'Connell Dr. Grove RS PDF	14	Final review and workshop

Table 2. Proposed time table of visits by KFRI scientists to Australia for training

Date	Personnel	Duration (days)	Purpose
Aug.1997	Dr. Balagopalan	90	Commissioning of analytical instruments in Perth
Oct.1998	Dr. Sankaran	30	Training in experimental procedures
Mar.1999	Dr. Kallarackal	30	Collaboration in plant physiological methodologies
Oct.1999	Dr. Pandalai	30	Training in silviculture
Mar.2000	Soils Div. RS	30	Training in soil chemistry
Oct.2000	Dr. Sankaran	30	Training in evaluation of project outcomes
Mar.2002	Dr. Sankaran	30	Project assessment

2.6 Collaboration / Coordination

Participating Institutions

Kerala Forest Research Institute conducts research in a wide range of different aspects of forestry, wood science and wildlife management. The Institute employs 45 scientists, 19 technical officers and 85 support and administrative staff. It has a well developed infrastructure, including laboratory, library and computing facilities. The Institute collaborates with other institutions in Kerala engaged in forestry research. The project leader in Kerala will be Dr KV Sankaran from KFRI and the project team will include scientists from the Divisions of Soil Science, Silviculture, Plant Physiology, Plant Pathology and Statistics.

CSIRO Forestry and Forest Products has its headquarters in Canberra and regional stations in Perth, Hobart, Mount Gambier and Melbourne. The research group in Perth is attached to the Hardwood Plantations Program and its scientists have extensive expertise in a wide range of nutritional aspects of forestry including soil science, nutrient cycling, plant nutrition, plant symbiotic relationships and growth modelling and water use. The group possesses a unique skills base, especially in the area of process-based studies, which can be applied to solving problems of plant nutrition common to plantation forestry in both India and Australia. Scientific participants from CSIRO in Australia will be Dr AM O'Connell (nutrient cycling, soil nutrient mineralization, computer modelling), Dr TS Grove (plant nutrition, nutrient uptake and storage, biochemical nutrient cycling), Mr SJ Rance (biomass estimation and modelling), Mr J Galbraith (instrumentation and site maintenance), Ms Tuyen Pham (analytical chemist), Research Officer (TBA - plant physiology , plant and soil water relations). We will also seek advice from expert scientists from the Australian Tree Seed Centre on species and provenance selection.

Professor R.J. Gilkes, Head of the Department of Soil Science and Plant Nutrition at the University of Western Australia will collaborate with us in parts of the project dealing with impacts of silvicultural treatments on organic matter dynamics and storage and supply of phosphorus. Professor Gilkes is a world authority on the mineralogy and chemistry of soil phosphorus and has extensive experience in application of this knowledge to problems of plant nutrition in agriculture (Gilkes and Hughes 1994; Kumar *et al.* 1992, 1994). He is also an authority on the chemical and mineralogical properties of lateritic soils, for which Kerala is a type location. Thus, the confluence of his expertise on phosphate and laterites provides a unique opportunity for advancing this aspect of the project. We are exploring options for attracting postgraduate students from the Kerala Agricultural University to undertake PhD programs at the University of Western Australia under the supervision of Professor Gilkes and Dr O'Connell. The students would develop research topics within the framework of experiments we set up in Australia. Professor Gilkes has worked extensively with colleagues in South and South East Asia and has a great deal of experience in supervision of overseas students in postgraduate programs. Potential candidates have been identified in discussions between Dr Sankaran and Dr Sudhakara of the Kerala Agricultural University and possible sources of funds to support postgraduate awards and travelling costs are being investigated. Although the success of our proposed research is not contingent on obtaining funding to support these students, we feel this approach has merit as it will facilitate technology transfer when students return to India. Funding avenues that will be explored are AusAID, Crawford Foundation and Forest and Wood Products R&D Corporation postgraduate awards.

Associate Professor Paul Saffigna, Head of the School of Applied Science at Griffith University, will collaborate with us on process-based studies, especially in estimating effects of treatments on volatile N losses and soluble soil carbon fluxes. Dr Saffigna has developed stable isotope tracing methodologies to estimate potential rates of denitrification. Thus far, these techniques have been utilized only in agricultural systems such as sugar cane farming, but they have potential application in intensive forestry. They will be particularly useful in estimating potential losses of nitrogen through de-nitrification during the inter-rotation period when high levels of soil nitrate can accumulate in association with increases in levels of soluble organic carbon compounds. We are exploring with Associate Professor Saffigna the possibility of collaboration on utilizing Griffith Univerity's C^{13} NMR facility to evaluate this methodology in investigating soil carbon status of intensively managed eucalypt plantations.

Associate Professor Ross McMurtrie and Dr Roddy Dewar, School of Biological Science at University of New South Wales, will collaborate with us during the final three years of the project. This collaboration will be facilitated by the appointment of a Post Doctoral Fellow to the Perth Laboratory of CSIRO during this period. Associate Professor McMurtrie is the leading researcher in Australia on application of process-based models to problems in forestry. He and Dr Dewar have developed a number of models to investigate impacts of management practices on sustainable production of forest ecosystems. These models have been applied to native forests in Australia, including the karri forest of south-western Australia, and elsewhere. We will utilize several of UNSW's models to evaluate the response of eucalypt plantations to the range of silvicultural practices we will apply in our experimentation. This will provide the framework for integrating results from a number of different experiments and disciplines and will form the basis for our identification of "best practice" options for silviculture of eucalypt plantations in India and Australia.

Consultation

Extensive consultation has taken place between CSIRO and KFRI over a period of more than two years as a precursor to the development of this proposal. Dr O'Connell visited KFRI in December 1995 with Dr John Fryer from ACIAR. Valuable discussions were conducted with the Director of the Institute, Dr K.S.S. Nair, on the management and administration of the proposed research. Dr Nair has expressed strong support for the project (letter of support attached). Meetings were also held with the Principal Chief Conservator of Forests, Kerala (Mr P.N. Surendran) and the Managing Director, Hindustan Newsprint Limited (Mr S.K. Saha). Mr Surendran and Mr Saha confirmed the priority of the theme of the proposed research for Indian forestry and identified amelioration of shortfalls in supply of raw materials for the local pulping industry, fuelwood and construction timber as major problems for the region. Pledges of support to various aspects of the program were forthcoming from both organisations (letters attached). At the technical level wide-ranging discussions were held with Dr K.V. Sankaran, project leader in India, and other senior research scientists from the Institute. In all, 10 scientists from a range of Divisions and disciplines have indicated a strong desire to contribute a significant proportion of their time to the proposed research. This provides an extremely broad spectrum of expertise on which we are able to draw and will greatly enhance the prospects for successful outcomes from our research.

Dr Glen Kile, Chief CSIRO Forestry and Forest Products, and Mr Robin Cromer, Manager of the Hardwood Plantation Program within the Division, have given their strong support to the planning and preparation of this proposal.

Interaction between KFRI (Dr J. Sharma) and the Australian Tree Seed Centre (Mr T. Vercoe) has already been extensive and will ensure the optimum choice of tree species and provenances for use in field trials. This will be particularly important for choice of eucalypt species which are resistant to fungal diseases in India. Consultation has also taken place with the Kerala Forests Department and Hindustan Newsprint Limited who will assist by providing land for the field program in India and expertise in establishing and maintaining the trials.

We have also discussed the proposal and had significant input from several other leading Australian Scientists as detailed below :

- Dr Partap Khanna, from CSIRO Forestry and Forest Products, has a copy of the Phase I outline and has made several useful suggestions. Dr O'Connell has other ongoing collaborative work with Dr Khanna and other scientists within the Division and the CRC for Temperate Hardwood Forestry on application of simulation modelling techniques for prediction of nitrogen supply rates in plantation and natural forests.
- We have had discussions with Dr Pax Blamey, University of Queensland, (ACIAR project 9414) regarding the prospects for collaboration, particularly on aspects of soil phosphorus partitioning and cycling. Although there are differences in the crops and to some extent climate and soils in our two projects, there are strong elements of similarity in regard to options for manipulating organic matter and impacts on nutrient supply and sustainable production. In our discussion, we agreed it would be very useful to maintain interaction especially during the early phase of Sub-project 1 of Dr Blamey's ACIAR project 9414 (*Establishment of Methodologies)*. This will assist us in development of methodologies for assessing soil phosphorus status in our own work. Indeed, Dr Blamey has suggested that one of our technicians could spend time in his laboratory to gain hands-on experience in the

phosphorus analytical procedures he is developing. We would also maintain these contacts throughout the life of the projects to facilitate linking outcomes from the research.

- We intend to test methods for evaluating labile carbon components of soil. As a starting point, Dr G.J. Blair of UNE has generously offered to analyse soil samples from contrasting treatments of our organic matter manipulation experiments in *Eucalyptus globulus* plantations in Western Australia using techniques he has developed. Use of these methods in our proposed project would enhance prospects for comparison between and collaboration with ongoing ACIAR projects.

- Dr John Turner of NSW State Forests is leader of a research project investigating issues of sustainable management of Australian native forests. This work relates to establishment of *Indicators of Sustainability* and *Codes of Forest Practice* mentioned previously. The project is funded by the *Forest and Wood Products R&D Corporation*. Dr Turner is also convenor of a sub-committee of the *Research Priorities Co-ordinating Committee* of the *Australian Forestry Council* looking at sustainabilty issues in native forests. There are clear parallels between this work and our ongoing studies in Western Australia and the project we propose for plantation forestry in India. Dr Turner recently visited our field sites in *Eucalyptus globulus* plantations near Manjimup as part of the *Soils and Nutrition Working Group* of the *Australian Forestry Council*. I have discussed prospects of cooperation and exchange of ideas with Dr Turner and we have agreed that the aspect of soil organic matter and establishing methodologies which provide early indication of changes caused by forest operations is an important area for collaboration and one we should pursue in the future. Dr Turner has read and commented on the Phase I proposal.

- Dr Peter Attiwill has a long established reputation for his research in forest ecology and nutrient cycling in Australian native forests and more recently in plantation forestry. I have discussed the project with Dr Attiwill and he has read and commented on the Phase I proposal.

Coordination

Dr AM O'Connell will be overall project leader. Dr O'Connell will liaise with and coordinate research activities of the Australian collaborators and will be responsible for linking this research with activities in India. Dr O'Connell will be in regular contact with KFRI to report progress on the Australian research sites. In addition to the research personnel listed in this proposal, Dr O'Connell will also maintain links with other related research programs, both within CSIRO Forestry and Forest Products and in other organisations. This will include interactions with the CRC for Temperate Hardwood Forestry in Tasmania (Dr P.J. Smethurst), research on sustainable management of native forest (Dr J. Turner), Bunnings Tree Farms (Mr G. McArthur and Mr. R. Breidahl), CALM (Dr J. McGrath), QFRI at Gympie (Mr J. Simpson and Dr Z. Xu) and related ACIAR projects (eg Dr P. Blamey, Dr. N. Malajczuk, Dr G Blair). Additionally Dr. O'Connell will maintain links with the CIFOR network through contacts with Dr John Turnbull and Dr Christian Cassolter at Bogor, Indonesia.

Dr KV Sankaran will be project leader in India and will have responsibility for coordinating the research activities conducted in Kerala. A critical component during the initial stages will be to oversee the selection of experimental areas, the preparation of nursery seedlings, the establishment of the research sites at four different locations and ongoing maintenance of the experimental plots. This will require close consultation with officers of the Kerala Forests Department. The research team in Kerala is a relatively large and multi-disciplinary group and monitoring progress on different aspects of the research will be time consuming and critical to the success of this project. Consequently, the Director of the KFRI, Dr K.S.S. Nair, has agreed that Dr Sankaran should allocate the majority of his time (80%) to this task. Coordination and reporting of progress will be facilitated at regular formal research team meeting held each month at KFRI as describe above. Dr Sankaran will communicate the outcomes from these meetings to Dr O'Connell.

2.7 Economic Impact of the Research

India

It is now almost four decades since large scale planting of eucalypts commenced in Kerala State, India. About 25% (37500 ha) of the total plantation area of the State is occupied by eucalypts, predominantly *E. tereticornis* (at low altitudes) and *E. grandis* (mainly in the high ranges). There are also smaller amounts of *E. globulus*, *E. robusta* and *E. citriodora* planted at higher altitudes. Except for restricted areas of afforestation of grassland, all of the eucalypt plantations in Kerala have been established after clearfelling the natural forest vegetation. Yield from these stands is variable, although productivity is often low (5 to 10 m^3 ha^{-1} yr^{-1}) in comparison with rates achieved in other parts of the world where eucalypts have been introduced (eg South America, Africa, Europe). Consequently, the Government of Kerala is unable to meet annual demand for eucalypt feedstock from the local pulping industry.

In assessing the possible outcomes of the proposed research project we have made a number of assumptions as detailed below and used cost and return analysis to calculate the economic impact of improved productivity of eucalypt plantations. The analysis is based on a 7 year rotation period with one seedling followed by two coppice crops, which is the current harvest cycle and management practice used in Kerala.

Cost of production of eucalypt pulpwood

Costs of production included in the analysis cover the time from the procurement of seeds for planting to the time of maturing of the final coppice crop for felling. Costs of raising and maintenance of seedling crop as well as coppice crops are estimated using data available in the files of the Kerala Forest Department for the years from 1989 to 1994 (unpublished). Costs of the seedling crop in the first year include cost of seed, preparation of seed bed nursery, sowing, watering, weeding, polythene bags, transplanting, planting in the field, weeding, fire control etc. The costs in the subsequent years are mainly for weeding and fire control. Costs of the coppice crop include replanting due to stump mortality, reduction of coppice shoots and fire control. Annual land rental costs are included at the current rate (Table 1).

Plantation productivity and wood price

Return of the eucalypt plantations is in the form of pulpwood and fuel wood and this depends on the productivity and level of stocking in the plantations. Most of the eucalypt plantations in Kerala are understocked. Mean annual yields of *Eucalyptus tereticornis* and *E. grandis* reported by Jayaraman and Krishnankutty (1990) are 5.15 and 9.77 m^3 ha^{-1} of solid wood - equivalent to a dry weight of 5.05 and 7.23 t ha^{-1}. Based on these data we have assumed average wood production rates for both species over a 7 year rotation of 43 t ha^{-1} . The price of this wood, which is utilized by the three pulp based industries in the State, is fixed in long-term contracts between the Kerala Government and industry and ranges from Rs 550 to Rs. 360 t^{-1}. The purpose of these selling arrangements, rather than a market-driven pricing structure, is to encourage development of the pulping industry which is a significant employer of labour both in the production and processing of wood products. The present analysis is based on a weighted average price of Rs 458 t^{-1} (weightings based on quantities and price of wood to individual users).

Table 1 **Cost of establishment and maintenance of eucalypt plantations. (Rs. ha^{-1} ; Source: Kerala Forest Department)**

Year	Cost of raising and maintenance			Establish-ment cost	Land rent	Total Costs		
	Seedling Crop	Coppice Crops I	Coppice Crops II			Seedling Crop	Coppice Crops I	Coppice Crops II
0	1	2	3	4	5	(1+4+5)	(2+4+5)	(3+4+5)
1989	9132	2797	3056	120	1300	10552	4217	4476
1990	1416	1108	1108	130	1300	2846	2538	2538
1991	1208	743	743	140	1300	2648	2183	2183
1992	770	794	794	150	1300	2220	2244	2244
1993	822	845	845	160	1300	2282	2305	2305
1994	947	970	970	160	1300	2407	2430	2430

Costs are compounded assuming an annual interest rate of 12%. (Table 2) The average total cost per crop, Rs. 29,732 ha^{-1}, is utilized in subsequent cost and return analysis.

Table 2 **Compounded total cost of establishing and maintaining eucalypt plantations (Rs. ha^{-1} ; Interest rate = 12%)**

Year	Seedling crop	Coppice Crops I	Coppice Crops II
1989	20828	8324	8835
1990	5016	4473	4473
1991	4167	3435	3435
1992	3119	3153	3153
1993	2863	2891	2891
1994	2695	2722	2722
Total	**38689**	**24998**	**25509**

Cost and return analysis

The costs and return of eucalypt plantations at a rotation age of 7 years are presented in Table 3 and indicates a gross negative margin of Rs. 10,038 ha^{-1}. Increased wood productivity is the only alternative to reverse this trend.

Table 3 Current costs and returns in the production of eucalypt pulp wood.

On-site price of standing timber (Rs t^{-1})	458
Eucalypt wood production during rotation (t ha^{-1})	43
Current gross income during rotation (Rs. ha^{-1})	19,694
Current total cost during rotation (Rs. ha^{-1})	29,732
Current gross margin during rotation (Rs. ha^{-1})	(-) 10,038

Current requirement of eucalypt pulpwood

Annual demand for wood pulp-based industries in Kerala is 390,000 tonne per year (Kerala Forest Department, 1993). Based a rotation period of 7 years, 5,347 ha is available for felling each year. Thus annual wood availability, assuming the current level of productivity, is 229,921 t, leaving a shortfall between pulp wood availability and demand of 160,079 $year^{-1}$ (Table 4).

Table 4 Current supply and demand for eucalypt pulp wood.

Pulp wood requirement (t $year^{-1}$)	390,000
Total area under eucalypt plantations in Kerala	37,429
Annual area available for felling (ha $year^{-1}$)	5,347
Average yield of (t ha^{-1})	43
Pulp wood availability (t $year^{-1}$)	229,921
Shortfall between wood availability and demand (t $year^{-1}$)	160,079

Projections

Increasing productivity from 43 to 73 t ha^{-1} would eliminate the shortfall if demand remains constant. The following analysis assumes that silvicultural options being investigated in this proposal (soil and organic matter conservation and other management practices such as soil trenching, fertilizer application, inter-cropping with legumes and total/partial weed control) provide the mechanisms for this increase. The additional costs of implementing improved silvicultural practices is assumed to be Rs 3500 ha^{-1} .

Table 5 Projected costs and returns in the production of eucalypt pulpwood

Timber price (Rs t^{-1})	458
Projected wood production with improved silviculture (t ha^{-1})	73
Projected gross income (Rs ha^{-1})	33,434
Projected total costs with improved silviculture (Rs ha^{-1})	33,232
Projected net margin with improved silviculture (Rs ha^{-1})	(+) 202

Table 5 shows the costs and returns after implementing the package of practices evolving from the proposed research project on the assumption that increased productivity projections can be attained. The additional gross income generated by enhancing the productivity will be Rs 13,740 ha^{-1} with a gross margin of Rs. 202 ha^{-1}.

The analysis in Table 5 shows plantation productivity increases over a complete rotation of from 43 to 73 t ha^{-1} are required if supply and demand for pulpwood are to be approximately in balance. Based on this scenario, current losses of Rs 53.67 million annually will be reversed to give a small positive margin of Rs 1.08 million $year^{-1}$. It is assumed that additional costs of Rs3,500 ha^{-1} $year^{-1}$ with improved silviculture result from supply of labour and materials. Based on a labour-material ratio of 2:3 and the wage rate as Rs.60 $man\text{-}day^{-1}$, the employment generated is estimated as 0.12 million man-days $year^{-1}$. This excludes the employment generated through supply of additional raw material to the pulp-based industries.

Table 6 **Projected supply of eucalypt pulpwood and added income and employment prospects. (Costs and returns in Rs million year^{-1}).**

Pulpwood demand (t year^{-1})		390,000
Projected pulpwood supply (t year^{-1})		390,331
Current income		105.30
Projected additional income		73.47
Projected total gross income		178.77
Current costs		158.98
Project additional costs @ Rs.3,500 ha^{-1}		18.71
Projected total costs		177.69
Current net income	(-)	53.67
Projected net income	(+)	54.75
Projected net margin	(+)	1.08
Additional employment generated (million man-days year^{-1})		0.12

As mentioned above, the preceding analysis is based on the wood selling policy adopted by the Kerala State Government of maintaining long-term fixed-priced contracts with the major processing industries. This policy is driven largely by social considerations and is aimed at maintaining and developing the employment prospects in the wood production and processing sectors and is unlikely to change in the near future. Nevertheless, it is interesting to explore the consequences of the projected production increases if costs and revenue are inflated at similar rates (12% per annum). Over the 6 year rotation period production returns for plantation wood then exceed Rs 900 t^{-1} and the net margin for harvested plantations increases to Rs 32,761 ha^{-1}. Clearly, if increased production can be achieved through improved silvicultural practices the potential for increased revenue to the State is markedly enhanced. However, the magnitude of this return will depend in part on the future policy adopted by the Government in marketing wood produced from plantation forests.

Australia

In Australia, hardwood plantation forestry is expanding in the southern states (Western Australia, Tasmania, Victoria, South Australia) and more recently new initiatives have commenced in NSW and Queensland. Because of the high production rates achieved in eucalypt plantations in Western Australia this region is expected to become a focal point for intensive forestry in the future. Although plantation forestry is small in comparison with other regions of the world where eucalypts are grown, this new industry has the capacity to impact significantly on Australia's trading position through value adding and import replacement. For example, Australia's consumption of wood based products in 1990-91 was 4 million m^3 of sawn timber, 1 million m^3 of wood based panels and 2.5 million tonnes of paper products. About 30% of sawn timber and paper based products was imported at an annual cost of $2 billion (ABARE 1992). In 1991, Australia's total export of wood products amounted to less than $0.8 billion dollars, more than 70% of which was made up of woodchips exported from native forests (Industry Commission 1993). Thus, Australia's trading deficit in wood products (more than $1 billion annually) derives largely from import of high value paper based products and export of low value raw wood products. Domestic processing of wood for paper based purposes (based on an average stumpage price of $25 m^{-3}) has the potential to increase the product value 3-6 fold through chip production and at least a similar proportion through pulp and paper production (ABARE 1993). Development of sustainable plantation forest systems, the focus of this proposal, will be critical in capturing these benefits in the future.

Significant environmental benefits also result from tree planting. Soil and stream salinity and eutrophication of rivers and estuaries are major environmental problems in many parts of Australia, including the south-west of WA. In this region soil salinity and waterlogging alone are estimated to cost the agricultural industry $140M annually (Bicknell, 1991). Bartle (1992) predicted that the overall costs to remedy land degradation problems in this region through revegetation programs would be between $640 million and $4.8 billion. Re-forestation on the scale required will proceed most rapidly where it is commercially-driven. Establishment of hardwood plantations for pulp production is providing this commercial opportunity in the higher rainfall zone. These plantations are now widespread and provide an ideal framework to examine the longer term impacts of trees on soil fertility.

Tree crops can provide economic benefits through production of wood products, diversification of farm income, and improved productivity of traditional agricultural enterprises (Prinsley, 1992). Economic analysis indicates that returns to landowners from wood production alone vary between 5% and 15% per year and can be as profitable as agricultural crops (Department of Resources Development, 1993; Shea and Bartle, 1988; Bunnings Treefarms). Based on log prices at the stump of $25 per cubic metre and growth rates of 30 cu.m/ha/yr, projected annual returns to growers are expected to be $575 per ha during the first rotation. As establishment costs remain fixed, any reduction in productivity due to decline in soil fertility in second rotation plantings will cause a proportionally larger decrease in annual returns to growers. For example, a decrease in growth from 30 to 25 cu.m/ha/yr would result in a 22% fall in annual returns. Significant loss of productivity and income can also be expected initially where land is returned to agriculture following many years under plantation.

Planning for this new industry has assumed that current high growth rates will be maintained in future rotations (Bunnings Forest Products Pty Ltd, Consultative Environmental Review [CER], 1993). The relatively poor growth of *E. globulus* on ex-forest sites emphasises the importance of developing practices which maintain or improve the productivity of plantations in successive rotations on ex-farm soils. Outcomes from the research detailed in this proposal will benefit plantation growers (private industry, State Government Authorities, individual landholders and private investors) by providing methodologies to assist in sustaining high productivity and minimising rotation length.

Land degradation resulting from changed patterns of land use and exploitive agricultural practices is a problem world-wide. When stable natural vegetation ecosystems are replaced by cropping systems, soil fertility can decline. Likewise, in some environments, where deep rooting perennial vegetation is replaced by annual shallow rooted plants, changes in soil hydrology can result in major environmental problems such as waterlogging, soil salinity and water erosion. This is a particularly important issue in many regions of Australia and in parts of India also. Introduction of trees into rural landscapes offers the opportunity to redress these problems.

2.8 Application of Research

The major thrust of the proposed research is to identify and evaluate at the process level, forest management practices which will allow sustainable production from eucalypt plantation systems. Response to some treatments, such as weed control and nutrient applications, are expected to be evident in the second year after planting and these results could be implemented in management plans immediately. Longer term responses to manipulation of organic matter are likely and their effects on plant growth may be evident to a more limited extent within the time frame of the proposal. Nevertheless, process based measures, such as rates of mineralization of soil nutrients may well provide advanced indications of responses to treatment effects and prove useful surrogates for predicting plant responses. Our ongoing work in Western Australia using similar treatments to those proposed here has shown marked differences between organic matter treatments in both storage and flux of plant-available nutrients within the first year of experimentation.

KFRI works in close collaboration with Kerala Forest Department. The Department is currently following several recommendations evolved through research at KFRI and is highly receptive to ongoing research results. Officers from Kerala Forest Department will assist with site selection and consult on field trial establishment and maintenance in India. This will facilitate immediate transfer of outcomes from our research to normal forest operations. In Australia, our industrial partner is Bunnings Tree Farms, who we are already working with collaboratively. We are also working on several projects with Department of Conservation and Land Management, the other major plantation manager in Western Australia, and we will seek to strengthen these relationships in the current proposal.

Outputs from this research will include scientific papers, contribution to international conferences and working groups (eg CIFOR framework), workshop proceedings, training courses, in-house training of technicians and scientists in our Australian laboratories and information that can be directly applied to soil and forest management prescriptions. In Australia and India some of these benefits will pass to industrial wood companies. CSIRO Forestry and Forest Products already has strong collaborative links with our industry partner in south-west Australia and they provide significant in-kind support for our research. Technology transfer in India will be assisted by collaboration with Kerala Forest Department, which has responsibility for managing Kerala's plantation forests. KFRI works closely with Kerala Forest Department and a number of technologies developed by the Institute are currently being applied on an on-going basis by the Department - eg. techniques for termite control (Nair 1981); disease control protocols for application in seedling nurseries (KFRI 1984). We have had discussions with the Principal Chief Conservator of Forests, Kerala Forest Department aimed at strengthening these ties and to elicit direct collaboration in our proposed project. The Chief Conservator has expressed strong interest in the work. We have also held discussions with the Managing Director and other senior executives of Hindustan Newsprint Limited and have prospects for land and assistance from the company for our experiments. These collaborative arrangements will enhance the possibilities for early application of research outcomes.

A number of scientific participants from KFRI will come to Australia to work in the CSIRO laboratories at Floreat Park. They will also benefit from our close working relationships with our industry partner and with the State Department of Conservation and Land Management. This will ensure exposure to practical silvicultural aspects of plantation forestry in Australia as well as the more detailed process-based scientific studies being conducted at CSIRO. Transfer of technology will result when these personnel return to Kerala after working in Australia. We also plan to hold workshops and field days in both Kerala and Australia to assist in transfer and implementation of research outcomes.

In Australia extensive work has been done during the last two years on developing standards and protocols for establishing *Sustainability Indicators* to be used in establishing *Codes of Forest Practice* (Raison and Khanna 1995). Dr O'Connell has been involved in this work through the Australian Forestry Council working group on Soils and Nutrition. This issue is currently the topic of a nation-wide research initiative recently funded by the *Forest and Wood Products R&D Corporation* and headed by Dr John Turner of NSW State Forests. Development of these codes is currently directed at native forest resources. However, it can be expected that attention will soon also focus on sustainable management of plantation systems. It is crucial that soundly based research underpins codes that are implemented to control future land use decision making in Australia. Such research is currently lacking. Furthermore, considerable work in agriculture has been directed at similar problems and the outcomes from these studies have been only applied to a limited extent to forest systems. We see good prospects for direct transfer of some of these technologies to plantation forestry, and indeed also to native forests, to address the issue of sustainable silvicultural systems. We anticipate that the studies outlined in this proposal will make a significant contribution to the development of quantitative sustainability indicators and forest management codes of practice. Dr O'Connell's ongoing active participation with the Australian Forestry Council working group on Soils and Nutrition will ensure rapid and effective transfer of research outcomes in Australia.

2.9 Impact Assessment

Social and environmental impacts

The social impact of introducing trees into rural landscapes is significant. A major benefit of plantation forestry is to reduce pressure on natural forest resources thus helping to preserve the natural environment and wilderness areas. Furthermore, if the productivity of industrial eucalypt plantations can be increased, it will create more employment opportunities for the local people in plantation forestry and the pulping industries. Raising of nurseries, planting, weeding and harvest operations will provide additional employment and increased income for the general population.

The area under eucalypts in the homesteads of Kerala is estimated to be only about 150 ha (Krishnankutty, 1990). In small homesteads, farmers mostly grow eucalypts in mixtures with other species and utilize the wood for fuel and poles. If the proposed project can demonstrate that growing eucalypts will not lead to adverse effects to soil and surroundings and that it is profitable, more farmers will be interested to grow eucalypts in the homesteads. Additionally, if the proposed silvicultural management options allow sustainable wood production, small landholders will be encouraged to introduce tree crops into their farming systems. This will provide a diversification of enterprise for farming families giving them greater economic freedom and reducing their dependence on traditional crops. This diversification is likely to lead to greater employment opportunities, both in growing and harvesting of trees and in the off-farm processing of wood products. These opportunities are likely to accrue to both men and women in farming areas and in larger towns where processing occurs.

Impact on gender

Kerala's economy is strongly interlinked with its forests and the forest industry is a major employer in the State. About one in ten men and women of the region are employed directly or indirectly in forest-related jobs. Plantations are an important component of the forest industry and the proposed project should have positive benefits for forestry through identification of sustainable forest practices with concomitant enhanced prospects of long-term employment men and women. The pulp and paper processing plants are major employers in the larger cities, while in the countryside both men and women are employed at various stages of planting, maintaining and harvesting of plantations. In general, women handle most of the nursery operations including sowing, thinning, weeding, watering, transportation of seedlings and fertilizer application to out-planted seedlings. If the productivity of eucalypts can be increased through application of research outcomes, more employment opportunities will be provided in the paper and pulp industries as well as in the establishment and maintenance of plantations.

Additionally, eucalypts are also increasingly being grown by small landholders in many parts of India for use in their own households and as a source of income for family units. An important outcome of the research program applied at this local community level should be the impact fuel supplies. Wood is the major source of domestic fuel for households in India. Research leading to improved plantation management and productivity will result in increased fuelwood resources which will ensure maintenance of firewood supply for families. Improved supply of local fuelwood amounts to an increased and more stable income to households and it is expected that this will benefit both men and women in local communities.

2.10 Personnel Involved

Personnel/position	Sex	Percentage time/annum	Funding agency
AUSTRALIA			
1. Dr A.M. O'Connell Senior Principal Research Scientist. Officer-in-Charge CSIRO F&FP, W.A. Overall Project leader	Male	50%	CSIRO

Activities and Responsibilities:

Dr O'Connell has worked in the area of forestry research for the past 20 years. The focus of his research has been the interaction of nutrient cycling and forest management. His work in jarrah and karri forest on the role of forest litter and decomposition processes has helped to provide a scientific basis for understanding the nutritional consequences of forest management practices such as fuel reduction burning in Australian native eucalypt forests. He has published widely in this field and has been invited to contribute several papers for conferences and books. During the past 3 years, Dr O'Connell has worked on nutrient cycling aspects of plantation forests in south-western Australia. His research has centred on the mineralisation of soil organic matter and its role in supplying nitrogen for tree growth. Recently he has developed an empirical model to predict the nitrogen supplying capacity of sites as a tool for managers in planning fertiliser regimes for hardwood plantations. This is being applied in a new project on sustainability, initially supported through *Industry Statement Funds* to CCMAR. Dr O'Connell will have overall responsibility for leading and coordinating the project. He will be in frequent contact with Dr Sankaran to link work in Australia with experiments established in India. He will also take specific responsibility for developing the nitrogen cycling aspects of the project and transferring appropriate technologies to KFRI.

2. Dr T.S. Grove Principal Research Scientist.	Male	50%	CSIRO

Activities and Responsibilities:

Dr Grove commenced his research career in the field of crop and pasture nutrition before moving into the forestry area where he has worked for the last 20 years. During this time he was awarded a PhD degree for studies on growth and nutrient uptake in karri forest species. Over recent years, Dr Grove's research has been in the field of plantation forestry nutrition where he has worked within a team investigating the growth enhancement potential of mycorrhizal fungi. This has been an extensive program funded by the forestry industry (W.A. and Tasmania), a CSIRO/University research grant and Australian Government overseas aid funds through ACIAR. His main role in the mycorrhizal program has been to investigate the functioning of mycorrhizal fungi in relation to soil nutrient supply and other soil factors, and to evaluate the effectiveness of fungal strains in improving tree growth. Through this research Dr Grove has contributed to four major reports to clients and to six invited review papers in addition to publication in journals. He is currently involved in research on the sustainability issues with Dr O'Connell through an initial grant of *Industry Statement Funds* granted to the

CCMAR. Dr Grove will develop the area of tree growth, plant nutrient uptake and assessment of indices of plant and soil nutrient status. He will have responsibility for transferring the technologies developed in Australia to KFRI

3. Mr S.J. Rance

Experimental Scientist.	Male	40%	CSIRO

Activities and Responsibilities:

Mr Rance has 25 years experience in forestry research and has particular expertise in the field of biomass estimation of plantation eucalypts. He has worked in the Northern Territory, Queensland and Western Australia. He has consulted to the Swedish company Interforest AB in Vietnam to establish protocols for estimating biomass production for feed stock to local pulp mills. Recently Mr Rance has been working with Dr O'Connell on nitrogen cycling in *E. globulus* plantations in south-western Australia and is a key member of the research team investigating sustainability in plantations. Mr Rance will collaborate with Dr Grove in developing and transferring methodologies for estimating tree biomass and nutrient uptake.

4. Mr J. Galbraith

Experimental Scientist.	Male	30%	CSIRO

Activities and Responsibilities:

Mr Galbraith has extensive experience in forestry research, having worked in the W.A forestry group for more than 15 years. His areas of expertise and past research experience include instrumentation for monitoring environmental variables, field experimentation and mensuration. He is also qualified in the use of drilling rigs and radioactive sources. His recent research has involved field studies associated with modelling of water use and plantation growth. Mr Galbraith will assist in maintenance of field instrumentation and in collecting data for sub-project 2 in Australia.

5. Ms Tuyen Pham	Female	30%	CSIRO
Chemical Analyst.			

Activities and Responsibilities:

Ms Pham has worked in the soil and plant chemistry laboratory of CSIRO Forestry and Forest Products for the past 3 years. She has extensive experience in laboratory techniques, especially in the use of instrumental methods, having spent more than ten years working with the CSIRO Division of Water Resources in a similar capacity. Ms Pham assumed management of the Division's chemistry laboratory at Floreat Park during 1994. She will be a critical member of the team involved in establishing the analytical facility at KFRI. Initially, Ms Pham will assist in commissioning the main instruments in Australia. The Chief Soil Chemist from KFRI will work in the Perth laboratory at this time to gain experience in instrumentation and to learn some of the experimental procedures. Ms Pham will participate in the initial workshop in Kerala in January-February 1997 and will then spend approximately 2 weeks at KFRI testing the new instruments and establishing the main methodologies to be used in the project.

6. TBA Research Officer	Level 5 Research Scientist	100% 5 years	ACIAR

Activities and Responsibilities:

The research scientists will be primarily responsible for developing and applying methodologies for studying soil carbon and phosphorus status and supply rates. He will work in close collaboration with Dr O'Connell, Dr Grove and Professor Gilkes and will consult frequently with Dr Pax Blamey (ACIAR 9414) on phosphorus methodologies. The scientist will also participate in other aspects of the project relating to nutrient supply and tree nutrition. Carbon and phosphorus methodologies developed in this part of the project will be transferred to researchers at KFRI.

7. TBA **Research Officer**	Post-doctoral Fellow or equiv	100% 3 years	ACIAR

Activities and Responsibilities:

The PDF will have responsibility for developing modelling aspects of the project and applying these to the experiments in India and Australia. He will interact strongly with Dr O'Connell, Associate Professor McMurtrie and Dr Dewar. A major thrust of his work will be to integrate aspects of the three other sub-projects with the aim of predicting consequences of silvicultural options. The aim is to use this methodology to identify "best practice" management options for plantations in India and Australia.

8. TBA **Research Officer**	Post-doctoral Fellow or equiv	30% 3-5 years	CSIRO

Activities and Responsibilities:

The Research Officer will be responsible for the plant physiological measurements with particular emphasis on linking tree water use to soil water storage in sub-projects 2 in Australia. He will interact with Dr Jose Kallarackal from KFRI on methodologies and in the interpretation and linking of results from Australia and India. This Officer will be appointed to the CSIRO laboratories in Perth during the second half of 1996.

9. TBA **Technical Assistant**	CSOF level 3	100% 5 years	ACIAR

Activities and Responsibilities:

The Technical Assistant will have well developed skills in field and laboratory experimentation and will assist in supporting sub-projects 1,2 and 3 in Australia.

10. Professor R.J. Gilkes Head, Department of Soil Science and plant Nutrition University of WA.	Male	10%	UWA

Activities and Responsibilities:

Professor Gilkes has many years experience in academia and soil science. His field of expertise is soil mineralogy and the interaction of applied phosphate fertilizers with the soil minerals. He has published extensively on the effects of soils, especially those of lateritic origin, on availability of various forms of applied phosphate. He has travelled extensively in South and South East Asia, including Kerala, and has been involved with supervision of a number postgraduate students from this region. Professor Gilkes will assist in developing appropriate methodologies to assess soil phosphate status and supply rate. He will act as academic supervisor to Indian post graduate students attached to the project in Australia.

11. Assoc Prof P. Saffigna Head, School of Applied Science Griffith University QLD.	Male	10%	Griffith University

Activities and Responsibilities:

Associate Professor Saffigna has many years experience in research on nutrient cycling in agricultural systems. His particular interest is in nitrogen nutrition and he has applied stable isotope techniques to elucidate the mechanisms of nitrogen turnover in a range of managed ecosystems. He has recently developed novel N^{15} techniques to measure denitrification potential of soils. Although applied initially to sugar cane farming systems, these techniques have wide application. They appear particularly relevant to the inter-rotation period of plantation forests when large stores of nitrate can accumulate in soil and nitrogen loss through denitrification is likely. We will collaborate with Associate Professor Saffigna in utilizing these methodologies to study denitrification potential in relation to silviculture in soils from eucalypt plantations in Australia and India. Additionally, we will evaluate the possibility of utilizing expertise and facilities within Griffith University to investigate soil organic matter characteristics using ^{13}C NMR spectroscopy.

12. A. Prof. R. McMurtrie Associate Professor. School of Biological Science. UNSW	Male	10%	University of New South Wales

Activities and Responsibilities:

Associate Professor McMurtrie's field of expertise is in the development and application of process-based models for study of natural and plantation forests. With Dr Roddy Dewar and other members of his research group at University of New South Wales, he has developed and tested a number of simulation models to describe the functioning of forests and predict their response to disturbance. Associate Professor McMurtrie is a world authority in his field. In recognition of his work in the application of modelling procedures to the understanding of the functioning of forest ecosystems he was awarded the International Union of Forestry Research Organisation's Scientific Achievement Award at the World IUFRO Congress in 1990. This is the highest honour for international forest research. The Post Doctoral Fellow appointed in the third year of the project will collaborate with Assoc. Professor McMurtrie in applying a suite of his models to integrate experimental results and predict long-term consequences of the various silvicultural options that we will apply.

<u>INDIA</u>

1. Dr K V Sankaran, Scientist-C Division of Pathology Project leader in India	Male	80%	KFRI

Activities and Responsibilities:

Major research interests include litter dynamics and nutrient cycling in tropical plantations, mycorrhizal association in forest trees and forest pathology. He has 20 years research experience in tropical forestry, soil microbiology and plant pathology. Undertaken and successfully completed five major research projects of which two were on litter dynamics and nutrient cycling in plantation forests. Author of over 50 research papers and 5 research reports. Publications include a review article on "Organic matter accretion, decomposition and mineralization in tropical plantation forests". Was awarded a Darwin Fellowship in Biosystematics (1994-95) by the UK Department of Environment to work at IMI, U.K. Experienced in project management, evaluation and monitoring. Overseas experience in U.K. Canada, Australia, Denmark, Indonesia and Singapore.

2. Dr M. Balagopalan Scientist E-1 Division of Soil Science	Male	60%	KFRI

Activities and Responsibilities:

Major research interest in soil organic matter studies and its role in plant nutrition. Other areas of interest are soil fertility decline studies with special reference to physical and chemical soil factors, nutrient management in plantations etc. Over 18 years experience in tropical forestry research. Has carried out studies relating to enhancement of productivity in *Eucalyptus grandis* through fertilizer inputs and other cost effective treatment, soil nutrient management of teak plantation and impact of successive rotations of teak on soil conditions. Author of 32 scientific papers and 19 conference papers. Overseas experience in Malaysia. Member of Indian Society of Soil Science, Academy of Plant Sciences and Life member of Society of Soil Biology and Ecology.

3. Dr S. Sankar Scientist E-1 Scientist-in-Charge Division of Soil Science	Male	25%	KFRI

Activities and Responsibilities:

Soil related research on sustainable management of forests. Experience in land capability, land suitability assessment, foliar analysis, determining limits to tree growth, nutrient recommendation, raising nurseries, planting and after care. Coordinates massive eco-restoration programmes and wasteland development activities. Exposed to hydrometeorology and upland-down stream linkages. Has published 4 papers and 10 research reports. Experienced in project management, evaluation and monitoring.

4. Dr Jose Kallarackal Scientist E-1 Division of Physiology	Male	50%	KFRI

Activities and Responsibilities:

Holds a doctorate in Botany from the University of Delhi and has 20 years of research experience in seed physiology, phloem translocation and environmental/tree physiology. Post doctoral work on phloem translocation at the university of New England, Australia. Was awarded on Alexander von Humboldt Fellowship and worked on water assimilate transport at the University of Bayreuth, Germany during 1986-87. Has published over 36 research papers and 3 research reports. Experienced in handling instrumentation in weather measurement, infra red gas analysis, data acquisition using data loggers, radio active tracer methods etc.

5. Mr C.K. Soman Senior Scientific Assistant Division of Physiology	Male	50%	KFRI

Activities and Responsibilities:

Holds M.Sc. degree in Botany. Has seventeen years research experience in physiology of tree propagation, seed storage, tree seedling growth, water relations and climatology. Experienced in handling various instruments used in eco-physiological, biochemical and environmental studies. Has authored 11 research papers, one research report and seven popular articles

6. Dr. J.K. Sharma Scientist F Scientist-in-Charge Division of Pathology	Male	10%	KFRI

Activities and Responsibilities:

Holds a doctorate in Botany - Plant Pathology. Has more than 25 years teaching experience on different aspects of epidemiology and control of diseases and tree improvement of eucalypts in relation to disease resistance and higher productivity. Dr Sharma has 30 years experience in research in Forest Pathology, including 4.5 years in Australia, and has presented research papers in International Conferences in USA, New Zealand, Japan, India, Australia, Canada and Finland. Has published 85 research papers and 4 research reports on forest disease survey and control of seedling diseases, epidemiology and control of cylindrocladium leaf blight of eucalypts and mycorrhiza. He has worked as an FAO consultant in Vietnam identifying disease problems in eucalypts, is an elected fellow of Indian Phytopathological Society and Chairman of IUFRO workshop party 52-06-15 (Diseases of plantations in the tropics).

7. Mr K.C. Chacko Silviculturist E1 and Scientist-in-Charge Division of Silviculture	Male	20%	KFRI

Activities and Responsibilities:

Holds an M.Sc. (Environmental Forestry) and Post Graduate Honours Diploma (Forestry). Over 20 years experience in forestry and silvicultural research. Experience include formulation, implementation and evaluation of multidisciplinary projects; editing research projects and research papers; extension activities in forestry; teaching post graduate and undergraduate students, establishment and management of forest nurseries and plantations, designing organising and conducting training programme for forestry personnel from India and abroad, and offering consultation to entrepreneurs in plantation forestry. Has about 25 research reports and papers. Overseas visits include United Kingdom, Ireland, Myanmar, Malaysia, Indonesia, Thailand and Singapore.

8. Dr R.C. Pandalai Silviculturist-C Division of Silviculture	Male	30%	KFRI

Activities and Responsibilities:

Has 13 years research experience in Silviculture. Major research interest include dry zone afforestation, afforestation of industrially polluted areas, cultivation and management of forest trees including bamboos and rattans. Published 8 research reports, 3 research papers and 2 popular articles. Recent work includes standardization of nursery and plantation techniques of 8 rattan species in the Western Ghats, Kerala funded by IDRC, Canada. Overseas experience in China and USA.

9. Dr M. Balasundram Scientist-C Division of Pathology	Male	30%	KFRI

Activities and Responsibilities:

Has 17 years research experience in soil microbiology and plant pathology. Research interests include nitrogen fixation in forest trees and soil microbiology. Successfully completed and prepared a research report on Root nodulation potentialities of *Leucaena leucocephala* in Kerala. Research components involving nitrogen fixation by *Rhizobium/Frankia* completed in two other major research projects. Published over 35 research papers and seven research reports. Overseas experience in Finland and Thailand.

10. Dr C.N Krishnankutty

Scientist-C	Male	20%	KFRI
Division of Statistics			

Activities and Responsibilities:

Holds Masters Degree in Statistics and Economics. Major research interest include econometrics. Published 5 research reports and 8 research papers. One of the major studies taken by him was in the demand and supply of wood in Kerala (aided by the World Bank). Recent work includes a study on Bamboo marketing in Kerala - India funded by National Resources Institute, U.K. Has recently submitted PhD thesis on the topic "Demand and Supply of teak wood in Kerala".

2.11 Project Review

Mid-term review at year 2.5 to 3. Final external review in year 5.

2.12 Literature Cited

ABARE (1992). In : Australian's Timber and Forest Industry : A Strategy for the future. Prospects for Australia's wood based industry : effect of some microeconomic policy reforms. Sydney, May 1992. pp2-14.

ABARE (1993). Competitiveness of selected Australian plantation forests. ABARE Research Report 93.10. 74pp.

Aber, J.D. and Melillo, J.M. 1982. Nitrogen immobilization in decaying hardwood leaf litter as a function of initial nitrogen and lignin content. Canadian Journal of Botany, 60, 2263-2269.

Aber, J.D., Melillo, J.M. and McClaugherty, C.A. 1990. Predicting long-term patterns of mass loss, nitrogen dynamics, and soil organic matter formation from initial fine litter chemistry in temperate forest ecosystems. Canadian Journal of Botany, 68, 2201-2208.

Abrams, M.M. and Jarrell, W.M. (1992). Bioavailability index for phosphorus using ion exchange resin impregnated membranes. *Soil Science Society America Journal* 56, 1532-1537.

Alexander, T.G. and Mary, M.V. 1984. Effect of mussoriephos on growth of *Eucalyptus tereticornis* seedlings. KFRI Research Report No. 23. 7p.

Alexander, T.G., Balagopalan, M., Mary, M.V. and Thomas, T.P. (1981). Properties of soils under eucalypts. KFRI Research Report No. 8, KFRI, Peechi, India. 12p

Anonymous (1994). Annual report 1993-94, Indian council of Forestry Research and Education, Dehra Dun, India. 274pp.

Attiwill, P.M. 1968. Loss of elements from decomposing litter. Ecology, 49, 142-145.

Attiwill, P.M. (1979). Nutrient cycling in *Eucalyptus obliqua* (L'Herit) forest. III. Growth, biomass and net primary production. Australian Journal of Botany 27, 439-458.

Attiwill, P. (1991). Nutritional resilience of wet sclerophyll forests: Recovery after disturbance. Proceedings Australian Forest Soils Nutrition Conference. (Ed P.J. Ryan). Forestry Commission of NSW. pp 172-179.

Attiwill, P.M. (1994). The disturbance of forest ecosystems : the ecological basis for conservative management. Forest Ecology and Management 63, 247-300.

Attiwill, P.M. (1994). Ecological disturbance and conservative management of eucalypt forests in Australia. Forest Ecology and Management 63, 303-348.

Avalakki, U.K., Strong, W.M. and Saffigna, P.G. (1995a). Measurement of gaseous emissions from denitrification of applied nitrogen-15. I. Effects of cover duration. *Australian Journal of Soil Research* 33, 77-87.

Avalakki, U.K., Strong, W.M. and Saffigna, P.G. (1995a). Measurement of gaseous emissions from denitrification of applied nitrogen-15. I. Effects of temperature and added straw. *Australian Journal of Soil Research* 33, 89-99.

Baker, T.G. and Attiwill, P.G. 1985. Loss of organic matter and elements from decomposing litter of Eucalyptus obliqua L'Herit and Pinus radiata D.Don. Australian Forest Research, 15, 309-319.

Balagopalan, M. (1992) Impact on soils of growing eucalypts in Kerala. In: Proceedings of workshop on Environmental problems in Kerala December 1992, Palakkad, Kerala.

Balagopalan, M. and Jose, A.I. 1983. Changes in organic carbon and different forms of nitrogen under first and second rotation (coppiced) eucalypt plantations. Agricultural Research Journal of Kerala, 21, 57-62

Balagopalan, M and Alexander, T.G. (1983). Organic matter dynamics in teak and eucalypt plantations. KFRI Research Report No. 20, KFRI, Peechi, India. 21p.

Bargali, S.S. and Singh S.P. 1991. Aspects of productivity and nutrient cycling in an 8-year-old *Eucalyptus* plantation in a moist plain area adjacent to central Himalaya, India. Canadian Journal of Forest Research, 21, 1365-1372.

Bargali, S.S, Singh, S.P. and Singh, R.P. 1992a. Structure and function of an age series of eucalypt plantations in Central Himalaya. I. Dry matter dynamics. Annals of Botany, 69, 405-411.

Bargali, S.S, Singh, S.P. and Singh, R.P. 1992b. Structure and function of an age series of eucalypt plantations in Central Himalaya. II. Nutrient dynamics. Annals of Botany, 69, 413- 421.

Bargali, S.S, Singh, S.P. and Singh, R.P. 1993. Patterns of weight loss and nutrient release from decomposing leaf litter in an age series of eucalypt plantations. Soil biology and Biochemistry, 25, 1731-1738.

Barrow, N.J. (1980). Differences amongst a wide-ranging collection of soils in the rate of reaction with phosphate. *Australian Journal of Soil Research*, 18, 215-224.

Bartle, J. (1992). Revegetating the Farm: How big is the job? *Land and Water Research News*, 13, 19-21.

Bekunda, M.A., Smethurst, P.J., Khanna, P.K. and Willett, I.R. (1990). Effects of post-harvest residue management on labile soil phosphorous in a *Pinus radiata* plantation. *Forest Ecology and Management*, 38, 13-25.

Berg, B. and Staaf, H. (1980). Decomposition rate and chemical changes in Scots pine needle litter. II. Influence of chemical composition. In: Person, T. ed, Structure and Function of Northern Coniferous Forests. Ecological Bulletins (Stockholm) 32, 373-390.

Berg, B. and Staff, H. (1981). Leaching, accumulation and release of nitrogen in decomposing forest litter. Ecological Bulletins, 33, 163-178.

Berg, B. and Soderstrom, B. 1979. Fungal biomass and nitrogen in decomposing Scots pine needle litter. Soil Biology and Biochemistry, 11, 339-341.

Bernhard-Reversat, F. 1993. Dynamics of litter and organic matter at the soil-litter interface in fast-growing tree plantations on sandy ferrallitic soil (Congo). Acta Ecologica, 14, 179-195.

Bicknell, D. (1991). The role of trees in providing shelter and controlling erosion in the dry temperate and semi-arid southern agricultural areas of Western Australia. *In* : "The role of Trees in Sustainable Agriculture". (Compiled by P. Scott), pp. 21-39.

Binkley, D. 1992. Mixtures of nitrogen-fixing and non-nitrogen-fixing species. In: Cannell, M.G.R., Malcolm, D.C. and Robertson, P.A., eds, The Ecology of Mixed-species Stands of Trees. Oxford, Blackwell Scientific, 99-123.

Binkely, D. and Matson, P. (1983). Ion exchange resin bag method for assessing forest soil nitrogen availability. Soil Sci. Soc. Am. J., 47, 1050-1052.

Binkley,D., Dunkin, K.A., DeBell, D. and Ryan, M.G. 1992. Production and nutrient cycling in mixed plantations of *Eucalyptus* and *Albizia* in Hawaii. Forest Science, 38, 393-408.

Biswas, K. 1934. Some foreign weeds and their distribution in India and Burma. Indian Forester 60: 861-864.

Bolland, M.D.A. and Bowden, J.W. (1986). Summary of rock phosphate experiments in south-western Australia. Journal of the Australian Institute of Agricultural Science, 4, 227-236.

Boland, M.D.A., Gilkes, R.J., Brennan, R.F. and Allen, D.G. (1996) Comparison of seven phosphorus sorption indices. *Australian Journal of Soil Research*. 34, 81-89.

Bormann, B.T. and Gordon, T.C. 1989. Can intensively managed forest ecosystems be self-sufficient in nitrogen. Forest Ecology and Management, 29, 95-103.

Bradstock, R. 1981. Biomass in an age series of *Eucalyptus grandis* plantations. Australian Forest Research, 11, 111-127.

Brasell, H.M. and Sinclair, D.F. 1983. Elements returned to forest floor in two rain forest and three plantation plots in tropical Australia. Journal of Ecology, 71, 367-378.

Brix, H. (1972). Nitrogen fertilization and water effects on photosynthesis and earlywood-latewood production in Douglas-fir. Canadian Journal of Forest Research, 2, 467-478.

Brown, A. (1996). Sustainable plantations. In Better Management of Soil, Water and Nutrients in Tropical Plantation Forests. (Eds A.G. Brown and EKS Nambiar). ACIAR-CIFOR-CSIRO, in preparation.

Bunnell, F.L and Tate, D.E.N. (1974). Mathematical simulation models of decomposition processes. In: Holding, A.J., Heal, O.W., MacLean Jr, S.F. and Flanagan, P.W., eds, Soil Organisms and Decomposition in Tundra. Stockholm, Tundra Biome Steering Committee, 207-255.

Bunnings Forest Products Pty Ltd, (1993). Proposal for the export of *Eucalyptus globulus* paper pulp woodchips through the port of Bunbury. Consultative Environmental Review [CER], 57pp.

Cabrera,M.L. (1993). Modeling the flush of nitrogen mineralization caused by drying and rewetting soils. Soil Sci. Soc. Am. J., 57, 63-66.

Cellier, K.M., Boardman, R., Boomsma, D.B. and Zed, P.G. (1985). Response of *Pinus radiata* D. Don to various silvicultural treatments on adjacent first- and second-rotation sites near Tantanoola, South Australia. I Establishment and Growth up to Age 7 Years. *Australian Forest Research*, 15, 431-437.

Choudhury, A.K. 1972. Controversial *Mikania* (Climber) - A threat to the forest and Agriculture. Indian Forester 98: 172-186.

Clark, J. (1995) Australia's Plantations. A Report to the State Conservation Councils. Environment Victoria Inc., North Melbourne.

Comins, H.N. and McMurtrie, R.E. (1993). Long-term biotic response of nutrient-limited forest ecosystems to CO_2 enrichment : equilibrium behaviour of integrated plant-soil models. *Ecol. Appl.* 3, 666-681.

Constantinides, M. and Fownes, J.H. 1994. Nitrogen mineralization from leaves and litter of tropical plants: relationship to nitrogen, lignin and soluble polyphenol concentrations. Soil Biology and Biochemistry, 26, 49-55.

Dalal, R.C. and Hallsworth, E.G. (1976). Evaluation of the parameters of soil phosphorus availability factors in predicting yield response and phosphorus uptake. *Soil Science Society America Journal* 40, 541-546.

Davidson, J. (1995). Ecological aspects of eucalypt plantations. In: Proceedings of the Regional Expert Consultation on Eucalyptus. FAO Regional Office for Asia and the Pacific, Bangkok. Vol. I, pp 35-72.

Deans, J.R., Molina J.A.E. and Clapp, C.E. (1986) Models for predicting potentially mineralizable nitrogen and decomposition rate constants. Soil Sci. Soc. Am. J., 50, 323-326.

Department of Resource Development (1993). Pulp and Paper Manufacture in the South West of Western Australia. TBW Print Productions, Perth. 16p.

Dewar R. and McMurtrie, R. (1966a). Analytical model of stemwood growth in relation to nitrogen supply. *Tree Physiology*, 16, 181-171.

Dewar R. and McMurtrie, R. (1966b). Sustainable stemwood yield in relation to the nitrogen balance of forest plantations. : a model analysis. *Tree Physiology*, 16, 173-182.

Farrell, P.W., Flinn, D.W., Squire, K.O. and Craig, F.G. (1986). Maintenance of productivity of radiata pine monocultures on sandy soils in southeast Australia. *In*: Forest Site and Productivity. (Ed. S.P. Gessel). pp. 127-136, Martinus Nijhoff Publishers, Dordrecht, Netherlands.

Fassbender, H.W., Alpizar, L., Heuveldop, J., Folster, H. and Enriquez, G. 1988. Modelling agroforestry systems in cacao (*Theobroma cacao*) with laurel (*Cordia alliodora*) and poro (*erythrina poeppigiana*) in Costa Rica. III. Cycles of organic matter and nutrients. Agroforestry Systems, 6, 49-62.

Fillery, I.R. and McInnes, K.J. (1992). Components of the fertiliser nitrogen balance for wheat production on duplex soils. *Australian Journal of Experimental Agriculture*, 32, 887-899.

Fox, R.H., Myers, R.J.K and Vallis, I. 1990. the nitrogen mineralization rate of legume residues in soil as influenced by their polyphenol, lignin, and nitrogen contents. Plant and Soil 129, 251-259.

Gadgil, R.L., Sandberg, A.M. and Graham, J.D. 1984. *Lupinus arboreus* and inorganic fertilizer sources of nitrogen for *Pinus radiata* on a coastal sand. New Zealand Journal of Forest Science, 14, 257-276.

Gentilli, J. (1989). Climate of the jarrah forest. In 'The Jarrah Forest. A Complex Mediterranean Ecosystem'. (Eds B. Dell, J.J Havel and N. Malajczuk) pp. 23-40. (Kluwer Academic Publishers : London).

George, M. and Varghese, G. 1990. Nutrient cycling in *Eucalyptus globulus* plantation I. Organic matter production, nutrient accumulation in standing crop and nutrient removal through harvest. Indian Forester, 116, 42-47.

Gholz, H.L., Perry, C.S., Cropper, W.P. and Hendry, L.C. 1985. Litterfall, decomposition, and nitrogen and phosphorus dynamics in a chronosequence of slash pine (*Pinus elliottii*) plantations. Forest Science, 31, 463-478.

Gilkes, R.J. and Hughes J.C. (1994). Sodium fluoride pH of South-western Australian soils as an indicator of P-sorption. *Australian Journal of Soil Research* 22, 755-766.

Goncalves, J.L.M. and Carlyle, J.C. (1994). Modelling the influence of moisture and temperature on net nitrogen mineralization in a forested sandy soil. Soil Biol. Biochem., 26, 1557-1564.

Golley, F.B. 1983a. Nutrient cycling and nutrient conservation. In: Golley,F.B., ed, Tropical Rain Forest Ecosystems. Structure and Function. Amsterdam, Elsevier Scientific, 137-156.

Golley, F.B. 1983b. Decomposition. In: Golley,F.B., ed, Tropical Rain Forest Ecosystems. Structure and Function. Amsterdam, Elsevier Scientific, 157-166.

Goncalves, J.L.M. and Carlyle, J.C. (1994). Modelling the influence of moisture and temperature on net nitrogen mineralization in a forested sandy soil. Soil Biol. Biochem., 26, 1557-1564.

Granhall, V. and Lindberg, T. (1977). Nitrogen fixation in some coniferous forest ecosystems. In: Granhall, V. ed., Environmental role of N2 fixing blue green algae and symbiotic bacteria. Ecological Bulletin (Stockholm), 26, 178-192.

Grove, T.S. (1990). Twig and foliar nutrient concentrations in relation to nitrogen and phosphorus supply in a eucalypt (*Eucalyptus diversicolor* F. Muell.) and an understorey legume (*Bossiaea laidlawiana* Tovey and Morris). *Plant Soil* 126, 265-275.

Grove, T.S. and O'Connell, A.M. (1995). Inter-rotation site management to maintain the productivity of eucalypt plantations. In: *Sustainable Forest Management.* Research Working Group 3 meeting, September 24-29, Busselton WA.

Hedley, M.J., Stewart, J.W.B. and Chauhan, B.S. (1982). Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. *Soil Science Society America Journal* 46, 970-976.

Herbert, M.A., Schonau, A.P.G. 1989. Fertilising commercial forest species in Southern Africa: research progress and problems. Part I. South African Forestry Journal 151: 58-70.

Herbert, M.A., Schonau, A.P.G. 1990. Fertilising commercial forest species in Southern Africa: research progress and problems. Part II. South African Forestry Journal 152: 34-42.

Herrera, R, and Jordan, C.F. 1981. Nitrogen cycle in a tropical Amazonian rain forest: the caatinga of low mineral status. In: Clark, F.E. and Rosswall, T., eds, Terrestrial Nitrogen Cycles. Ecological Bulletins, 33, 493-505.

Hillerdal-Hagstromer, K., Mattson-Djos, E. and Hellkvist, J. (1982). Field studies of water relations and photosynthesis in Scots pine. II Influence of irrigation and fertilization on needle water potential of young pine trees. Physiol. Plant. 54, 295-301.

Hingston, F.J., O'Connell, A.M. and Grove, T.S. 1989. Nutrient cycling in jarrah forest. In : The Jarrah Forest. A Complex Mediterranean Ecosystem (edited by B. Dell, J.J. Havel and N. Malajczuk) Kluwer Academic Publishers. pages 155-177.

Holt, J.A. and Spain, A.V. 1986. Some biological and chemical changes in a North Queensland soil following replacement of rain forest with *Araucaria cunninghamii* (Coniferae: Araucariaceae). Journal of Applied Ecology, 23, 227-237.

Industry Commission (1993). Draft report : Adding further value to Australia's forest products. 318pp.

James, E.J. and Mohan R. 1986. Regional monthly rainfall run-off model for the Chaliyar basin - Malabar Coast. Proceeding of the 53rd Annual R&D Session, CWRDM, Kerala.

Jayaraman, K. and Krishnankutty, C.N. (1990). A data bank for forestry sector in Kerala. KFRI Research Report No. 66, KFRI, Peechi, India. 27p

Kadeba, O. and Aduayi, E.A. (1985). Litter production, nutrient cycling and litter accumulation in *Pinus caribaea* Morelet va. *hondurensis* stands in the northern Guinea savanna of Nigeria. *Plant and Soil* 86, 197-206.

Kadeba, O. and Aduayi, E.A. (1985). Dry matter production and nutrient distribution in a *Pinus caribaea* stand planted in a subhumid tropical savanna site. *Oikos* 46, 237-242.

Kallarackal, J. (1993) Studies on water use, photosynthesis and growth of eucalypts. KFRI Research Report No. 88, KFRI, Peechi, India. 76p

Kallarackal, J. and Soman, C.R. 1996. Water use of *Eucalyptus tereticornis* stands of differing density in southern India. Tree Physiology. (in press).

Keeney, D.R. and Bremner, J.M. (1966). A chemical index for soil nitrogen availability. Nature, 211, 892-893.

Keeves, A. (1966). Some evidence of loss of productivity with successive rotations of *Pinus radiata* in the south-east of South Australia. *Australian Forestry*, 30, 51-63.

KFRI (1984) Nursery diseases of eucalypts in Kerala and their control. KFRI Information Bulletin No. 6. KFRI, Peechi, India. 6pp.

Khanna, P.K. (1994). Evaluating various indices for measuring N and P status of forest stands with examples from pine and eucalypt sites. Interciencia 19, 366-372.

Kinchesh, P., Powlson, D.S. and Randall, E.W. (1995a). ^{13}C NMR studies of organic matter in whole soils : I. Quantitation possibilities. *European Journal of Soil Science* 46, 125-138.

Kinchesh, P., Powlson, D.S. and Randall, E.W. (1995b). ^{13}C NMR studies of organic matter in whole soils : II. A case study of some Rothamstead soils. *European Journal of Soil Science* 46, 139-146.

Kirschbaum, Miko U.F. (1995). Modelling carbon and nitrogen dynamics in soils with a modified version of CENTURY model. In : Measurement and modelling of soil nitrogen mineralization in Australian forests. Workshop Proceedings June 19-21, Hobart. CSIRO Division of Forestry. pp 19-32.

Konboon, Y. and Lefroy, R.D.B. (1995). Development of an in-vitro perfusion method to estimate residue breakdown rates. In: Soil Organic Matter Management for Sustainable Agriculture. Eds RDB Lefroy, GJ Blair and ET Craswell. pp 120-123. ACIAR, Canberra.

Krishnankutty, C.N. (1990). Demand and supply of wood in Kerala. KFRI Research Report No. 67, KFRI, Peechi, India. 66p.

Kumar, V. (1991). Eucalyptus in the forestry scene in India. In: Proceedings Symposium on Intensive Forestry : The Role of Eucalypts. Durban, South Africa. Vol 2, pp1105-1116.

Kumar, V., Gilkes, R.J. and Bolland, M.D.A. (1992). A comparison of seven soil P tests for plant species with different external P requirements grown on soils containing rock phosphate and superphosphate residues. *Fertilizer Research* 33, 35-45.

Kumar, V., Gilkes, R.J., Armitage, T.M. and Bolland, M.D.A. (1994). Identification of residual P compounds in fertilized soils using density fractionation, X-ray diffraction, scanning and transmission electron microscopy. *Fertilizer Research* 37, 133-149.

Lefroy, R.D.B. and Blair, G.J. (1994). The dynamics of soil organic matter changes resulting from cropping. In: Transactions 15th World Congress of Soil Science, Vol 9, pp235-245.

Lisanework, N. and Michelsen, A. 1994. litterfall and nutrient release by decomposition in three plantations compared with a natural forest in the Ethiopian highland. Forest Ecology and Management, , 65, 149-164.

Lodge, D.J. 1987. Nutrient concentrations, percentage moisture and density of field-collected fungal mycelia. Soil Biology and Biochemistry, 19, 727-733.

Lodge, D.J., McDowell, W.H. and McSwiney, C.P. 1994. The importance of nutrient pulses in tropical forests. Tree, 9, 384-387.

Loginow, W., Wisniewski, W., Gonet, S.S and Ciescinska, B. (1987). Fractionation of organic carbon based on susceptibility to oxidation. *Polish Journal of Soil Science* XX/1, 47-52.

Lousier, J.D. and Parkinson, D. 1976. Litter decomposition in a cool temperate deciduous forest. Canadian Journal of Botany, 54, 419-436.

Lousier, J.D. and Parkinson, D. 1978. Chemical element dynamics in decomposing leaf litter. Canadian Journal of Botany, 56, 2795-2812.

Lugo, A.E., Wang, d. and Bormann, F.H. 1990a. A comparative analysis of biomass production in five tropical tree species. Forest Ecology and Management, 31, 153-166.

Lugo, A.E. , Cuevas, E. and Sanchez, M.J. 1990b. Nutrient and mass in litter and top soil of ten tropical tree plantations. Plant and Soil, 125, 263-280.

Maclean, D.A. and Wein, R.W. 1978. Weight loss and nutrient changes in decomposing litter and forest floor material in New Brunswick forest stands. Canadian Journal of Botany, 56, 2730-2749.

Madhavan Nair, J., Deo, A.D., Nair, T.J.C., Kumar, D. and Ramaswamy, V. (1986). Reclamation of grasslands at Kumamavu, Kerala. In: Eucalypts in India : Past, Present and Future. Eds J.K. Sharma *et al.* pp 200-209. KFRI, Peechi.

Maheswari, S. and Jivendra, A. (1988). Pulp and paper making characteristics of a few hardwoods of Indian origin. In : Proceedings of the Tropical Wood Pulp Symposium 1988. Ed Alfred Wong. Arboken Inc. Canada and Benn Publ. Ltd. pp 112-124.

Maheswaran, J. and Gunatilleke, I.A.U.N. 1988. Litter decomposition in a lowland rain forest and a deforested area in Sri Lanka. Biotropica, 20, 90-99.

Mailly, D. and Margolis, H.A. 1992. Forest floor and mineral soil development in *Casuarina equisetifolia* plantations on the coastal sand dunes of Senegal. Forest Ecology and Management, 55, 259-278.

Maimone, R.A., Morris, L.A. and Fox, T.R. (1991). Soil nitrogen mineralization potential in a fertilized loblolly pine plantation. Soil Sci. Soc. Am. J., 55, 522-527.

Mary, M.V. and Sankaran, K.V. (1991). Ex-situ decomposition of leaf litters of teak, eucalypt and albizia. KFRI Research Report No. 71, KFRI, Peechi, India.

Mason, M.G. and Rowland, I.C. (1990). Nitrogen fertiliser response of wheat in lupin-wheat, subterranean clover-wheat and continuous wheat rotations. *Australian Journal of Experimental Agriculture*, 30, 231-236.

Mason, M.G. and Rowland, I.C. (1992). Effect of amount and quality of previous crop residues on the nitrogen fertiliser response of a wheat crop. *Australian Journal of Experimental Agriculture*, 32, 363-370.

Mathew T.J. 1987. Simple methods of localised water conservation. Bhagirath (Quarterly Journal of the Central Water Commission), October issue.

McArthur, W.M. (1991). Reference soils of south-western Australia. 265pp.

McArthur, W.M. and Clifton, A.L. (1975). Forestry and agriculture in relation to soils in the Pemberton area of Western Australia. CSIRO Australia. Division of Soils. Soils and Land Use Series No. 54.

Mead, J.A. (1981). A comparison of the Langmuir, Freundlich and Temkin equations to describe phosphate adsorption properties of soils. *Australian Journal of Soil Research* 19, 333-342.

Menon, R.G., Chien, S.H., Hammond, L.L. and Arora, B.R. (1990) Sorption of phosphorus by iron oxide-impregnated filter paper (P_i soil test) imbedded in soil. *Plant and Soil* 126, 287-294.

Menon, P.A. and Rajan, C.K. (1989). Climate of Kerala. Classic Publishing House, Cochin, India. 136p

Molina, J.A.E., Clapp, C.E. and Larson, W.E. (1980). Potentially mineralizable nitrogen in soil: the simple exponential model does not apply for the first 12 weeks incubation. Soil Sci. Soc. Am. J., 44, 442-443.

Morris, A.R. (1986). Soil fertility and long term productivity of *Pinus patula* plantations in Swaziland. Thesis, University of Reading, U.K.

Motavalli, P.P., Palm, C.A.., Parton, W.J., Elliott, E.T. and Frey, S.D. 1994. Comparison of laboratory and modeling simulation methods for estimating soil carbon pools in tropical forest soils. Soil Biology and Biochemistry, 26, 935-944.

Myers, B.J. (1988). Water stress integral a link between short-term stress and long-term growth. Tree physiology. 4:315-323.

Myers R.J.K., Palm, C.A., Cuevas, E., Gunatilleke, I.U.N. and Brossard, M. (1994). The synchronisation of nutrient mineralization and plant demand. In: The Biological Management of Tropical Soil Fertility (eds. P.L. Woolmer and M.J. Swift). John Wiley and Sons, Chichester. pp81-136.

Nair, K.S.S. and Varma, R.V. (1981) Termite control in eucalypt plantations. KFRI Research Report No. 6, KFRI, Peechi, India. 48pp.

Nambiar, E.K.S. and Sands, R. 1993. Competition for water and nutrients in forests. Canadian Journal of Forest Research, 23, 1955-1968.

Nambiar, E.K.S. (1995). Sustained productivity of forest: A challenge. In: Soil Science Society of America Proceedings on Sustained Productivity of Forests, Seattle.

Nambiar, E.K.S. and Nethercott, K.H. 1987. Nutrient and water availability to growth of young radiata pine plantations intercropped with lupins. New Forests, 1, 117-134.

Nambiar, E.K.S. and Brown, A.G. (1995). A strategy for sustained productivity of tropical plantations : Science and practice. In: Soils of Tropical Forest Ecosystems. Eds A. Schulte and D. Ruhiyat. Vol 4 pp 5-20. Mulawarman University Press, Samarinda.

Nandi, A., Basu, P.K. and Banerjee, S.K. 1991. Modification of some soil properties by *Eucalyptus* species. Indian Forester, 117, 53-57.

Nye, P.H. 1961. Organic matter and nutrient cycles under moist tropical forest. Plant and Soil, 13, 333-346.

Nye, P.H. and Greenland, D.J. 1964. Changes in the soil after clearing tropical forest. Plant and Soil, 21, 101-112.

O'Connell, A.M. 1986. Effect of legume understorey on decomposition and nutrient content of eucalypt litter. Plant and Soil. 92: 235-248.

O'Connell, A.M. 1987. Litter dynamics in karri (*Eucalyptus diversicolor*) forests of south-western Australia. Journal of Ecology, 75, 781-796.

O'Connell, A.M. 1988. Nutrient dynamics in decomposing litter in karri (*Eucalyptus diversicolor* F. Muell.) forests of south-western Australia. Journal of Ecology, 76, 1186- 1203.

O'Connell, A.M. (1990). Microbial decomposition (respiration) of litter in eucalypt forests of south-western Australia : an empirical model based on laboratory incubations. *Soil Biology and Biochemistry* 22, 153-160.

O'Connell, A.M. (1994). Decomposition and nutrient content of litter in a fertilized eucalypt forest. *Biology and Fertility of Soils*, 17, 159-166.

O'Connell, A.M. (1996). Decomposition of slash residues in thinned regrowth eucalypt forest. *Journal of Applied Ecology*, in press.

O'Connell, A.M. and Menage, p. (1983). Decomposition of litter from three major plant species of jarrah (*Eucalyptus marginata* Donn ex Sm.) forest in relation to site fire history and soil type. *Australian Journal of Ecology* 8, 277-286.

O'Connell, A.M. and Grove, T.S. (1985). Acid phosphatase activity in karri (*Eucalyptus diversicolor* F. Muell.) in relation to soil phosphate and nitrogen supply. *Journal of Experimental Botany* 36, 1359-1372.

O'Connell, A.M. and Grove, T.S. (1987). Seasonal variation in C_2H_2 reduction (N_2-fixation) in the litter layer of eucalypt forests of south-western Australia. *Soil Biology and Biochemistry* 19, 135-142.

O'Connell, A.M. and Grove, T.S. (1991). Processes contributing to the nutritional resilience or vulnerability of jarrah and karri forests of Western Australia. In: Ryan, P.J., ed, Productivity in Perspective, Proceedings of Third Australian Forest Soils and Nutrition Conference. Sydney, Forestry Commission of NSW.

O'Connell, A.M. & Grove, T.S. (1993). Influence of nitrogen and phosphorus fertilizers on amount and nutrient content of litterfall in a regrowth eucalypt forest. *New Forests*, 7, 33-47.

O'Connell, A.M. and McCaw, W.L. (1995). Impact of thinning and burning on nitrogen status of regrowth karri forest. In: *Sustainable Forest Management*. Research Working Group 3 meeting, September 24-29, Busselton WA.

O'Connell, A.M. and Rance, S.J. (1995). Predicting nitrogen supply in plantation eucalypt forests. In: Soils of Tropical Forest Ecosystems. Eds A. Schulte and D. Ruhiyat. Vol 4 pp 136-147-30. Mulawarman University Press, Samarinda.

O'Connell, A.M. & Grove, T.S. (1996). Biomass production, nutrient uptake and nutrient cycling in the jarrah (*Eucalyptus marginata*) and karri (*Eucalyptus diversicolor*) forests of south-western Australia. *Nutrition of the Eucalypts*. (Ed by P.M. Attiwill & M.A. Adams), pp xx-yy. CSIRO, Melbourne.

O'Connell, A.M. and McCaw, W.L. (1996). Prescribed Burning of Thinning Slash in Regrowth Stands of karri (*Eucalyptus diversicolor*). 2. Nitrogen Budgets in Pre- and Post-burn Fuel. *Journal of Wildland Fire*, submitted.

Olson, J.S. 1963. Energy storage and the balance of producers and decomposers in ecological systems. Ecology, 44, 322-331.

Palm, C.A. and Sanchez, P.A. 1991. Nitrogen release from leaves of some tropical legumes as affected by their lignin and polyphenolic contents. Soil Biology and Biochemistry, 23, 83-88.

Parton, W.J., Stewart, J.W.B. and Cole, C.V. 1988. Dynamics of C, N, P and S in grassland soils: a model. Biogeochemistry, 5, 109-131.

Parton, W.J., Woolmer, P.L. and Martin, A. (1994). Modelling soil organic matter dynamics and plant productivity in tropical ecosystems. In: The Biological Management of Tropical Soil Fertility (eds. P.L. Woolmer and M.J. Swift). John Wiley and Sons, Chichester. pp171-188.

Polglase, P.J., Attiwill, P.M. and Adams, M.A. (1992) Nitrogen and phosphorus cycling in relation to stand age of *Eucalyptus regnans* F. Muell. *Plant and Soil*, 142, 177-185.

Powlson, D.B., Brookes, P.C., Christensen, B.T. (1987). Measurement of microbial biomass provides an early indication of changes in total soil organic matter due to straw incorporation. *Soil Biology and Biochemistry* 19, 159-164.

Prasad, K.G., Dinesh Kuman, Chandrasekharan Nair T.J., Madhavan Nair, J. and Deo, A.D. 1984a. Fertilization in *Eucalyptus grandis* on a severely truncated soil. I. Growth studies. Indian Forester 110 : 132-141.

Prasad, K.G., Gupta, G.N., Singh, S.B., Mohan, S., Madhavan Nair, J. and Deo, A.D. 1984b. Fertilization in *Eucalyptus grandis* on a severely truncated soil. I. Growth studies. Indian Forester 110 : 142-149.

Prinsley, R.T. (1992). The role of trees in sustainable agriculture - an overview. *Agroforestry Systems*, 20, 87-115.

Raison, R.J., Connell, M.J. and Khanna, P.K. (1987). Methodology for studying fluxes of soil mineral nitrogen *in situ*. Soil Biol. Biochem., 19, 521-530.

Raison, R.J., O'Connell, A.M., Khanna, P.K. and Keith, H. (1993). Effects of repeated fires on nitrogen and phosphorus budgets and cycling processes in forest ecosystems. In: Fire in Mediterranean Ecosystems. (Eds L. Trabaud and R. Prodon). Commission of European Communities, Brussels, pp 347-363.

Raison, R.J. and Khanna, P.K. (1995). Sustainability of forest fertility : some proposed indicators and monitoring considerations. In: Caring for the Forest : Research in a Changing World. Proceedings IUFRO XX World Congress Tampere, Finland. 12 pp.

Richter, D.D., Markewitz, D., Wells, C.G., Allen, H.L., April, R., Heine, P.R. and Urrego, B. (1994) Soil chemical changes during three decades in an old-field loblolly pine (*Pinus taeda* L.) ecosystem. Ecology, 75, 1463-1473.

Robson, A.D. and Gilkes, R.J. (1980). Fertiliser responses (N,P,K,S, micronutrients) on lateritic soils in south Western Australia - A review. *In* "Lateritisation Processes". pp. 381-390. International Geological Correlation Programme Project No. 129. (Oxford and IBH Publishing Company: New Delhi).

Romanya, J., Khanna, P.K. and Raison, R.J. ((1994). Effects of slash burning on soil phosphorus fractions and sorption and desorption of phosphorus. *Forest Ecology and Management* 65, 89-103.

Rovira, A.D. (1992). Dryland Mediterranean farming systems in Australia. *Australian Journal of Experimental Agriculture*, 32, 801-809.

Rowland, I.C., Halse, N.J. and Fitzpatrick, E.N. (1984). The role of legumes in Australian dryland agriculture. *In*: "Proceedings of the International Congress on Dryland Farming, Adelaide". pp. 676-698. (South Australian Department of Agriculture: Adelaide).

Rowland, I.C., Mason, M.G. and Hamblin, J. (1988). Effect of lupins and wheat on the yield of subsequent wheat crops grown at several rates of applied nitrogen. *Australian Journal of Experimental Agriculture*, 28, 91-97.

Sanchez, P.A., Palm, C.A., Davey, C.B. Szott,L.T. and Russell C.E. 1985. Tree crops as soil improvers in the humid tropics. In: Cannell, M.G.R. and Jackson, J.E., eds, Attributes of Trees as Crop Plants. Washington, Institute of Terrestrial Ecology, Natural Environmental Resource Council, pp 327-358.

Sankar, S. (1986). Foliar analysis in *E. tereticornis* and *E. grandis* to assess soil test methods for N, P and K. KFRI Research Report No. 53, KFRI, Peechi, India.

Sankaran, K.V. 1993. Decomposition of leaf litter of albizia(*Paraserianthes falcataria*), eucalypt (*Eucalyptus tereticornis*) and teak (*Tectona grandis*) in Kerala, India. Forest Ecology and Management, 56, 225-242.

Sankaran, K.V., Balasundaran, M., Thomas, T.P. and Sujatha, M.P. 1993. Litter dynamics, microbial associations and soil studies in *Acacia auriculiformis* plantations in Kerala. Research Report No 91, KFRI, Kerala, India, 56p.

Shea, S. and Bartle, J. (1988). Restoring natures balance: The potential for major reforestation of south western Australia. Department of Conservation and Land Management, 26pp.

Sim, B.L. and Nykvist, N. (1991). Impact of forest harvesting and replanting. Journal of Tropical Forest Science. 3, 251-284.

Singh, B. (1982). Nutrient content of standing crop and biological cycling in *Pinus patula* ecosystems. *Forest Ecology and Management* 4, 317-332.

Singh, S.B., Prasad, K.G., Gupta G.N. and Subramanian, V. (1988). Causes of decline of *E. grandis. Advances in Forest Research in India.* 114, 189-199.

Singh, O., Sharma, D.C. and Rawat, J.K 1993. Production and decomposition of leaf litter in sal, teak, *Eucalyptus* and poplar forests in Uttar Pradesh. Indian Forester, 119, 112-121.

Smethurst, P.J and Nambiar, E.K.S. (1990). Effect of contrasting silvicultural practices on nitrogen supply to young radiata pine. In: Impact of intensive harvesting on forest site productivity. Proceedings IEA/BE A3 Workshop, South Island NZ. (Eds W.J. Dyck and C.A. Mees). Forest Research Institute, Rotorua, FRI Bulletin 159, pp 85-96.

Smethurst, P.J and Nambiar, E.K.S. (1995). Changes in soil carbon and nitrogen during establishment of a second rotation crop of *Pinus radiata*. *Forest Ecology and Management* 73, 145-155.

Spain, A.V. and Le Feuvre, R.P. 1987. Breakdown of four litters of contrasting quality in a tropical Australian rainforest. Journal of Applied Ecology, 24, 279-288.

Sparling, G.P. (1992) Ratio of microbial biomass carbon to soil organic carbon as a sensitive indicator of changes in soil organic matter.

Staaf, H. and Berg, B. 1982. Release and accumulation of plant nutrients in needle litter during decomposition. Long term decomposition of Scots pine needle litter. II. Canadian Journal of Botany, 60, 1561-1568.

Sundar, S.S. (1995). the ecological, economic and social effects of Eucalyptus. In: Proceedings of the Regional Expert Consultation on *Eucalyptus*. 8 October 1993. pp. 90-128. FAO Regional Office for Asia and Pacific, Bangkak.

Swamy, R.H. 1989. Study of organic productivity, nutrient cycling and small watershed hydrology in natural forests and in monoculture plantations in Chikmagalur District, Karnataka. J.C.B.M. College, Karnataka. Final Report submitted to Government of India, 261p.

Swift, M.J., Heal, O.W. and Anderson, J.M. 1979. Decomposition in Terrestrial Ecosystems. Oxford, Blackwell Scientific, 372 p.

Swift, M.J., Russell-Smith, A. and Perfect, T.J. 1981. Decomposition and mineral-nutrient dynamics of plant litter in a regenerating bush-fallow in sub-humid tropical Nigeria. Journal of Ecology, 69, 981-995.

Switzer, G.L. and Nelson, L.E. 1972. Nutrient accumulation and cycling in Loblolly Pine (*Pinus taeda* L.) plantation ecosystems: the first twenty years. Proceedings of the Soil Science Society of America, 36, 143-147.

Syers, J.K. and Craswell, E.T. (1995). Role of soil organic matter in sustainable agricultural systems. In: Soil Organic Matter Management for Sustainable Agriculture. Eds RDB Lefroy, GJ Blair and ET Craswell. pp 7-14. ACIAR, Canberra.

Tandon, V.N., Pande, M.C. and Singh, R. (1988). Biomass estimation and distribution of nutrients in five different aged *Eucalyptus globulus* plantation ecosystems in Kerala State. *Indian Forester* 114, 184-189.

Tennant, D., Scholz, G., Dixon, J. and Purdie, B. (1992). Physical and chemical characteristics of duplex soils and their distribution in the south-west of Western Australia. *Australian Journal of Experimental Agriculture*, 32, 827-843.

Thornley, J.H.M. and Cannell, M.G.R. 1992. Nitrogen relations in a forest plantation - soil organic matter ecosystem model. Annals of Botany, 70, 137-151.

Tiessen,H., Cuevas, E. and Chacon, P. 1994. The role of soil organic matter in sustaining soil fertility. Nature, 371, 783-785.

Toky, O.P. and Singh, V. 1993. Litter dynamics in short-rotation high density tree plantations in an arid region of India. Agriculture, Ecosystems and Environment, 45, 129- 145.

Trofymow, J.A., Preston, C.M. and Prescott, C.E. (1995). Litter quality and its potential effects on decay rates of materials from Canadian forests. Water, Air and Soil Polution 82, 215-226.

Tuohey, C.L., and Robson, A. D. (1980). The effect of cropping after medic and non-medic pastures on total soil nitrogen, and on the grain yield and nitrogen content of wheat. *Australian Journal of Experimental Agriculture and Animal Husbandry, 20, 220-228.*

Turton, A.G., Marsh, N.L., McKenzie, R.M. and Mulcahy, M.J. (1962). The chemistry and mineralogy of lateritic soils in the south-west of Western Australia. CSIRO Australia. Soil Publication No. 20.

Upadhyay, R.K. 1982. Release of nutrient elements from decomposing leaf litter of Eucalyptus globulus. Indian Forester, 108, 550-553.

Upadhyay, V.P. and Singh, J.S. 1989. Patterns of nutrient immobilization and release in decomposing forest litter in central Himalaya, India. Journal of Ecology, 77, 127-146.

Van Veen, J.A., Ladd, J.N. and Frissel, M.J. 1984. Modelling C and N turnover through the microbial biomass in soil. Plant and Soil, 76, 257-274.

Venugopal, S. (1988) Impact of eucalypt plantations on the industrial climate, Malur Taluk. *My Forest*, Dec 1988.

Vitousek, P.M. (1982) Nutrient cycling and nutrient efficiency. *American Naturalist*, 119, 553-572.

Vitousek, P.M. and Sanford, R.L. 1986. Nutrient cycling in moist tropical forests. Annual Review of Ecology and Systematics, 17, 137-167.

Vitousek, P.M., Turner, D.R., Parton, W.J. and Sanford, D.R. 1994. Litter decomposition in the Mauna Loa environmental matrix, Hawaii: patterns, mechanisms and models. Ecology, 75, 418-429.

Walker, J., Raison, R.J. and Khanna, P.K. (1986). Fire. In: Australian Soils, the Human Impact (Eds. J.S. Russell and R.F. Isbell). Queensland University Press, St. Lucia. PP 185-216.

Wang, D., Bormann, F.H., Lugo, A.E. and Bowden, R.D. 1991. Comparison of nutrient use efficiency and biomass production in five tropical tree taxa. Forest Ecology and Management, 46, 1-21.

Ward, S.C., Majer, J.D. and O'Connell, A.M. 1991. Decomposition of eucalypt litter on rehabilitated bauxite mines. Australian Journal of Ecology, 6, 251-257.

Wilson J.R. and Ludlow, M.M. 1991. The environmental and potential growth of herbage under plantations. In: Forage for plantation crops (Eds. H.M. Shelton and W.W. Stur) ACIAR Pro. No 32, ACIAR Canberra, pp 10-24.

Wilson J.R. and Wild D.W.M. 1991. Improvement of nitrogen nutrition and grass growth under shading. In: forage for plantation crops (Eds. H.M. Shelton and W.W. Stur). ACIAR Pro. No 31, ACIAR Canberra, pp. 77-82.

Wood, T.G 1974. Field investigations on decomposition of leaves of *Eucalyptus delegatensis* in relation to environmental factors. Pedobiologia, 14, 343-371.

Woods, R.V. (1976). Early silviculture for upgrading productivity on marginal *Pinus radiata* sites in the south-eastern region of South Australia. Woods and Forests Department South Australia Bulletin 24.

Woods, R.V. (1981). Management of nitrogen in the *P. radiata* plantations of the south east of South Australia. *In*: "Managing Nitrogen Economies of Natural and Man Made Forest Ecosystems". (Eds R.A, Rummery and F.J. Hingston). pp. 354-367. CSIRO, Division of Land Resources Management, Perth.

Zech, W. and Drechesel, P. (1995). Degradation and amelioration of soils and tree nutrient status without and with mineral fertilizer. In: Soils of Tropical Forest Ecosystems. Eds A. Schulte and D. Ruhiyat. Vol 5 pp 5-30. Mulawarman University Press, Samarinda.

Zen, S. and do Couto, H.T.Z. (1991). Length of rotation and spacing for *Eucalyptus grandis* and *Eucalyptus saligna*. *In*: "Intensive Forestry : The Role of Eucalypts". (Ed. A.P.G. Shonau). pp. 952-963.

BUDGET

PROJECT NO. FST/95/106

IMPROVING AND MAINTAINING PRODUCTIVITY OF EUCALYPT PLANTATIONS IN INDIA AND AUSTRALIA

PART A AUSTRALIAN COMMISSIONED ORGANISATION
PART B AUSTRALIAN COLLABORATING ORGANISATION
PART C DEVELOPING COUNTRY PARTNER
PART D SUMMARY OF ACIAR FUNDS
PART E REVIEW AND CO-ORDINATION COSTS
PART F DEVELOPING COUNTRY PARTNER CONTRIBUTIONS
PART G COMMISSIONED ORGANISATION AND COLLABORATING INSTITUTE CONTRIBUTION
PART H ESTABLISHMENT COSTS
PART I TRAINING COSTS

ALL COSTS SHOWN IN THIS BUDGET ARE AS AT MARCH 1996.

KNOWN COST INCREASES ARE INCLUDED

NO ALLOWANCE HAS BEEN BUILT IN FOR INFLATION IN FUTURE YEARS.

PART A : ESTIMATED PROJECT EXPENDITURE FROM ACIAR FUNDS

COMMISSIONED ORGANISATION

CSIRO FORESTRY AND FOREST PRODUCTS

1. CORE PROGRAM - AUSTRALIA

		YEAR 1 (1/7/97 30/6/98)	YEAR 2 (1/7/98 30/6/99)	YEAR 3 (1/7/99 30/6/00)	YEAR 4 (1/7/00 30/6/01)	YEAR 5 (1/7/01 30/6/02)	TOTAL
(15)	**PERSONNEL**						
	(a) Salary						
1, 2	(i) Prof. Qualified	47887	50129	93835	94970	97113	383934
3	(ii) Other (Technical)	27554	28391	29227	30061	30061	145294
4	(iii) Casual labour	7000	7000	7000	7000	6700	34700
	Sub-total	82441	85520	130062	132031	133874	563928
	(b) Salary related On-costs						
	Percent of Annual Salary made up as follows:						
	(i) Payroll Tax (%)						
	(ii) Workers Compensation Insurance (%)						
	(iii) Superannuation (%)						
	(iv) Holiday Pay (%)						
	(v) Long Serv Lve (%)						
5	(vi) Other (Specify)	28854	29932	45522	46211	46856	197375
	Sub-total	28854	29932	45522	46211	46856	197375
	TOTAL PERSONNEL	111295	115452	175584	178242	180730	761303
(16)	**SUPPLIES AND SERVICES**						
	(i) Equipment						
	(ii) Contracted Expenditure						
6	(iii) Research Maintenance	10000	11000	11000	10000	10000	52000
	TOTAL SUPPLIES AND SERVICES	10000	11000	11000	10000	10000	52000

		YEAR 1 (1/7/97 30/6/98)	YEAR 2 (1/7/98 30/6/99)	YEAR 3 (1/7/99 30/6/00)	YEAR 4 (1/7/00 30/6/01)	YEAR 5 (1/7/01 30/6/02)	TOTAL
(17)	**TRAVEL**						
7	(a) Domestic Fares		1000	1000	1000	1000	4000
8	(b) Subsistence	10000	11000	11000	12000	12000	56000
	TOTAL TRAVEL	10000	12000	12000	13000	13000	60000
(18)	**OTHER COSTS**						
	Project Maintenance						
9	Other (specify)	1000	1000	1000	1000	1000	5000
-	**TOTAL OTHER COSTS**						
	TOTAL CORE PROGRAM (AUSTRALIA)	132295	139452	199584	202242	204730	878303

Footnotes:

1. Scientist Level 5. Employed for the duration of the project. Principal tasks will be to lead research on impact of the appled silvicultural treatments on soil organic matter fractions and soil phosphorus forms and indices (Sub-project 1). The scientist will be responsible for developing and standardizing methodologies for soil carbon and phosphorus evaluation and for transferring these technologies to colleagues at KFRI. Will be required to interact strongly with Dr O'Connell and Dr Grove as well as with our external Australian collaborators - Professor RJ Gilkes (UWA) and Associate Professor P Saffigna (GU), and with Dr Pax Blamey (ACIAR Project 9414).

2. Post Doctoral Fellow. Employed for the final 3 years of the project and will work within sub-project 4 of the research program. This scientist's role will be crucial for integrating the results of the experimental program (sub-projects 1, 2 and 3) and for generalizing and extrapolating the research outcomes. He will test and apply a range of existing and developing models to describe soil processes (primarily related to carbon and nitrogen turnover) and whole system function. The purpose of this component of the study is to integrate the results from the experimental program and to evaluate methodologies applicable as longer term predictors of response of plantation forests to intensive silvicultural management. An outcomes from this work will be identification of "best practice" management options for sustained production from eucalypt plantations. The scientist will be required to interact strongly with Dr O'Connell and Associate Professor McMurtrie (UNSW).

3. Technical support for research on soil carbon and nutrients status, tree and soil water status, tree growth, and nutrient uptake in WA (sub-projects 1, 2 and 3).

4. Casual labour to assist with field work and sample preparation, particularly grinding of plant and soil samples for chemical analysis, in Australia.

5. On costs applied at 35% salary as standard formula for CSIRO Forestry and Forest Products.

6. Research maintenance items include costs in consumable laboratory items, chemicals, repair and maintenance of laboratory equipment, laboratory gases for analytical equipment, fabrication of minor items of laboratory equipment; maintenance of computers and supply of computer consumables (paper, disks, printer cartridges etc); maintenance and repair of field equipment including data loggers, weather stations, neutron moisture meter, syntec moisture meter, leaf area meter (LAI 2000), drilling equipment; soil coring equipment, insulated field storage boxes for transport of soil samples under controlled temperature conditions etc.

7. Airfare to Sydney (in years 2 to 5) for Dr O'Connell and Post-doctoral Fellow (PDF) with responsibility for implementing soil nitrogen, carbon and whole system models (see 2 above). This component will be conducted in close collaboration with Associate Professor Ross McMurtrie of UNSW and his research team.

8. TA at $100 / day to support travel to field sites in south-western Australia and inter state travel identified in 6, above. Costs are estimated as follows :

PDF one trip to Sydney in each of years 3,& 4, and 2 trips year 5 to consult with Associate Professor McMurtrie on soil and whole system modelling. Duration of each visit 10 days. Subsistence @ $100/day = $1000 per visit. Total $4000.

Establishment and maintenance of field sites in South Western Australia, regular collection of soil and plant samples, data acquisition from weather stations, data loggers, leaf area, plant physiological measurements, soil water monitoring etc. Estimated travel @ 8 person days per 4 week sampling period = 8 x 13 x 5 = 520 person days during the 5 year period of the project. Travel costs estimated at $100/person day. Then, subsistence to support field trials in SW Australia for 5 years = 520 x $100 = $52000.

Thus, total subsistence covering interstate visits by PDF plus field work in SW Australia = $4000+$52000 = $56000.

9. Contingency funds for use at discretion of Australian Project Leader.

PART A. ESTIMATED PROJECT EXPENDITURE FROM ACIAR FUNDS

COMMISSIONED ORGANISATION -

2. ACIAR FUNDS EXPENDED IN AUSTRALIA FOR

KFRI INDIA PROGRAM (FUNDS NOT SENT OVERSEAS)

		YEAR 1 (1/7/97 30/6/98)	YEAR 2 (1/7/98 30/6/99)	YEAR 3 (1/7/99 30/6/00)	YEAR 4 (1/7/00 30/6/01)	YEAR 5 (1/7/01 30/6/02)	TOTAL
(19)	PERSONNEL						
	(a) Salary						
	(b) Salary related costs						
	TOTAL PERSONNEL						
(20)	SUPPLIES AND SERVICES						
1	(i) Equipment	96000					96000
	(ii) Contracted Expenditure						
	(iii) Research Maintenance						
	TOTAL SUPPLIES AND SERVICES	96000					96000
(21)	TRAVEL						
	(a) Fares						
	(i) International	15700	11400	11400	11800	13700	64000
	(ii) Domestic						
	(b) Subsistence	15800	11600	11600	10000	11400	60400
2	TOTAL TRAVEL	31500	23000	23000	21800	25100	124400
(22)	OTHER COSTS						
	(i) Project Maintenance						
	(ii) Other (Specify)						
	TOTAL OTHER COSTS						
	TOTAL CORE PROGRAM COUNTRY	127500	23000	23000	21800	25100	220400

Footnotes:

1. Purchase of chemistry laboratory equipment, commissioning in Perth and transferring equipment to KFRI. Written quotations attached to main proposal. Major items of equipment, costs and suppliers are as follows (*)

Item number	Item	Price (A$)	Supplier
1	AAS Varian Spectra - 200	28000	Varian Australia
2	Auto- Analyser Technicon 4-ch	38136	Bran & Luebbe
3	Digestion System AIM500	9340	A.I. Scientific
4	pH meter Activon - 210	676	Activon Scientific
5	Soil Extract Shaker	1000	CSIRO Workshop
6	Sample Incubator Memmert BM500	2180	Selby Scientific
7	Laboratory Hotplate Thermoline	705	Scott Scientific
8	Sample dispensers Optifix 50, 100	929	Rowe Scientific
9	Sample diluter Hamilton	3617	Perth Scientific
10	Sample Mixer MS1 IKA	495	Crown Scientific
11	Data Loggers	4959	Dataflow Systems
12	Notebook Computer	4000	Selected supplier
13	Air freight to Cochin, India	2000	Omega Cargo
	TOTAL	96037	

2. Economy airfare Cochin-Perth rtn @ $1700; TA $100/day - 7 training visits by KFRI scientists (6 x 1 month; 1 x 2 months). Total project costs $35900. Details of timing of training visits and KFRI personnel are as follows :

Date	Personnel	Costs ($A)	Duration (days)	Purpose
Aug 1997	Dr Balagopalan	7700	60	Commissioning of analytical instruments in Perth
Oct 1998	Dr Sankaran	4700	30	Training in experimental procedures
Mar 1999	Dr Kallarackal	4700	30	Collaboration in plant physiological methodologies
Oct 1999	Dr Pandalai	4700	30	Training in silviculture
Mar 2000	Soils Div. RS	4700	30	Training in soil chemistry
Oct 2000	Dr Sankaran	4700	30	Training in evaluation of project outcomes
Mar 2002	Dr Sankaran	4700	30	Project assessment

3. Economy airfare Perth-Cochin rtn @ $2000 for Western Australian scientists. Airfare Sydney-Cochin rtn @ $2100 for Dr McMurtrie in June 2001. TA $100/day in all cases. Total project costs $88500.

Travel as detailed and individual costs as follows :

Date	Personnel	Costs ($A)	Duration (days)	Purpose
Dec 1997	Dr O'Connell	3400	14	Initial workshop and training program
	Dr Grove	3400		Soil evaluation and site selection
	Ms Pham	3400		Chemistry laboratory establishment
	Prof. Gilkes	3400		Analytical methodology training
Mar 1998	Dr O'Connell	3400	14	Project evaluation
June 1998	Dr O'Connell	3400	14	Planting of sites.
	Dr Grove	3400		
Dec 1998	Dr O'Connell	3400	14	First measurements of trees on experimental plots and tree sampling for biomass and nutrients
	Dr Grove	3400		
June 1999	Dr O'Connell	3400	14	Project evaluation
	RS	3400		Transfer of phosphorus and carbon methods
Dec 1999	Dr O'Connell	3400	14	Measurements of trees on experimental plots and tree sampling for biomass and nutrients
	Dr Grove	3400		
June 2000	Dr O'Connell	3400	14	Project evaluation
	RS	3400		
Dec 2000	Dr O'Connell	3400	14	Mid term review
	Dr Grove	3400		Training workshop
				Tree measurements and biomass sampling
June 2001	Dr O'Connell	3400	14	Project evaluation. Application of models to KFRI data
	PDF	3400		
	A/R McMurtrie	3500		
Dec 2001	Dr O'Connell	3400	14	Measurements of trees on experimental plots and tree sampling for biomass and nutrients
	Dr Grove	3400		
June 2002	Dr O'Connell	3400	14	Final review and workshop
	Dr Grove	3400		
	RS	3400		
	PDF	3400		

PART B. ESTIMATED PROJECT EXPENDITURE FROM ACIAR FUNDS

COLLABORATING AUSTRALIAN INSTITUTION(S)

GRIFFITH UNIVERSITY

1. CORE PROGRAM (AUSTRALIA)

	YEAR 1 (1/7/97 30/6/98)	YEAR 2 (1/7/98 30/6/99)	YEAR 3 (1/7/99 30/6/00)	YEAR 4 (1/7/00 30/6/01)	YEAR 5 (1/7/01 30/6/02)	TOTAL
(23) **PERSONNEL**						
(a) Salary						
(i) Professionally Qualified						
(ii) Other						
Sub-total						
(b) Salary related On-costs						
Percent of Annual Salary made up as follows:						
(i) Payroll Tax (%)						
(ii) Workers Compensation Insurance (%)						
(iii) Superannuation (%)						
(iv) Holiday Pay (%)						
(v) Long Serv Lve (%)						
(vi) Other (Specify)						
Sub-total						
TOTAL PERSONNEL						
(24 **SUPPLIES AND SERVICES**						
(i) Equipment						
(ii) Contracted Expenditure						
(iii) Research Maintenance						
TOTAL SUPPLIES AND SERVICES						

		YEAR 1 (1/7/97 30/6/98)	YEAR 2 (1/7/98 30/6/99)	YEAR 3 (1/7/99 30/6/00)	YEAR 4 (1/7/00 30/6/01)	YEAR 5 (1/7/01 30/6/02)	TOTAL
(25)	**TRAVEL**						
	(a) Fares						
	(i) International						
	(ii) Domestic						
	(b) Subsistence						
	TOTAL TRAVEL						
(26)	**OTHER COSTS**						
	Project Maintenance						
	Other (specify)						
	TOTAL OTHER COSTS						
	TOTAL COLLABORATING AUSTRALIAN INSTITUTION PROGRAM (AUSTRALIA)						

Footnotes:

PART B. ESTIMATED PROJECT EXPENDITURE FROM ACIAR FUNDS

COLLABORATING AUSTRALIAN INSTITUTION(S)

GRIFFITH UNIVERSITY

2. ACIAR FUNDS EXPENDED IN AUSTRALIA FOR

KFRI INDIA PROGRAM

		YEAR 1 (1/7/97 30/6/98)	YEAR 2 (1/7/98 30/6/99)	YEAR 3 (1/7/99 30/6/00)	YEAR 4 (1/7/00 30/6/01)	YEAR 5 (1/7/01 30/6/02)	TOTAL
(27)	PERSONNEL						
1	(a) Salary		4000	4000	2000		10000
	(b) Salary related costs						
	TOTAL PERSONNEL		4000	4000	2000		10000
(28)	SUPPLIES AND SERVICES						
	(i) Equipment						
	(ii) Contracted Expenditure						
2	(iii) Research Maintenance		4000	4000	2000		10000
	TOTAL SUPPLIES AND SERVICES		4000	4000	2000		10000
(29)	TRAVEL						
	(a) Fares						
	(i) International						
	(ii) Domestic						
	(b) Subsistence						
	TOTAL TRAVEL						

		YEAR 1 (1/7/97 30/6/98)	YEAR 2 (1/7/98 30/6/99)	YEAR 3 (1/7/99 30/6/00)	YEAR 4 (1/7/00 30/6/01)	YEAR 5 (1/7/01 30/6/02)	TOTAL
(30)	**OTHER COSTS**						
	(i) Project Maintenance						
	(ii) Other (Specify)						
	TOTAL OTHER COSTS						
	TOTAL COLLABORATING AUSTRALIAN INSTITUTION PROGRAM (COUNTRY)		8000	8000	4000		20000

Footnotes:

1. Contribution to salary support for Research Associate operating N15 mass spectrometer for denitrification potential estimates on soils from experiments in India

2. Purchase of chemicals (mainly N15) and other consumable laboratory items.

PART B. ESTIMATED PROJECT EXPENDITURE FROM ACIAR FUNDS

COLLABORATING AUSTRALIAN INSTITUTION(S)

UNIVERSITY OF WESTERN AUSTRALIA

1. CORE PROGRAM (AUSTRALIA)

		YEAR 1 (1/7/97 30/6/98)	YEAR 2 (1/7/98 30/6/99)	YEAR 3 (1/7/99 30/6/00)	YEAR 4 (1/7/00 30/6/01)	YEAR 5 (1/7/01 30/6/02)	TOTAL
(27)	**PERSONNEL**						
	(a) Salary						
	(b) Salary related costs						
	TOTAL PERSONNEL						
(28)	**SUPPLIES AND SERVICES**						
	(i) Equipment						
	(ii) Contracted Expenditure						
1	(iii) Research Maintenance		2000	2000	2000	2000	8000
	TOTAL SUPPLIES AND SERVICES		2000	2000	2000	2000	8000
(29)	**TRAVEL**						
	(a) Fares						
	(i) International						
	(ii) Domestic						
2	**(b) Subsistence**		3000	3000	3000	3000	12000
	TOTAL TRAVEL		3000	3000	3000	3000	12000

		YEAR 1 (1/7/97 30/6/98)	YEAR 2 (1/7/98 30/6/99)	YEAR 3 (1/7/99 30/6/00)	YEAR 4 (1/7/00 30/6/01)	YEAR 5 (1/7/01 30/6/02)	TOTAL
(30)	**OTHER COSTS**						
	(i) Project Maintenance						
	(ii) Other (Specify)						
	TOTAL OTHER COSTS						
	TOTAL COLLABORATING AUSTRALIAN INSTITUTION PROGRAM (COUNTRY)		5000	5000	5000	5000	20000

Footnotes:

1. Laboratory consumables to support research on phosphorus methodologies, P fractionation, and evaluation of indices of soil and plant P status in soils from experiments in south western Australia.

2. TA @ $100 / day for field trips to remote sites in Western Australia by Professor RJ Gilkes and Research Associates.

PART B. ESTIMATED PROJECT EXPENDITURE FROM ACIAR FUNDS

COLLABORATING AUSTRALIAN INSTITUTION(S)

UNIVERSITY OF WESTERN AUSTRALIA

2. ACIAR FUNDS EXPENDED IN AUSTRALIA FOR

KFRI INDIA PROGRAM

		YEAR 1 (1/7/97 30/6/98)	YEAR 2 (1/7/98 30/6/99)	YEAR 3 (1/7/99 30/6/00)	YEAR 4 (1/7/00 30/6/01)	YEAR 5 (1/7/01 30/6/02)	TOTAL
(27)	**PERSONNEL**						
	(a) Salary						
	(b) Salary related costs						
	TOTAL PERSONNEL						
(28)	**SUPPLIES AND SERVICES**						
	(i) Equipment						
	(ii) Contracted Expenditure						
	(iii) Research Maintenance						
	TOTAL SUPPLIES AND SERVICES						
(29)	**TRAVEL**						
	(a) Fares						
	(i) International						
	(ii) Domestic						
	(b) Subsistence						
	TOTAL TRAVEL						

	YEAR 1 (1/7/97 30/6/98)	YEAR 2 (1/7/98 30/6/99)	YEAR 3 (1/7/99 30/6/00)	YEAR 4 (1/7/00 30/6/01)	YEAR 5 (1/7/01 30/6/02)	TOTAL
(30) **OTHER COSTS**						
(i) Project Maintenance						
(ii) Other (Specify)						
TOTAL OTHER COSTS						
TOTAL COLLABORATING AUSTRALIAN INSTITUTION PROGRAM (COUNTRY)						

Footnotes:

PART B. ESTIMATED PROJECT EXPENDITURE FROM ACIAR FUNDS

COLLABORATING AUSTRALIAN INSTITUTION(S)

UNIVERSITY OF NEW SOUTH WALES

2. ACIAR FUNDS EXPENDED IN AUSTRALIA FOR

KFRI INDIA PROGRAM

		YEAR 1 (1/7/97 30/6/98)	YEAR 2 (1/7/98 30/6/99)	YEAR 3 (1/7/99 30/6/00)	YEAR 4 (1/7/00 30/6/01)	YEAR 5 (1/7/01 30/6/02)	TOTAL
(27)	**PERSONNEL**						
	(a) Salary						
	(b) Salary related costs						
	TOTAL PERSONNEL						
(28)	**SUPPLIES AND SERVICES**						
	(i) Equipment						
	(ii) Contracted Expenditure						
1	(iii) Research Maintenance			1000	1000	1000	3000
	TOTAL SUPPLIES AND SERVICES			1000	1000	1000	3000
(29)	**TRAVEL**						
	(a) Fares						
	(i) International						
2	(ii) Domestic			1000	1000	1000	3000
3	**(b) Subsistence**			1000	1000	1000	3000
	TOTAL TRAVEL			2000	2000	2000	6000

		YEAR 1 (1/7/97 30/6/98)	YEAR 2 (1/7/98 30/6/99)	YEAR 3 (1/7/99 30/6/00)	YEAR 4 (1/7/00 30/6/01)	YEAR 5 (1/7/01 30/6/02)	TOTAL
(30)	**OTHER COSTS**						
	(i) Project Maintenance						
	(ii) Other (Specify)						
	TOTAL OTHER COSTS						
	TOTAL COLLABORATING AUSTRALIAN INSTITUTION PROGRAM (COUNTRY)			3000	3000	3000	9000

Footnotes:

1. Maintenance of computer hardware equipment and software, supply of consumables such as disks, printer paper, printer cartridges etc.

2. Economy airfare Sydney-Perth rtn @ $1000 for Associate Professor McMurtrie to visit WA to consult with Post-doctoral Fellow on application of CENTURY and whole system models (NBAL, SFP, G'DAY, SUSTAIN) to data from experiments in India in years 3, 4 and 5 of project.

3. TA @ $100 / day for 10 days annually (years 3, 4 and 5) to support above visits to WA by Associate Professor McMurtrie.

PART C. ESTIMATED PROJECT EXPENDITURE FROM ACIAR FUNDS DEVELOPING COUNTRY PARTNERS

FUNDS SENT OVERSEAS KFRI, INDIA

RATE OF EXCHANGE \$A = Rs 25 **(March 1996)**

		YEAR 1 (1/7/97 30/6/98)	YEAR 2 (1/7/98 30/6/99)	YEAR 3 (1/7/99 30/6/00)	YEAR 4 (1/7/00 30/6/01)	YEAR 5 (1/7/01 30/6/02)	TOTAL
(31)	PERSONNEL						
1	Salary or wages	12200	12500	12850	13130	13300	63980
(32)	SUPPLIES AND SERVICES						
2	(i) Equipment	32900	8000				40900
	(ii) Contracted Expenditure						
3,4	(iii) Research Maintenance	45500	40000	27000	27000	27500	167000
(33)	TRAVEL						
	(i) International						
5	(ii) Domestic	1600	1600	1600	1600	1600	8000
6	(iii) Subsistence	5540	5540	5540	5540	5540	27700
(34)	OTHER COSTS						
	(i) Project Administration Maintenance						
7	(ii) Other (Specify)	3492	2982	2350	2364	2397	13585
	TOTAL	101232	70622	49340	49634	50337	321165

Footnotes:

1. Salary for 6 Research Associates, 4 Technical assistants and 1 driver. Salaries are approximately \$1400, \$850 and \$800, respectively, per annum. This includes loadings for medical benefits and other overheads

2. Equipment to be purchased for use in India. Written quotations attached to main proposal. Costings and suppliers as follows :

Item number	Item	Price (A\$)	Supplier
1	2 x Weather stations Campbell Scientific	16500	Elron Instruments
2	4WD Vehicle Mahindra Armada	15200	TV Sundram Iyengar & Sons
3	Sap-flow Gauge	8000	Greenspan Technology Pty Ltd
4	Survey Equipment (Site establishment)	1200	Various
	TOTAL	40900	

3. Site establishment costs $45500 in the first 6 months of the project. Annual costs are for maintenance of sites and consumable items. Detailed costings of establishing the 4 experimental sites are as follows :

A. Site preparation	
(4.2ha x 4 sites - excludes 1.5 ha for OMM expt + 1.8 ha of weed management of the total 7.5 ha.)	
1. Weeding $ 80/ha x 4.2 x 4	1344
2. Skinning $ 120/ha x 4.2x2	1008
3. Burning $ 12/ha x4.2x4	202
4. Debris removal $ 30/hax4.2x2	252
B. Planting (7.5 ha x 4 sites)	
5. Supply of stakes 75000 ($ 8per1000)	600
6. Staking @ $30/ha x 7.5 ha x 4 site	900
7. Digging pits (75000 @ $ 60 for 1000)	4500
8. Insecticide treatment @$60/ha	1800
9. Planting @ $72 /ha	2160
C. Organic matter experiment	
Site preparation	
10. Removal and laying of slash in 16 plots	40
11. Removal of all slash except leaf in 16 plots	40
12. Removal of all organic matter in 16 plots	100
13. Burning (16 plots)	20
D. Nutrient addition	
14. Initial Fertilizer + application	6300
E. Inter-row legumes	
15. Pelleting of Rhizobium	20
16. Alignment and planting	126
F. Soil trenching	
17. Labour charges	200
G. Ground vegetation management	
18. Manual weed control 6 times in a year	432
H. General	
19. Clearing of path & labelling plots	600
20. Name boards for experimental sites	240
21. Fencing (material $2800, labour $600)	3400
22. Cost to provide electrical fencing	4000
23. Fire breaks @ $40/ha	1200
I. Established stands	
24. Litterbags & litter traps @ $100/site	400
25. Soil collection & transport	120
26. Fencing established stands ($ 2000/site x 4)	8000
J. Nursery	
Total requirement of seedlings 75,000 (37500 of Et+37500 Eg.)	
10 bed nursery (12 x 1.2 m beds) at each site (1 bed contains 2500 seedlings)	
Total seedlings raised at each site = 25,000	
Total required for planting = 18750 at each site	
For casualty replacement etc. = 6250 at each site	
27. Weeding, burning and levelling ($ 40/site x 4)	160
28. Support for stacking filled Polythene bags	80
29. Polythene bags ($ 3/kg x 80 kg/site x 4 sites)	960
30. Collection of soil, sieving and filling bags	1200
31. Sowing eucalypts seeds (4-5 /bag)	64
32. Providing shade for beds using coir mat	960
33. Construction of temporary shed ($ 80/ site)	320
34. Watchman for protection of seedlings	1728
35. Fencing around nursery	160
36. Watering nursery (twice daily @ $360/site)	1440
37. Pricking out seedlings, transport, planting	440
Total cost of site establishment	**45506**

4. Ongoing maintenance of 4 experimental sites, including cost of full time on-site watchmen at each location to protect experimental areas from interference by local people, fire and wild animals (mainly elephants), regular weeding of plots, Maintenance of weed control experiments, maintenance of fire breaks, fertilizer applications including cost of fertilizers (first three years only), fungicide application as required and maintenance of temporary accommodation facilities for field parties from KFRI (see 6, below). Repair and maintenance of field equipment including data loggers, weather stations, LAI meter etc. Regular site photography, minor computing items (disks, printer paper and cartridges etc). Repair and maintenance of laboratory analytical equipment, maintenance of air conditioned instrument room, expendable laboratory supplies (eg filter papers, membranes etc), minor chemistry laboratory equipment (eg test tubes, glassware etc), chemicals for analytical work, gas supplies for analysers (atomic absorption spectrometer). Fabrication of litter traps and litter bags for decomposition studies. Minor equipment and disposable items for glasshouse studies including pots, plastic bags, fungicides and nutrients. Minor equipment for soil sampling including steel soil core tubes, hammers, extraction equipment and insulated sample boxes.

5. Fuel for Jeep to make regular field trips to experimental sites.

6. Cost of food and lodging for overnight stays at field sites. It is proposed to minimize travelling costs of field parties through provision of on-site temporary field huts constructed from local materials at each experimental location. Scientists and technical staff will be accommodated in these huts for stays of up to one week at a time during regular field trips. Local travel costs for staff at KFRI will then be limited to provision of transport (largely diesel fuel for jeeps - see 5 above) and food which will be cooked on-site. It is estimated that food costs will be less than $5 per day per person.

7. KFRI overheads calculated at 5% of non-equipment expenditure.

PART D. TOTAL ESTIMATED EXPENDITURES FROM ACIAR FUNDS : SUMMARY

COMMISSIONED ORGANISATION

	COST ITEM	YEAR 1 (1/7/97 30/6/98)	YEAR 2 (1/7/98 30/6/99)	YEAR 3 (1/7/99 30/6/00)	YEAR 4 (1/7/00 30/6/01)	YEAR 5 (1/7/01 30/6/02)	TOTAL
(39)	Personnel	111295	115452	175584	178242	180730	761303
(40)	Supplies and Services	106000	11000	11000	10000	10000	148000
(41)	Travel	41500	35000	35000	34800	38100	184400
(42)	Other	1000	1000	1000	1000	1000	5000
(43)	**TOTAL**	259795	162452	222584	224042	229830	1098703
(43a)	(Of which Country Program equals)=	127500	23000	23000	21800	25100	220400

COLLABORATING AUSTRALIAN INSTITUTIONS

	COST ITEM	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5	TOTAL
(44)	Personnel		4000	4000	2000		10000
(45)	Supplies and Services		6000	7000	5000	3000	21000
(46)	Travel		3000	5000	5000	5000	18000
(47)	Other						
(48)	**TOTAL**		13000	16000	12000	8000	49000
(48A)	(Of which Country Program equals)=		8000	11000	7000	3000	29000

DEVELOPING COUNTRY ORGANISATIONS - FUNDS SENT OVERSEAS

	COST ITEM	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5	TOTAL
(49)	Personnel	12200	12500	12850	13130	13300	63980
(50)	Supplies and Services	78400	48000	27000	27000	27500	207900
(51)	Travel	7140	7140	7140	7140	7140	35700
(52)	Other	3492	2982	2350	2364	2397	13585
(53)	**TOTAL**	101232	70622	49340	49634	50337	321165
(54A)	**GRAND TOTAL** (43+48+53)	361027	246074	287924	285676	288167	1468868

OVERALL ACIAR FUNDING

	COST ITEM	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5	TOTAL
(55)	Personnel	123495	131952	192434	193372	194030	835283
(56)	Supplies and Services	184400	65000	45000	42000	40500	376900
(57)	Travel	48640	45140	47140	46940	50240	238100
(58)	Other	4492	3982	3350	3364	3397	18582
(59)	**TOTAL**	361027	246074	287924	285676	288167	1468868
	Distribution - Australia %	37	59	71	73	77	61
	Overseas %	63	41	29	27	27	39

Of which development expenditure =
(this is part of, not additional to, the above figures)

PART E. ESTIMATED CO-ORDINATION AND REVIEW EXPENDITURE

BY ACIAR DIRECTLY RELATED TO THE PROJECT

(COMPLETION OF THIS SECTION IS NOT REQUIRED FOR PROJECT DEVELOPMENT)

PART F. DEVELOPING COUNTRY CONTRIBUTIONS

(not met from ACIAR funds)

KFRI INDIA
$(A) Value

	COST ITEM	YEAR 1 (1/7/97 30/6/98)	YEAR 2 (1/7/98 30/6/99)	YEAR 3 (1/7/99 30/6/00)	YEAR 4 (1/7/00 30/6/01)	YEAR 5 (1/7/01 30/6/02)	TOTAL
1	Personnel	21395	21765	22141	22524	22914	110739
(61)	Supplies and Services						
(62)	Travel						
(63)	Other						
	TOTAL	21395	21765	22141	22524	22914	110739

Footnotes:

1. KFRI contribution based on salaries of participating scientists x percentage time contribution to the project

PART G. COMMISSIONED ORGANISATION CONTRIBUTIONS

(not met from ACIAR funds)

$(A) Value

	COST ITEM	YEAR 1 (1/7/97 30/6/98)	YEAR 2 (1/7/98 30/6/99)	YEAR 3 (1/7/99 30/6/00)	YEAR 4 (1/7/00 30/6/01)	YEAR 5 (1/7/01 30/6/02)	TOTAL
1	Personnel	190079	190079	190079	190079	190079	950395
2	Supplies and Services	15000	10000	10000	10000	10000	55000
2	Travel	15000	10000	10000	10000	10000	55000
(67)	Other						
	TOTAL	220079	210079	210079	210079	210079	1060395

Footnotes:

1. Personnel costings calculate as Annual salary x Time contribution x 1.35 for O'Connell, Grove, Rance, Galbraith, Pham, White.

2. Supplies , services and travel contributions estimated as CSIRO appropriation plus Industry Statement Funds for Western Australian component.

COLLABORATING AUSTRALIAN INSTITUTION CONTRIBUTIONS

(not met from ACIAR funds)

$(A) Value

	COST ITEM	YEAR 1 (1/7/97 30/6/98)	YEAR 2 (1/7/98 30/6/99)	YEAR (1/7/99 30/6/00)	YEAR 4 (1/7/00 30/6/01)	YEAR 5 (1/7/01 30/6/02)	TOTAL
1	Personnel	5400	21600	29700	29700	18900	105300
(65)	Supplies and Services						
(66)	Travel						
(67)	Other						
	TOTAL	5400	21600	29700	29700	18900	105300

Footnotes:

1. Calculated at 1.35 x salary x time contribution in active years of staff at UWA, UNSW and GU. (Professor Gilkes, Associate Professor Saffigna, Associate Professor McMurtrie)