UNIVERSITY OF SOUTHERN QUEENSLAND

RE-EVALUATING LAND USE CHOICES TO INCORPORATE CARBON VALUES: A CASE STUDY IN THE SOUTH BURNETT REGION OF QUEENSLAND, AUSTRALIA

A dissertation submitted by

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For the award of

DOCTOR OF PHILOSOPHY

2007

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I certify that the ideas, investigations, analysis, results, discussions, and conclusions reported in this dissertation are entirely my own work, except where otherwise acknowledged. I also certify that the work is original and has not been previously used to earn academic awards.

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Abstract

Land use change from forest to non-forest use is a major source of greenhouse gases in Australia. From 1996, the Queensland Government provided incentives for landholders to plant ex-pasture and cropping areas with hardwood plantations through the Southeast Queensland Regional Forest Agreement program. Spotted gum (*Corymbia citriodora* subspecies *Variegata*) was a target hardwood species for Southeast Queensland (SEQ); however, the long-term viability of timber-alone plantations relative to cropping and livestock production, in the medium to low rainfall areas of SEQ, and elsewhere in Australia, is questionable. Carbon credits resulting from additional carbon sequestration may change the relative profitability of these land uses. The aim of this research was to compare spotted gum plantations with peanut-maize cultivation and beef pasture in low rainfall areas, incorporating carbon values.

This study covers all variable costs and benefits, and different sources and sinks of three major greenhouse gases: carbon dioxide, methane and nitrous oxide. For the case study of three land use systems (maize-peanut cropping, pasture, and spotted gum plantations in the Kingaroy district of SEQ), production, carbon sequestration and emissions data were supplemented by formal and informal interviews with landholders, agronomists, sawmill staff and government extension personnel. Forest inventory, biomass and soil sampling, and stakeholder interviews were used as sources of primary data. The costs and benefits of all land use systems were converted into monetary terms and discounted to produce net present values.

If the comparison of net present values is limited to traditional benefits (i.e. income from crops and hay in cultivation, beef in pasture and timber in plantation), cultivation is the most profitable option, followed by pasture and plantations. Even after the inclusion of beef value, plantations could not compete with other land use systems. After the inclusion of greenhouse gas value, plantations were the most profitable option, followed by pasture and cultivation. However, if the carbon price was reduced from the price assumed in this thesis of \$10.5 $t^{-1}CO_2e$ to \$4.3 $t^{-1}CO_2e$, cultivation would remain the most profitable option.

If the currently used nominal (pre-text) discount rate (six percent) increased to seven or eight percent, the optimal rotation of plantation would reduce from 34 to 31 years and 29 years, respectively. At a seven percent discount rate, plantations would be a less profitable than pasture, but marginally more profitable than cultivation. If the discount rate were eight percent, plantations would be less profitable than both pasture and cultivation.

These findings have some implications for attempts to increase the plantation estate to three million hectares by 2020, through policy frameworks such as the Australian Government's 'Vision 2020'. Therefore, this study has recommended several measures to increase the benefits from plantations.

List of Publications during the PhD Study Period

1. List of Journal Papers

Maraseni, TN, Cockfield, G & Apan, A 2007*,* 'Estimation of taper rates and volume of smaller size logs in spotted gum saw timber', *Southern Hemisphere Forestry Journal* (accepted with minor revision)

Maraseni, TN, Cockfield, G & Apan, A 2007, 'A Comparison of Greenhouse Gas Emissions from Inputs into Farm Enterprises in Southeast Queensland, Australia', *Journal of Environmental Science and Health, Part A,* Vol 42 pp 11-19

Maraseni, TN, Cockfield, G & Apan, A 2005, 'Community Based Forest Management Systems in Developing Countries and Eligibility for Clean Development Mechanism', *Journal of Forest and Livelihood*, Vol 4 No 2, pp 31-42

Maraseni, TN, Cockfield, G, Apan, A & Mathers, N 2005, 'Estimation of Shrub Biomass: Development and Evaluation of Allometric Models Leading to Innovative Teaching Methods', *International Journal of Business & Management Education*, Special Issue, pp 17-32. (awarded IJBME 2005 prize for best paper)

2. List of Conference Papers

Maraseni, TN, Cockfield, G & Apan, A 2007, 'Analysis of Spacing for Spotted Gum Plantations for Maximizing Merchantable Logs' Volume in South East Queensland, Australia', Proceedings of the IUFRO 3.08 Conference, Ormoc City, Leyte, Philippines, 17-21 June 2007

Mathers, N, Dalal, R, Moody, P & Mareseni, TN 2006, 'Carbon Sequestration: A Case Study from the South Burnett', Proceedings of the Managing the Carbon Cycle Kingaroy Forum, 25-26 October 2006

Maraseni, TN, Mathers, NJ, Harms, B, Cockfield, G & Apan, A 2006, 'Comparing and Predicting Soil Carbon Quantities under Different Land Use Systems on the Red Ferrosol Soils of Southeast Queensland', paper presented to International Workshop on Development of Models and Forest Soil Surveys for Monitoring of Soil Carbon, 5-8 April 2006, Koli, Finland

Maraseni, TN, Cockfield, G & Apan, A 2005, 'Valuing Ecosystem Services from Forest: A Multidisciplinary Field Based Approach', a paper presented to the XXII International Union of Forest Research Organization (IUFRO) World Congress, 8-13 August 2005, Brisbane, Australia. Abstract published in The International Forestry Review, 7 (5), pp 299 (2005) and the complete paper posted on http://www.wiso.boku.ac.at/rwfh/torpap.htm

Maraseni, TN, Cockfield, G & Apan, A 2005, 'Community Based Forest Management Systems in Developing Countries and Eligibility for the CDM'*, Proceeding of the ITTO International Workshop on Clean Development*

Mechanism-Opportunities for the Forestry Sector in the Asia-Pacific Region, Seoul, Korea, 21st-23rd September, 2004

Maraseni, TN 2004, 'Re-evaluating Land Use Choices to Incorporate Carbon Values: A Case Study in the South Burnett Region of Queensland', a paper presented to the Science, Technology and Economic Progress (or Policy) Workshop (STEP-2004), the University of Queensland, 28 Nov –03 Dec 2004

3. List of edited Book Chapter

Maraseni, TN, Cockfield, G & Apan, A 2006, 'Community Based Forest Management Systems in Developing Countries and Eligibility for the CDM', *Climate Change, Kyoto Protocol and Forest Sector: Afforestation/Reforestation Clean Development Mechanism in Asia,* edited by Yeo-Chang Youn, Chapter 9 pp 214-254 (reprinted by special request from the book editor and with permission of the editor of the *Journal of Forest and Livelihood*).

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Abbreviations

3PG	Physiological Principle Predicting Growth Model
AGO	Australian Greenhouse Office
ANU	Australian National University
BAU	Business as Usual
BFN	Biologically Fixed Nitrogen
CAMAg	Carbon Accounting Model for Agriculture
CAMFor	Carbon Accounting Model for Forestry
CBA	Cost Benefit Analysis
CDM	Clean Development Mechanism
CER	Certified Emissions Reduction
CH_4	Methane
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
COPs	Conferences of Parties
CRC for GA	Cooperative Research Centre for Greenhouse Accounting
CSIRO	Commonwealth Scientific Industrial and Research Organisation
DBH	Diameter at Breast Height
DNRM	Department of Natural Resources and Mines
DPI&F or DPIF	Department of Primary Industries and Fisheries
ERU	Emissions Reduction Unit
EUETS	European Union Emissions Trading System
FAO	Food and Agricultural Organisation
FullCAM	Full Carbon Accounting Model
GENDEC	General Microbial Mulch Decay Model
GHG	Greenhouse Gas
GtC	Giga Ton Carbon
ha	Hectare
IBRA	Interim Bio-geographic Regionalisation of Australia
IPCC	Intergovernmental Panel on Climate Change
IRMS	Isoprime Isotope Mass Spectrometer
JI	Joint Implementation
KWh	Kilowatt Hour
MJ	Mega Joule
MLA	Meat and Livestock Australia
MSG	Mature Spotted Gum
Mt	Million Tonne
N_2O	Nitrous Oxide
NCAS	National Carbon Accounting System
NPV	Net Present Value
PCF	Prototype Carbon Fund
POM	Particulate Organic Matter
RothC	Rothamsted Carbon Model
SEQ	Southeast Queensland
SEQRFA	Southeast Queensland Regional Forest Agreement
TWh	Tegawatt Hour
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework Convention on Climate Change

Chapter 1

Introduction

1.1 Background

Forest clearing was part of the drive to "civilisation". The process is still continuing in many parts of the world, because people perceive that the natural forest is of less economic value than alternative uses (Filho, 2004). For example, highly valuable tropical rainforests of the Amazon (Brazil) are being replaced by soybean plantations, while Indonesian and Malaysian forests are being replaced by oil palm (Filho, 2004). If the world trend of forest clearing continues, an additional 10 billion hectares (about 1.3 times the size of Australia) of natural ecosystem could be converted to agriculture by 2050 (Tilman *et al.,* 2001). Forest clearing is one of the major sources of global warming (Stern, 2006), and the Kyoto Protocol aimed to curb global warming by limiting Annex B[1] countries to a particular level of emission reduction (UNFCCC, 1997). However, the continued deforestation rate of Brazil and Indonesia alone would equal 80% of the greenhouse gas emission reductions target for Annex B countries in its first commitment period of 2008-2012 (Santilli *et al.,* 2003).

In Australia, forest has been extensively cleared for cropping and grazing. Although the rate of clearing decreased from 546,000 hectares per year in 1988 to 187,000 hectares per year during 2000 to 2003, it is still relatively high (AGO, 2000; BRS, 2005). Therefore, unlike Europe, the United States of America and Canada, Australia was a net emitter of carbon (37.2 $MtCO_2e$) by virtue of land use change in 2000 (Kooten, 2004; Mitchell and Skjemstad, 2004). Forest clearing alone accounted for 12% of the total emission in Australia (AGO, 2000).

Around 80% of the total clearing in Australia has occurred in the state of Queensland. There were many motivating factors for forest clearing in Queensland,

[1] These are the 39 emissions-capped industrialised countries and economies in transition listed in Annex B of the Kyoto Protocol. Legally binding emission reduction obligations for Annex B countries range from an 8% decrease (EC) to a 10% increase (Iceland) on 1990 levels by the first commitment period of the Protocol, 2008-2012 (Auckland *et al*., 2002). Annex I and Annex B are used interchangeably in some papers. However, Annex I refers to the 36 industrialised countries and economies in transition listed in Annex I of the United Nations Framework Convention on Climate Change. They have a non-binding commitment to reduce their GHG emissions to 1990 levels by 2000 (Auckland *et al*., 2002).

but the driving force was economic return, availability of cheap land, and high and immediate profit—immediate profit from crop production, and long-term profit from increased land values (AGO, 2000). Clearing was perceived as development and land was considered wasted unless it was developed. In fact, clearing in Queensland accelerated in the second half of the twentieth century under a government-sponsored development scheme. Cheap land and low-interest loans were offered under the condition that land holders improved the land by clearing (Fensham and Fairfax, 2003).

The cleared land was predominantly used for the grazing of livestock. However, in certain areas with favourable climatic and topographic factors (such as the inland Burnett region of Southeast Queensland), much of the cleared land was used for crop production. By the 1980s, increasing costs of production and decreasing commodity prices, especially of the major cereals, created economic pressure on farmers (Zammit *et al*., 2001). Technological innovation did not keep pace with increasing costs. This caused a shift in land use around the 1980s from cultivation to grazed pasture in less productive or degraded cropping land (Zammit *et al.,* 2001; Maraseni *et al.,* 2006). Recently, due to increased environmental concerns focusing on land degradation and the risk of dry land salinity, the Queensland Government has encouraged farmers to plant hardwood plantations on some degraded ex-cultivation and pasture areas (DPI&F and DNR, 1999; DPI&F, 2000; Brown, 2002).

One of the main hardwood species being promoted by government agencies in the Southeast Queensland (SEQ) region is spotted gum (*Corymbia citriodora* subspecies *Variegata*). There are a number of reasons for this. Firstly, over time, large areas of SEQ were World Heritage listed, became National Parks or tenure was restricted. This diminished the supply of native timber including spotted gum, but demand still increased by two to three percent every year (DPI&F and DNR, 1999). Secondly, although the full rotation plantation data are not available, the early age performance of spotted gum is quite encouraging (Huth *et al*., 2004). Thirdly, preliminary results of the genetic improvement program of spotted gum are promising, as the seedlings are given vegetative propagative capacity, frost tolerance and *Ramularia* shoot blight resistance (Lee, 2005). Fourthly, the timber is highly valued for its durability, hardness and pale colour (Huth *et al.,* 2004). Finally, of the 3.42 million hectares of cleared land evaluated for plantation in the South East Queensland Regional Forest

Agreement (SEQRFA) region, 2.72 M ha met the slope and size constraint, and 73% of that land was found suitable for spotted gum (Queensland CRA/FRA Steering Committee, 1998).

The national policy statement '*Plantation for Australia: The 2020 Vision'* has its target a trebling of the national plantation state to about three million hectares by the year 2020 (Kirschbaum, 2000). In order to support this target, the Queensland Government committed to increase the plantation estate by 320,000 hectares from 1996 to 2020 (DPI&F, 2000). A 20-year Federal-State agreement, known as the Southeast Queensland Regional Forest Agreement (SEQRFA), was implemented in 1996 for native forest conservation and timber resources management in SEQ (Brown, 2002). As a part of this SEQRFA program, the Queensland Government approved a $30 million plan to increase the hardwood plantation area, especially of spotted gum, in SEQ (DPI&F, 2004b). This initiative was not solely or even primarily a carbon sequestration strategy, but flowed from earlier concerns at the national political level about logging in native forests (Resource Assessment Commission, 1992) and the consequent decision that there was a need to expand the plantation area as a substitute in supply (Commonwealth of Australia, 1995).

While it was recognised that small-scale farm plantations would only be a small part of that total expansion, it was considered that in light of the other social benefits, including carbon sequestration, such plantations should be encouraged (Centre for International Economics, 1997). Since then, several reports have proposed that carbon payments for sequestration could be used to make farm plantations financially attractive (Binning *et al.,* 2002; Buffier, 2002). This is an important consideration, given that timber values alone are unlikely to yield a positive return in medium to low rainfall areas of SEQ (600-800 mm/year) (Venn, 2005).

In inland SEQ, mean monthly rainfall is always lower than mean monthly evaporation (Mills and Schmidt, 2000), and so, soil moisture is the major limiting factor for non-irrigated crops. The Red Ferrosol soils of inland SEQ were considered suitable for different types of crops but, due to traditional continuous cultivation practice, yield potential has declined or plateaued (Australian Institute of Agricultural Science and Technology, 1994; Bell *et al*., 1995; Cotching, 1995; Bell *et al.,* 1997; Bell *et al*., 2001). Spotted gum plantations could be a competitive land use on these soil types, if carbon sequestration is considered; particularly as the Red Ferrosol soils are a target area of the SEQRFA program for plantation establishment.

As of 2007, Australia had decided not to ratify the Kyoto Protocol. However, the national Government was committed to meeting the target of 108% of 1990 emissions levels by 2012, agreed at the Protocol (Booth, 2003). Some domestic carbon markets are also emerging. Setting aside the issues in creating a functional carbon market, this research investigates the relative carbon budgets that would be generated by two current conventional enterprises (pasture and crops) and a proposed new land use activity (hardwood plantations) in inland SEQ.

In Australia, so far, competing land uses have been generally judged only on the basis of net present value from tangible benefits. With emerging carbon markets, it would be worthwhile to consider the carbon sequestration potential when comparing different land use systems. In this context, the original concept of net present value maximisation would be extended to capture carbon value. How to select the appropriate land use types in order to maximise the overall net present value (both from tangible benefits and carbon) is becoming a pressing concern for stakeholders at all levels. The goal of this study is to compare three competing land use systems (peanut-maize cropping system, pastureland and spotted gum plantation[2]) in inland SEQ, incorporating both carbon[3] and tangible values.

In summary, land use systems could be a net source or sink of greenhouse gas, based on their nature and management practices. Changing land use and land management practices may sequestrate additional carbon and therefore mitigate the effect of global warming to some extent; however, there are several areas of concern which require attention by researchers. In the next section, some of the common and site-specific problems relevant to this PhD research, are discussed.

[2] Throughout the thesis, the words ‘spotted gum plantation’ and ‘plantation’ are used interchangeably. Similarly the words ‘peanut-maize cropping’, ‘cultivation’ and ‘cropping’ are used interchangeably, and the word ‘stock of livestock” value in pasture and plantation refers to the ‘beef’ value of ‘livestock’ value.

[3] Similarly, the words ‘carbon’ and ‘greenhouse gases (GHG)’ are used interchangeably. In land use systems, three GHGs, CO_2, CH_4 and N_2O are most common. Therefore, the carbon or GHGs values cover the value from these three GHGs.

1.2 Problem statement

The overarching policy problem driving this research is that greenhouse gases are likely to be contributing to climate change, but it is difficult to rapidly and drastically reduce industrial emissions and so sinks need to be considered. Timber plantations in medium to low rainfall areas are not generally profitable relative to other land uses. The research "problem" is that there is a chance of increasing plantation benefits by incorporating carbon values, but the carbon budgeting to date has not been comprehensive enough to demonstrate the potential for carbon payments to induce landholders to change land use. In this section, gaps in carbon budgeting research and estimations are identified and then the site and species-specific research gaps are discussed.

1.2.1 Research gaps in carbon budgeting estimations

This study has identified six common problems in carbon budgeting estimation. First, there is a lack of accounting for all greenhouse gases when comparing different land use systems. There are many anthropogenic gases responsible for global warming; however, six gases are major contributors (UNFCCC, 1997). Among them, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are responsible for 60%, 20% and 6% respectively of the observed global warming (Dalal *et al,* 2003). These are the only gases related to land use systems. Thus, when comparing the different land use systems, these gases need to be taken into account. However, there is a lack of comprehensive research that accounts for all these gases in one place or with one activity. Accounting for one and omitting other greenhouse gases could not give a holistic picture of the production area in question and could result in the wrong land use decisions. For example, carbon sequestration in soil may be increased through improved pasture systems, as the system introduces exotic grasses and nitrogen fixing legume species (Paul *et al*., 2002). However, due to increased stocking rates, emissions of CH_4 by cattle burping and emissions of N_2O due to de-nitrification of cattle excretion would also be increased.

Second, greenhouse gas emissions associated with production, packaging, transportation and the application of primary farm inputs are largely ignored in most accounting frameworks. Primary farm inputs include agrochemicals, fuel and machinery. Agrochemicals include fertilisers, herbicides, pesticides, insecticides and fungicides. Intensification in agriculture not only contributes to increased productivity but can indirectly contribute to preserving sinks through reducing the pressure to clear native vegetation (Vlek *et al.,* 2003). However, intensification has never been an emissions-free mechanism. It demands more fuel, farm machinery and agrochemicals; in turn, their production, packing, transportation and application require significant energy, which results in even more greenhouse gases being emitted.

The practice of increasing biomass and yield of crops, pastures and forests by applying different types of fertilisers is widespread (Turner *et al.,*1999; IPCC, 2000; Gardenas & Eckersten, 2006). Compared to the 1950s, the global use of fertilisers in 1999 was about 23 times as higher in the case of nitrogen, almost eight times higher for phosphorus and more than four times higher for potassium (Smil, 1999). In Australia, between 1987 and 2000, nitrogen fertiliser use increased by 325% (Dalal *et al.,* 2003). The worldwide use of agricultural pesticides also increased from an equivalent value of US$20.5 billion in 1993 by an average of three percent per year to US$27.5 billion in 2003 (Vlek *et al.,* 2003).

Researchers highlight the increase in biomass (carbon sequestration) and yield due to increasing use of agrochemicals, but hardly think about the emission of carbon during the production, packing, transportation and application of these agrochemicals (Gower, 2003). For example, applied nitrogen fertiliser also emits some nitrous oxide during de-nitrification, which has 310 times more global warming potential than CO_2 (IPCC, 2000). Furthermore, applied nitrogen may leach and can create an eutrophication problems in lowland areas. However, these problems are not generally considered in the literature.

Emissions associated with farm machinery are other areas of concern. In developing countries, people use little in the way of farm machinery (Stout, 1990), whereas due to higher labour costs, mechanisation in farming has been a common practice in developed countries. Of the total energy used in world agriculture, about 51% goes on farm machinery manufacture and 45% on the production of chemical fertiliser (Helsel, 1992). Around 83.7 mega joule energy is required to produce a kilo of farm machinery (Stout, 1990), yet the emission of greenhouse gases from the production of farm machinery is largely ignored in the research. Similarly, many land use activities, such as the production, transportation and utilisation of different land use products, need fossil fuels. The production, transportation and combustion of fuels emit significant amounts of greenhouse gases into the atmosphere, but the emissions associated with these activities are again not properly accounted for (Gower, 2003).

Researchers are developing different chemicals/vaccines/hormones to reduce the emission of N_2O and CH_4. For example, it has been claimed that the application of 3, 4-dimethylpyrazole phosphate with urea reduced N_2O emission by 45% over a three-year period in Germany (Dalal *et al.,* 2003); however, greenhouse gas emissions caused by the production, transportation and application of that chemical are not taken into account. Similarly, research from Australia showed that placing cattle on a 2-5 month on a grain-based feedlot diet resulted in 43-54% reduction in lifetime CH_4 production per kg saleable beef yield (McCrabb *et al.,* 1998 cited in McCrabb and Hunter, 1999); however, this finding did not consider the amount of greenhouse gas emissions produced by the cultivation and processing of feed grains.

Including negative externality can result in accurate or complete conclusions. Therefore, for a realistic comparison of different land use systems, a comprehensive study covering the production, transportation and application of primary farm inputs for both on-and off-farm activities is crucial.

Third, emission of nitrous oxide from biologically fixed nitrogen is also not usually considered. The atmosphere contains about 79% nitrogen, yet no plant can utilise it directly from the atmosphere except legumes. Legumes can fix atmospheric nitrogen and make it available for the plants in a usable form. In that sense the legume is a friend of the farmer, but it is an enemy too, as part of the biologically fixed nitrogen (BFN) goes to the atmosphere in the form of N_2O. This gas accelerates global warming and the ozone layer depletion process. There is a tendency to incorporate legumes in pasture, silvipasture and cropping systems for soil carbon, soil nitrogen and nutrients benefits (Paul *et al*., 2002). However, because the proportion of legumes vary in different land use systems omitting the emissions of N_2O from BFN would not only underestimate their contribution to global warming but also lead us to make a wrong comparison of different land use systems.

Fourth, with reference to climate change, research is largely based on broadscale models and assumptions. Each Annex I country is required to submit its 'National Communications' (greenhouse gas estimations) to the United Nations Framework Convention on Climate Change (UNFCCC) Secretariat. Consequently, the greenhouse gas amounts in different land use systems at the global and national levels are well researched, but are poorly understood at a local and species-specific level. Furthermore, most of these studies have used different models based on varying assumptions; consequently the results are not homogenous (Haripriya, 2001). For example, the carbon sequestration rates of Indian forests estimated by Teri (1998) and Ravindranath *et al.* (1996) are not comparable because different methodologies and assumptions are used to determine those rates (Haripriya, 2001). Similarly, Faubert *et al.* (2006) reported that the soil carbon estimates for four forest sites in Finland and two forest sites in Germany by four popular soil carbon models (in each site) developed for that region (4C, YASSO, ROMUL and RothC) were different. This shows that the choice of model makes a big difference to predicted soil carbon. Therefore, where possible, the same model should be used to compare various land use systems.

Fifth, the fates of harvested products are poorly documented. The Intergovernmental Panel of Climate Change (IPCC), a body of leading scientists in the world, is responsible for developing and/or validating greenhouse gas accounting methodologies. Even the IPCC framework does not consider the fate of harvested wood, litter and debris and it assumes that entire harvested products release carbon into the atmosphere immediately after harvesting (Haripriya, 2001). It is obvious that these products could store carbon for many years depending on their end uses, preservatives used and mechanical properties (Maraseni *et al.,* 2005). There are, however, some models on the estimation of annual emission from harvested products (see Bateman and Lovette, 2000 and Haripriya, 2001 for detail). These models need to be used cautiously on the basis of local consumption patterns and characteristics of the species. People may use forest products as timbers, logs, furniture etc. for a few years and recycle them again for different uses.

Finally, the optimal rotation age of plantation is not properly recalculated to incorporate carbon values. Carbon sequestration is the increase in carbon concentration other than in the atmosphere (IPCC, 2000). It not only covers carbon in standing biomass, but also in harvested products and soil. Liski *et al.* (2001) report that the rotation age of tree species not only determines the carbon stored in forests, but also in soil and wood products. By shortening the rotation length, carbon stock in trees may decrease, but it may increase in soil. The production residues increase due to a higher number of felling and the trees harvested at a younger age leave more harvest residue per harvested stem wood volume (Liski *et al.,* 2001). However, this is not always the case. In many cases, after harvesting trees, people may collect the residue for different purposes (maybe for firewood, fodder or compost), or they may burn the residue during the cultural operation. Moreover, the planting operation followed by harvesting may lead to significant soil carbon emissions (Paul *et al.,* 2002; Paul *et al.*, 2003).

Harvesting age determines the types, sizes and quantities of wood products that can be extracted, which, in turn, determines the types and quantity of products that can be manufactured (Liski *et al.,* 2001). Shorter rotation produces small wood products for which the life span is lower, thus, it may reduce the benefit of carbon stored in wood. If the wood is used for pulp, fossil fuel is necessary which may emit carbon into the atmosphere (Gower, 2003). If the pulp mill is taxed for carbon emissions, it will reduce the payment to the farmers it gives for the wood, which reduces their profit and may also affect rotation age (Gower, 2003). However, if small wood products were used as bio-fuel sources with 100% substitution efficiency, it could be more beneficial (Kirschbaum, 2003).

Hence, it can be said that the consideration of carbon sequestration in standing biomass and total costs and benefits is not enough to determine optimal rotation of a plantation. An estimation of emissions of all greenhouse gases (CO_2, CH_4 and N_2O) associated with primary farm inputs, cattle burping and excretion, biologically fixed nitrogen, and the sequestration of carbon in standing biomass, soil and harvested products, is necessary to account for optimal rotation of a plantation[4]. However, these factors are so far poorly accounted for in the determination of optimal rotation.

[4] The optimal rotation, including GHG value, is a useful output of the thesis. However, the Faustmann rotation incorporates more than GHG value, considers both the private and social payoff from forestry. Therefore, determinion of the optimal economic rotation is a secondary issue.

1.2.2 Site- and species-specific research gaps

Pasture and peanut cropping systems are well established in the South Burnett district (study district). Collecting costs and benefits data and greenhouse gas emissions and/or sequestration data about these systems is relatively easy. However, plantations of spotted gum only started in 2001, after implementation of the Southeast Queensland Regional Forest Agreement (SEQRFA) program. In order to examine the competitiveness of spotted gum plantations against other land use systems, it is necessary to investigate the optimum spacing and rotation of plantations in that region. Selecting appropriate spacing and rotation age is important in order to maximise the return of plantations. The spacing which is most appropriate for maximum economic return in a minimum timeframe is a major issue of concern. Similarly, the rotation age which is most appropriate for harvesting, once carbon and tangible values are considered, is another research issue. However, the production research of spotted gum is limited due to the scarcity of age research plots. Therefore, there is no growth model for spotted gum in Australia. Moreover, the lack of mid and full rotation plantation data in the research site added another complication for model development (Huth *et al.,* 2004).

This study addressed the first issue by analysing and modelling the fifteen-year time series data of the Warril View hardwood experiment site near Ipswich, the oldest spotted gum experimental site in SEQ. The second issue (rotation age) was addressed by interpolating and extrapolating Warril View data and research site data. Another major problem in the research area was about the estimation and prediction of long-term soil carbon under the newly established plantation. This problem was addressed by measuring and predicting the soil carbon under naturally regenerating mature spotted gum and triangulating the timeline of land use change.

1.3 Justification of the study

The South Burnett region has three main features relevant to this study: degraded and deteriorated soils (Cotching, 1995; Bell *et al*., 1997); higher monthly evaporation than monthly rainfall (Mills and Schmidt, 2000); and dominance of non-irrigated or dry land farming. Continuous traditional peanut cropping has been blamed for the deteriorating soil condition (Cotching, 1995; Bell *et al*., 1997). There are at least three reasons to target this area for hardwood plantation via the SEQRFA program:

1) Red Ferrosol soil is considered relatively better for many crops, including hardwood species (Australian Bureau of Statistics, 2002). 2) Hardwood plantations can not compete financially with peanut and other cropping in high rainfall or irrigated areas; however, it could be competitive on degraded non-irrigated land in a low rainfall area. 3) There is a need to meet the increasing demand for hardwood species from the region (DPI&F and DNR, 1999; DPI&F, 2000).

For the reasons discussed above, spotted gum is becoming a popular hardwood plantation species in this region (Queensland CRA/FRA Steering Committee, 1998; Lee, 2005), but there is a knowledge gap on its performance at mid and full rotation age (Huth *et al.,* 2004). Furthermore, there is a lack of information about the long-term performance of spotted gum, even though it is highly recommended for plantations. Therefore, a study that can furnish reasonable information about optimum spacing and optimal rotation for spotted gum plantations in a poor data environment is highly desirable.

Although the Queensland Government has made considerable effort to encourage hardwood plantations, the long-term viability of the plantation program for timber in medium to low rainfall areas remains questionable (Venn, 2005). The ultimate driving force for plantations is economic return, so if the economic return of a plantation is comparable to other land use systems, it can be expected that farmers will be motivated to grow plantations. In that sense, it is an interesting area for this kind of PhD research, as its applicability could be greater.

It is hypothesised that plantations could be competitive with other land use systems, if carbon and grazing[5] (stock) benefits are considered. The newly established plantation under the SEQRFA at the research site is actually a silvipastoral system, which includes nitrogen fixing legumes along with exotic and native grasses species that are planted as an intercrop with the spotted gum. Although inclusion of grazing would add some extra cost, the additional benefit of inclusion could be higher than that cost. A thorough literature research failed to identify any reports of research that compares the total benefit (including three greenhouse gases and tangible benefits) of peanut-maize cropping, pastureland and spotted gum plantations in the non-irrigated

[5] Throughout the study, the words ‘stock’ and ‘grazing’ are used interchangeably.

red Ferrosol soil of these low rainfall areas, or for that matter other areas of Australia.

This study attempts to be more comprehensive than other related studies discussed in previous sections. There are some studies at the local level; however, they have limited scope, being either related to only one land use type, or considering only the tangible benefits, or only one greenhouse gas. This study analyses different land use types incorporating all three greenhouse gases from different sources and sinks and tangible benefits in one place. Moreover, it is partly field-based empirical research which could relatively reflect the real world scenario, as opposed to entirely model-based research.

1.4 The goal and objectives of the study

The overarching goal of the study is to compare the net benefits from cropping, pasture and plantation, incorporating both traditional products (peanuts and maize in cultivation, beef in pasture and timber in plantations) and carbon[6] values. The specific objectives and their respective complementary research questions are:

1. to assess the optimum spacing and optimum rotation age of spotted gum plantations;
    a. What is the optimum spacing for maximising timber volume?
    b. What is the optimum rotation, if we consider timber value, timber plus stock value, and timber plus stock plus carbon value?
2. to assess the soil and biomass carbon of different land use systems;
    a. How much carbon is stored in the soil, particulate organic matter and surface litter?
    b. What is the soil carbon trend in different land use systems?
    c. How much carbon is stored in the standing biomass in different ages?
3. to assess the greenhouse gas emissions from farm inputs, general land use, biologically fixed nitrogen, and animal excretion and belching in different land use systems;
    a. How much carbon is emitted due to production, packaging, transportation and application of agrochemicals?

[6] Carbon covers all three greenhouse gases (CO_2, CH_4 and N_2O). CH_4 and N_2O, where necessary, are converted into carbon dioxide equivalent (CO_2e).

   b. How much carbon is emitted for the production and transportation of fuels?
   c. How much fuel is used for the production, harvest and transportation of land-use products?
   d. How much carbon is emitted from the use of farm machinery?
   e. How much carbon is emitted by biologically fixed nitrogen?
   f. How much carbon is emitted from cattle burping and excretions?
4. to re-evaluate land use choices incorporating carbon and stock values;
   a. What are the sources and amount of costs and tangible benefits in different land use systems?
   b. What is the price for carbon credit?
   c. What are the net present values of different land use systems with and without carbon values?

These objectives are inherent in the hypotheses, which are discussed in the next section.

1.5 Research hypotheses tested

It is expected that the net present value (NPV) of crop production will be higher than plantations and pasture, if we do not consider stock and carbon value of plantation. The NPV from plantation would increase by including the livestock component. However, even after inclusion of stock NPV, plantations are unlikely to compete with cultivation and pasture. If three main greenhouse gases from all sources and sinks of all land uses were considered, the NPV from cultivation and pasture would reduce and the NPV from plantation would increase significantly. Therefore, the plantation will be the most profitable option followed by pasture and cultivation if carbon and stock values of plantations are considered. In this context, the major hypothesis of this research is:

> The NPV of plantation will be greater than the NPV of pasture, and the NPV of pasture will be greater than the NPV of cultivation, if carbon and stock values of plantation are considered.

This presumes an inferred carbon value of at least \$10 $t^{-1}CO_2e$. It is expected that the emissions associated with primary farm inputs (agrochemicals, machinery and fuels) in cultivation will be much higher than in plantations and pasture, and the accumulation of carbon in the plantations biomass will be much higher than in other land use systems. Therefore, changing land-use from cropping and pasture to plantation would be more profitable.

This hypothesis is supported by several sub-hypotheses. In order to clarify the sub-hypotheses, it is worth noting that the land for the primary study site was originally scrubland; peanuts-maize cultivation began in 1950 in scrubland, pasture in 1983 in the cropping land, and plantation in 2001 in pastureland. Sub-hypotheses are as follows:

- Traditional cultivation practices will result in a decrease in soil carbon amount. The soil carbon problem will be compounded because part of the biologically fixed nitrogen will emit into the atmosphere in the form of N_2O.
- In the case of pasture land, soil carbon should have increased from the cultivation stage due to improved ground cover, but this would be offset by CH_4 and N_2O emission from beef production.
- In the case of plantations, soil carbon would increase in the long run. More importantly, more carbon would be locked in the standing biomass (both above and underground biomass) compared to pastureland.
- If we consider both carbon and tangible benefits, the optimal rotation age (time) of spotted gum would be longer than the optimal rotation age of timber-alone plantations.

These hypotheses are based on the current body of literature.

1.6 Significance of the study

Australian greenhouse gas emissions increased 23% during the thirteen years from 1990 to 2003 (BRS, 2005). Including land use, land-use change and forestry activities this would have been 18.2% (von Kooten, 2004). In order to encourage farmers towards eco-friendly land uses, several markets for ecosystem services have been developed at national and state levels (Binning *et al.*, 2002; Cacho *et al.,* 2003). Federal and state governments have developed several supportive policies for market development (Fung *et al.,* 2002; Booth, 2003). The joint decision of the New South

Wales and Victorian governments in 2005 for greenhouse gas emissions reduction at the state level was an important step that could advance the carbon market. Similarly, in July 2005, Australia joined hands with the governments of the United States of America, India, China, Korea and Japan, and announced the Asia Pacific Partnership on Clean Development and Climate pact to promote technology deployment and transfer. This will help to develop carbon markets. This thesis provides information for farmers about the most profitable land use system (if carbon market becomes a reality), and level of carbon payment needed to exceed cultivation and pasture productions.

The Queensland Government committed to increase the amount of land under plantations by 320,000 hectares from 1996 to 2020 (DPI&F, 2000). For this to happen, expansion into an area further inland (a medium rainfall dry land farming area) is necessary, which is the focus area of our research. In order to realise the plantation target, the private sector should be motivated and the key motivating factor is economic return. As this research focuses on the maximisation of return by recommending optimal spacing and rotation age of spotted gum, it would provide a signpost toward achieving the plantation target.

Although the exact production system cannot be copied to other areas, or to other species, it is anticipated that similar analyses and reasoning could be adopted in other states/species. There is much research in the area of carbon, but all have a piecemeal approach. This is the first comprehensive field-based study that analyses all sources and sinks of greenhouse gases and tangible costs and benefits in one place.

1.7 Scope and limitations of the study

The research sites have three parameters: medium to low rainfall in a rain-fed region, degraded soil (Red Ferrosols) and Southeast Queensland Regional Forest Agreement (SEQRFA) areas. These characteristics limit the scope of the research. Although there were several land-uses in practice in the South Burnett region, the study was limited to only three competing land uses, which were of special interest to farmers and policy makers.

In the research area, the age of planted spotted gum was approximately four years. It was not possible to get mid and full rotation data from the research site; therefore, the major limitation of the study was the poor forest data environment. This was especially a problem for growth model development, long-term soil carbon trend prediction and estimation of cost and benefit data. So, proxy values from other sites and species were used.

Because of the same data problem, the optimal rotation estimation was limited to a single harvest. While taking proxy values from other sites, some assumptions were used for the determination of optimal rotation. Estimation of optimal rotation for multiple harvests needs more assumptions: such as that stumpage value at each rotation is the same, productivity is unimpaired by continuous cropping, climatic factors remain the same, and all types of prices, costs and benefits remain constant over time. In fact, none of these assumptions are likely to be true. Logging can cause erosion which can reduce the site productivity. Climatic factors can change which could affect productivity. The price of timber could rise and technological changes could reduce the costs (Campbell, 1999). Moreover, once the first rotation data was complete, there would be more information that could be used to develop a more accurate model. Therefore, the optimal rotation for multiple harvests was not predicted. More importantly, discounting cash flows from such a long rotation of spotted gum will have small net present value. Therefore, single rotation is preferable to multiple rotation.

Since the results were based on a case study, they should be used cautiously. In particular, the soil carbon data is applicable only if the cultivation was initiated on native scrub land, semi-improved pasture replaced cultivation and spotted gum plantations replaced semi-improved pasture. More importantly, the overall research findings are currently only applicable to the Red Ferrosols of dry land farming areas having similar edaphic, topographic and climatic factors. Further research would be required to adapt the model to other soil types or climatic regions.

1.8 The structure of the thesis

This thesis is divided into nine chapters. In the first three chapters, the introduction, literature review, research methodology and study area overview are covered. In the fourth chapter, results and discussions about the soil and biomass carbons of different land use systems are presented. In the fifth chapter, the greenhouse gas emissions from farm inputs, general land use, biologically fixed nitrogen, and animal excretion and belching[7] in different land use systems are assessed. In the sixth and seventh chapters, the optimum spacing (density) and optimum rotation age of plantations are discussed. In chapter eight, the net present values (NPVs) of cropping and pastures lands by incorporating their carbon values are estimated first, and then these NPVs were compared with NPV of plantation at rotation age. The last chapter comprises conclusions, policy implications and research contributions. Although the results and discussions chapters (five to eight) are designed to serve different objectives, they all are contributing to the final goal of the thesis as nested chapters. Therefore, in some places, suggestions are given to see some information from another chapter.

1.9 Conclusions

Forest clearing is a major environmental problem as a source of the greenhouse gases that contribute to global warming. In Australia, the cleared lands are either used for cultivation or for grazing. Recently, state governments have encouraged farmers to plant hardwood tree species in degraded pasture and cultivation lands, including in medium to low rainfall areas. However, the viability of plantations in such areas is still questionable. In the context of the Kyoto Protocol and domestic carbon markets, farmers could get paid for changing and/or managing land use for additional carbon sequestration. It is hypothesised that plantations could be competitive with cultivation and pasture in medium rainfall and degraded Red Ferrosol areas of inland SEQ, if stock and carbon values are rewarded.

This chapter identified some common and site specific research gaps with reference to carbon sequestration and land use systems and it was argued that there is no comprehensive research that compares different land use systems incorporating three greenhouse gases and tangible values. This PhD research will address all those common and site and species-specific issues by taking the case example of three competitive land use systems in Kingaroy. The work in this thesis is necessarily multidisciplinary work, involving tangible benefits and three greenhouse gases from three land use systems. It involves farm production economics, carbon market analysis, soil survey and analysis, spacing and growth modelling and analyses, stakeholders' interviews and an in depth literature review for various data sources. This type of study was intentionally chosen for three reasons. First, it reflects the

[7] Throughout the thesis, the words 'belching' and 'burping' are used interchangeably

multidisciplinary background of the researcher. Second, without comprehensive analysis of three greenhouse gases and any tangible benefits the holistic picture of the land uses in question was not possible. Third, this type of study may influence policy makers and landholders' advisors therefore the applicability of research could be broader.

In order to meet the specified objectives, a detailed analysis of current practices and models are necessary. This analysis will not only help to identify more issues in the area of carbon and land use choices but will also help to derive some important information and to develop more robust models. In the next chapter, this research will evaluate the current literature.

Chapter 2

A Review of Carbon Sequestration and Farm Economics

2.1 Introduction

In this chapter, the current literature on carbon sequestration and its relation to land use systems and farm economics are critically reviewed. Special focus is given to the land use changes and recent policy of government, soil and biomass carbon, methane emission from cattle, and nitrous oxide emission from different sources including the biologically fixed nitrogen in legumes. It has identified and discussed the key research issues and their relevance to this study, which helped me to justify the reason for my research and establish research framework. Identified research issues ranges from site- and species-specific to more general in nature.

2.2 Land use changes and the Queensland policy environment

In the first chapter, the discussion focused on forest clearing and its environmental consequences, the changing scenarios in past decades, and why spotted gum was a popular hardwood species for plantation. In this section, motivators of forest clearing, current policies of government to combat forest clearing, and changing paradigms of plantations are discussed. This section explains why this research has been designed in Queensland.

2.2.1 Motivators of forest clearing

Europeans settled in Australia in late 1780s, valuing its rich land resources. As agriculture was the dominant land use occupation around the world, it was perceived as a pathway to progress and civilisation, the backbone of an economy and as having inherent cultural value (Cockfield, 2005). The major pressure of European settlement occurred on native vegetation, which was cleared for pasture, cropping, mining and urbanisation. Government deregulation and incentives also encouraged land clearing. When Queensland gained self-government in 1859 the new state was close to bankruptcy (University of New South Wales, 1999). Resource mobilisation was an overarching priority to encourage investment and raise tax revenue. As a result, the State Government stimulated a decentralised agrarian settlement pattern, which in turn, exacerbated the land clearing problem (University of New South Wales, 1999).

There were many motivating factors for forest clearing but the driving force was economic return. However, a high return was possible due to many complementary factors. For simplicity, Australian Greenhouse Office (AGO, 2000) describes this phenomenon, as shown in Figure 2.1. In fact, four of the factors; economic, environmental and social, incentives, and research and development, directly and indirectly help to increase agriculture profits, which in turn accelerate the rate of forest clearing. The availability of relatively low-cost land and financing from the financial institutions, including Commonwealth Development Bank and Rural Credit Development Bank, were major drivers of forest clearing until 1990, as clearing was categorised as development work by the banks.

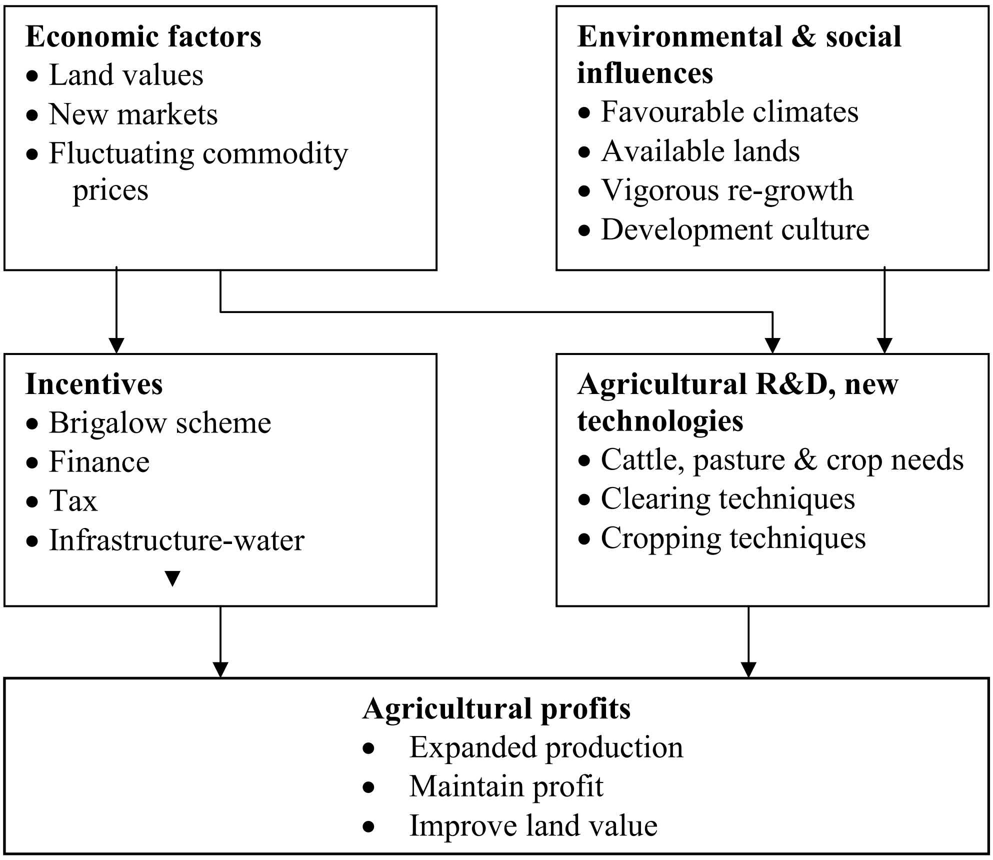


Figure 2.1 Drivers of land clearing (Source: AGO, 2000)

Government sponsored development schemes, closer settlement, providing cheap land and low interest loans with the conditions that land holders improve the land accelerated the forest clearance activities during the second half of the twentieth century. The $23 million government sponsored Brigalow Land Development Scheme covered some 11.1 million hectares from 1962-1985 (Fensham and Fairfax, 2003). Governments offered better land titles (leases to freehold) for those who cleared the forest in a given timeframe and brought it into full production. Tax concessions, deduction of clearing costs from the farm income, and low cost finance are other accessory factors of clearing (AGO, 2000).

Research and development activities helped forest clearing in several ways, as it ultimately boosted profits. Inventions of new machinery for faster and cheaper forest clearing, new varieties of crops and pastures, identification of trace elements and fertilisers are some examples of research outputs. For example, after the introduction of buffel grass the carrying capacity of Brigalow land increased significantly. Similarly, the introduction of heat and tick resistant cattle breeds accelerated the growth of beef industries (AGO, 2000).

New markets and changing commodity prices also played a big role in forest clearing. For example, the advent of a market for woodchips in the early 1970s provided additional revenue for forest clearing. Similarly, forest clearing was accelerated for the beef industry after Japan and Korea emerged as new markets for beef in the 1970s and 1980s (AGO, 2000). It was assumed that forest clearing would have decreased at the time of the beef crisis in the early 1970s but the clearing continued due to the shift from beef to profitable crops (AGO, 2000). Construction of the Fairbairn and Burdekin Dams speeded-up forest clearing for cotton and horticulture and the construction of Beef Roads to transport cattle from remote areas to abattoirs also facilitated the forest clearing as all these activities helped to increase profit margins. Because of these forest clearing, around 25% of Australia's emissions are associated with the use and management of lands whereas other developed countries which manage large land masses such as the US and Canada are net sinks for greenhouse gases in land use sector (Mitchell and Skjemstad, 2004).

2.2.2 Recent policies to slow down forest clearing rate

There are some policies in place to slow down the forest clearing rate and increase plantation estates. Regarding land use decisions, the Queensland Government has the sole responsibility, however, the provisions of the Australian Heritage Commissions Act (1975) and the Environmental Protection Act (1974) of the Federal Government must be met (AGO, 2000). In Queensland, before 1990, there was no legislation controlling native forest management in all land title types. The Land Act (1994) makes provision for seeking permission for native vegetation clearing in leasehold lands, but not for previously cleared land (AGO, 2000). However, after the implementation of a native vegetation management framework in the 1990s the legislation applies to all tenures (AGO, 2000). There are new schemes to preserve vegetation in farm landscape. The Victorian Government has implemented the Bush Tender initiative through which landholders have been paid to conserve any areas of native species on their properties. New South Wales has followed this with an Environmental Service Scheme in which landholders will receive payments for changing their land-use practices and improving the environmental services they provide through their properties (Cacho *et al*., 2003).

Another important policy that affects states governments is the 'Plantation for Australia: The 2020 Vision' set by the Federal Government. This policy has targeted trebling the national plantation state to about three million hectares by the year 2020, for which an average new planting rate of 100,000 $hayr^{-1}$ is needed (Kirschbaum, 2000). Although, the current forest clearing rate (187,000 $hayr^{-1}$) is much higher than the targeted plantation (100,000 $hayr^{-1}$), it would bring a significant change in the long-run, if the clearing rate were to continue to decrease. State governments are supporting this policy in their own way and through a State-Federal partnership program. One notable program in Queensland is the Southeast Queensland Regional Forest Agreement (SEQRFA) program implemented in 1999, which has been discussed in the first chapter.

The federal and state governments recommend native hardwood species for plantation (DPI&F and DNR, 1999; DPI&F, 2000). They are more environmentally friendly than exotic pine species (Turner *et al*., 1999). Moreover, there is a difference in the soil carbon sequestration amount under the soil of hardwood and pine plantation on ex-agriculture lands. A study at the Billy Billy field site near Canberra has shown that conversion of ex-pasture to pine has resulted in a 15% loss of soil carbon (CRC for GA, 2004) whereas afforestation of hardwood on ex-agricultural land is likely to increase soil carbon (Paul *et al*., 2002; Paul *et al*., 2003; Saffigna *et al*., 2004, Maraseni *et al*., 2006). Among the hardwood species, spotted gum is gaining popularity, the reasons for which were discussed in the first chapter.

2.2.3 Changing paradigm of plantations

In Australia, plantation history began with softwood (pine) plantations in 1867 to meet the growing domestic softwood demand. Until the post-World War II period, decisions on plantation was made to reduce unemployment and to furnish raw material for small scale industries. Soft loans were provided by the Commonwealth to the states with the objective of becoming self-reliant in timber requirements which facilitated the conversion of native forests to pine plantations. In the 1980s, due to environmental pressure, commercialisation of forest services and reduced land availability in some places, site specific management was started. Since then, significant pressure has been mounted to reduce the exotic pines area planted each year, especially the *Pinus radiata* species (Turner *et al.,* 1999).

While analysing the plantation history in Australia, two significant changes are apparent: shifting from softwood to hardwood, and shifting from public to private plantations. The total plantation area in Australia in 2005 included 675,962 ha (41%) hardwood species (mainly eucalypts) and 988,223 ha (59%) of softwood species (mainly *Pinus radiata*). The average annual plantation during the period 2000-2004 was 74,000 ha (Australian Government, 2005). Of the total area planted in 2003, 74% was hardwood and 26% was softwood. The hardwood proportion increased from 15% of plantings in 1994 to 74% in 2003. Similarly, the proportion of private plantations was 46% in 1999, but in 2003, about 71% of the new plantations were privately owned and another 11% were jointly owned (National Forest Inventory, 2004). Although the plantations area in Queensland is very small compared to the total plantations area in Australia (around 13% or 214,585 ha out of 1,664,185 ha), the general pattern is similar. Until 2004, approximately 16% of total planted area in Queensland was hardwood and 84% was softwood. However, in 2004, the trend was reversed; of the total planted area of 5,470 ha, more than 84% (4,618 ha) was hardwood and around 16% (852 ha) was softwood (BRS, 2005).

The current trends both at state and national levels show some positive correlation with government policy but the annual rate of 70,000 hectare plantations is less than the 100,000 hectares of annual plantation necessary to meet the target of Vision 2020. In order to meet this goal, inland low rainfall areas could be targeted. However, in those areas, timber (alone) plantations would not be competitive with other land use systems, unless the farmers are convinced of a higher financial return they will not shift their land use. If a plantation is managed as a silvipastoral system and the stock and carbon values are considered, it could be more viable. If the enterprises emitting excessive greenhouse gases can buy 'carbon credits' from those able to establish net carbon sinks, farmers can earn carbon credits if they change to net carbon sequestrating production practices. This research has been designed with this in mind.

2.3 Reviewing the policy problem: carbon and climate change

Greenhouse gases are expected for survival of living-beings, as they act like a warming blanket around the earth. The problem is that the greenhouse gases are accumulating and the blanket is becoming thicker and posing a threat to the whole planet. In order to elaborate the overarching policy problem, the following concepts are discussed in this section: carbon sequestration and global carbon scenario; Kyoto target and current status of emissions; strategies to mitigate global warming; and issues of carbon credit under the Kyoto mechanism.

2.3.1 Carbon sequestration and global carbon scenario

Carbon sequestration is the increase in carbon stocks other than in the atmosphere, or sequestration of carbon out of atmosphere (IPPC, 2000). There are several carbon pools such as oceans, the atmosphere, fossil fuel, forests, soils, harvested forest products etc. The flux of carbon from atmospheric pool to non-atmospheric pools is, for the purpose of this research, carbon sequestration. The ocean, the largest pool, contains 50 times higher CO_2 (39,000 GtC) than in the atmosphere (760 GtC). Among the other pools, carbon in soil (2011 GtC) is more than four times the carbon in vegetation (466 GtC). The ratio ranges from 1:1 in tropical forest and 5:1 in boreal forest and is much greater in grassland and wetlands (IPCC, 2000). Although, tropical and temperate forests have 4-5 and 2-3 times more respectively, litter fall than boreal forests, the cold climate and poorly drained soil of boreal forest severely restricts the decomposition of detritus, resulting in the large accumulation of carbon in soil, much of it frozen in the form of permafrost (Gower, 2003).

Currently, the global carbon cycle is dominated by the flux from fossil fuel to atmosphere, estimated as 6.3 $GtCyr^{-1}$ during the 1990s, and the uptake by the ocean estimated as 1.7 $GtCyr^{-1}$. Overall, from land use change, the forest is losing 0.9 $GtCyr^{-1}$, consisting of losses in the tropics (1.65 $GtCyr^{-1}$) and gains in higher altitude due to reforestation (Kirschbaum, 2003) and carbon and nitrogen fertilisation (IPCC, 2000).

2.3.2 Kyoto Protocol and emissions

The United Nations Framework Convention on Climate Change (UNFCCC) and the subsequent Conferences of Parties (COPs) have raised the levels of concern to stabilise greenhouse gas concentrations in the atmosphere so as to avoid climatic calamities. The Kyoto Protocol (UNFCCC, 1997) was to be a milestone whereby individual nations were allocated differentiated targets to achieve the collective target of greenhouse gases reduction by at least 5.2% of 1990 levels by the first commitment period (2008-2012). To achieve these targets in a cost-effective manner, the Protocol adopted three market-based mechanisms, namely Emissions Trading, Joint Implementation and Clean Development Mechanism (CDM).

In the Kyoto Protocol, the European Union and Canada have agreed to reduce emissions by eight percent, USA by seven percent while Australia was generously allowed to increase greenhouse gas emissions by eight percent from 1990 levels by 2012. On top of that, Australia was allowed to include land clearing in its 1990 baselines as a net-net basis compared to gross-net arrangement of other Annex-I countries (AGO, 2000) for two main reasons. First, it is a net emitter of greenhouse gases from land use and the forestry sector. Second, it has relative larger average greenhouse gas emissions due to fire (107 $Mtyr^{-1}$ from 1996-2000), equivalent to 14% of the continental net primary production (AGO, 2000). However, in all countries (except some countries in Europe), the emissions of greenhouse gases are on an upward trend (UNFCCC, 2003 cited in von Kooten, 2004). In 2000, Canadian emissions were 19.6% above their base year (1990) and, by business-as-usual, emissions are expected to be 35.2% higher in 2010 than in 1990. In 2000, the greenhouse gas emissions in USA and Australia were 13.4% and 18.2% above what they were in 1990 (UNFCCC, 2003 cited in von Kooten, 2004). The unachievable target is one of the reasons why both Australia and USA decided not to ratify the Protocol (von Kooten, 2004). These facts and figures show that the countries that ratified the Kyoto Protocol would need to make an extraordinary effort to reach targeted levels by 2012.

During the period 1988 to 2000 the emissions due to land use change in the world decreased by 3.25%, from 2151 to 2081 MtCO_2e. Although China is not an Annex-I country and thus is not legally bound to emissions reduction, it has the highest reduction rate from 65 to -13 MtCO_2e in 12 years (1988-2000) from land use change. During the same period, Europe (-19 to -18 MtCO_2e) and Canada (32 to 27 MtCO_2e) are reducing emissions marginally (Fig 2.2).

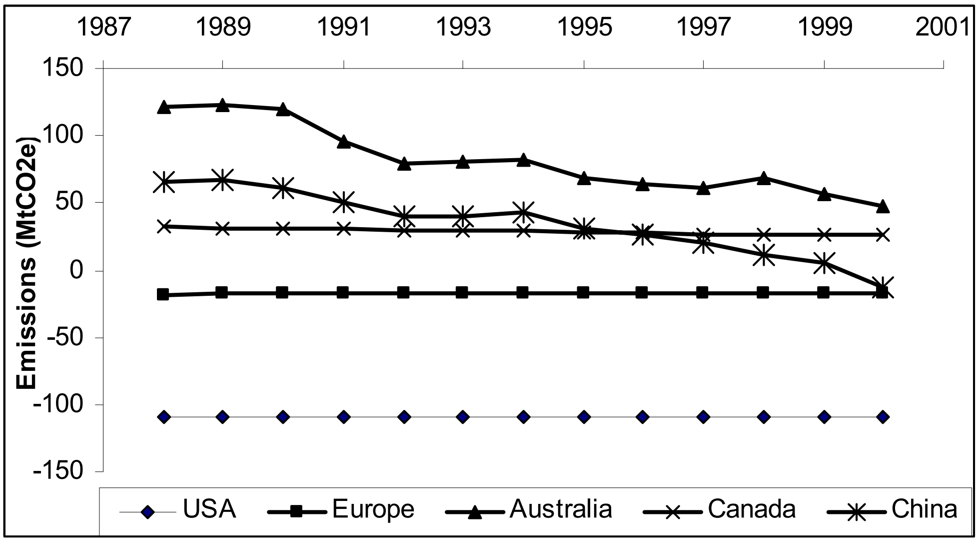


Figure 2.2 Emissions from land use change in Australia & selected countries/continents (Source: Houghton and Hackler, 2002)

In Australia, the total emission from land-use change has decreased significantly (69%) from 121.9 MtCO_2e in 1988 to 37.2 MtCO_2e in 2001. During the same period, the land use change related emissions in Queensland decreased from 65.9 to 22.6 MtCO_2e (National Forest Inventory, 2004), but in totality its share has increased from 54% (65.9/121.9) to 60% (22.6/37.2) mainly due to higher native forest clearing rate. Therefore, Queensland, where this research has been focused, is more problematic in comparison to other states. However, considering this overall decreasing trend of emissions from land use change in Australia, it is argued that Australia could meet its target of 108% by 2012 (Hunt, 2004), if there were some reduction in emissions from the energy and transport sectors.

2.3.3 Global warming strategies: mitigation or adaptation?

As a result of climate change, the global temperature could increase by 1.8°C to 4.0°C while the sea level could rise by 9 cm to 88 cm over the next 100 years (IPCC, 2007). Cool areas that are below the climatic optimum for particular crop will benefit and areas already above the climatic optimum will suffer (Quiggin and Horowitz, 2003). If we assume that the upper limit of global warming (2.5°C) would happen and the rate of increase in temperature is uniform over 50 years (0.05° C yr^{-1}), then the zone of grain production will shift away from the equator by 10 km per year (Quiggin and Horowitz, 2003).

According to Preston and Jones (2006), in a business-as-usual scenario, Australia's annual temperature is projected to increase by 0.4°C to 2°C above 1990 levels by the year 2030 and 1°C to 6°C by 2070. Precipitation trends will vary across the continent with a decline in southeast and southwest Australia and an increase in the northwest. This would have varying effects on Australia's environment, economy and public health. Ecosystems habitats will change or shift and threatened and localised populations could become extinct. Due to increased temperatures, the thickness of ozone layer in the troposphere will increase, and many respiratory and cardiovascular diseases will increase. The number of Queensland fruit fly, light brown apple moth and mosquitoes will increase, which will negatively affect the economy. Coral bleaching and frequencies of heat waves, cyclone and extreme precipitation will increase. Water quality will be poor, as there will be less water for saline base flow. The productivity of crops, livestock and forest will depend on an interactive effect of changing temperature, rainfall and CO_2 fertilisation (Preston and Jones, 2006). Therefore, the costs and benefits associated with global warming depend upon the location with respect to climatic optima. Hence, adjustment costs are a major concern.

Farmers may select some species (crops, livestock and trees), which have the capability of adjusting to a range of temperatures, though selection could be complicated in long rotation forest plantations. After each harvest, there would need to be a re-consideration of the more heat tolerant species. In this regard, Sohngen and Mendelsohn (1998) for example claimed that the current dominancy of four species in the USA forestry system will not be permanent. Even if the temperature increases only by 3°C, one species, i.e. loblolly pine, will dominate most USA forestry. In these circumstances, it is natural for many stakeholders to be curious as to which approach is economically more efficient — emission reduction or adaptation.

Unlike regional pollutants (SO_2 for acid rain), the impact of greenhouse gases are global in nature. An activity could be financially viable until the marginal costs of mitigation do not exceed the marginal benefit of doing that activity. Von Kooten (2004) argued that even if all Annex I countries meet their targeted amount of emissions reduction, they will reduce 250 MtC emissions (compared to 1990 level) by 2012, which is less than four percent of annual emissions (6.25 GtC) and less than 0.03% of the atmospheric stock of carbon. Citing this fact and analysing the annual contingency fund (0.5% of GDP) allocated for emissions mitigation, von Kooten concluded against mitigation. Von Kooten further estimates that as long as the rate of return to annual contingency funds exceeds 1.7%, it will be possible to cover the costs of future damages from climate change.

The Kyoto Protocol set legally binding targets for each of the Annex B countries. In order to achieve this target cost effectively, the Kyoto Protocol adopted three market based mechanisms for cost effective emissions reduction. However, von Kooten (2004) claims that the setting of targets for each country is by command and control rather than as an economic instrument. Countries can buy cheap carbon from 'hot air' in Russia and afforestation and reforestation activities in developing countries, but the question is for how long? Are they additional and permanent in nature? Mendelsohn *et al.* (1999) argued that the cost incurred by IPCC for the research on mitigation activities rather than adaptation activities is not-convincing. Because of the mounting uncertainty of costs of climate change, the tenth Conference of Parties (COP) in Berlin focused on adaptation and this COP is famous as the 'COP for Adaptation'.

Because there is a high climatic variation across Australia, adaptation to climate change has become a regular feature along with mitigation. Strategies, such as crop diversification, developing suitable animal and plant breeds, alteration of the timing or intensity of agricultural crops are some of the options farmers have been adopting to cope with a long time with climatic variability. Heat tolerant cattle have been selected in many parts of dry Australia (AGO, 2000). More than 80% of food production in Australia is reliant on genetic resources that were sourced from outside Australia (Kokic *et al.,* 2005). Without developing adaptive characters in line with the Australian climate, translocation of genetic material and their continued success would not be possible.

If the rate of climate change is faster than expected (the increased rate of 2.54 ppm in 2003 was much higher than the long-term average value of 1.5 ppm), we may need accelerated adaptation, which increases costs relative to mitigation costs. In case of a slower rate, adaptation could be relatively less costly than mitigation. The uncertainty of climate change demands an estimation of 'option value' for the implementation of these options (Kokic *et al.,* 2005). To wait for improved information means both options could be more costly. Therefore, it is better to implement both options simultaneously.

2.3.4 Issues of carbon credit under Kyoto Protocol

There are some eligibility issues with respect to the types and age of forest under the Kyoto Protocol. The COP9 (UNFCCC, 2003 p5) set out several important definitions regarding articles 3.3 and 3.4 of the Kyoto Protocol. Most notable is that…'*forest is a minimum area of land of 0.05-1.0 hectare with tree crown cover of more than 10-30 percent with trees with the potential to reach a minimum height of 2-5 meters at maturity in situ'*. Each party shall select a single minimum value of crown cover, height and area from the given ranges (UNFCCC, 2003 p5). Consistent with these criteria, Australia defines forest as an area with a potential to reach a minimum of 20% crown cover, two metres in height and minimum area of 0.2 ha (BRS, 2005). Any land which does not meet these criteria is non-forest land. A second definition is about reforestation. For the first commitment period (2008-2012), eligible reforestation is on those lands that did not contain forest as of 31 December 1989. Similar definition applies for afforestation but it should be on land that has not been forested for at least 50 years.

Due to these critical definitions, an increase in carbon sequestration, for example in community forests in Nepal and an increase in forest soil organic carbon in Europe due to changing forest age class structure are not eligible for carbon credit, as much of the effect is due to afforestation/reforestation before 1990 (Maraseni *et al*., 2005; Smith *et al.,* 2006). More importantly, whatever the achievement in carbon sequestration, the activity would be not eligible if it is not human induced. For example, soil carbon in Europe is increasing due to increased net primary productivity (mainly due to increased temperature, and CO_2 and N_2O fertilisations) of the forest. However, the increased soil carbon is not eligible because it is not due to direct human-induced activity (Smith *et al.,* 2006).

This PhD study is related to spotted gum planted in 2001, on land that did not contain forest as of 31 December 1989. The plantations would fit with the definition of forest set by the Australian government, which is already accepted by the UNFCCC secretariat. Therefore, these plantation activities are quite compatible with COP9 definition, even though there are some other issues (including ratification) which preclude direct participation in the Kyoto Protocol. Australian Government wants mitigation through sequestration and is making policy in that line.

Global warming is the overarching problem, while sequestration is one possible solution. There is however, the research problem that the actual impact of different systems is not easily estimated. The following sections review some approaches to carbon accounting.

2.4 Soil carbon measurement

Soil is an important pool of carbon, second to the ocean. As a result, even a slight change in soil carbon makes a big difference to the concentration of CO_2 in the atmosphere. As discussed earlier, due to different cultivation and management practices, soil carbon amounts and long-term trends in different land use systems could vary, as could the need to account for comparing different land use systems. In this section, the field-based, micrometeorological and model based approaches of soil carbon estimation around the world are presented. Then, the Australian approaches to soil carbon estimation and the characteristics and distribution of Red Ferrosol soils are described. Finally, changes in soil carbon due to changes in management and climatic factors and afforestation on ex-agricultural lands are discussed.

2.4.1 Field based methods of soil carbon measurement

Broadly speaking, for the estimation of soil carbon trends in different land uses and stand ages, three different methods are in practice around the world.

- Repeated sampling, in which the same site is sampled repeatedly over time.
- Paired site studies, in which sites are selected in such a way so that we can be assured that any changes in soil carbon among the pairs are due to changes in land use rather than natural variation.
- Chronosequence studies, in which soil under the different ages of timber stands are sampled at the same time.

Each study type has pros and cons but the first method gives the lowest error rate, as all measurements are done on the same site over time (Murty, 2002). Chronosequence methods are likely to generate more errors, as soil shows natural spatial variability (Murty *et al.,* 2002; Paul *et al.*, 2002), however, they account for 23% of the studies in the world (of 204 studies reviewed) and 25% of the total studies in Australia (Paul *et al.,* 2002). Paired site comparison is used for 54% of the research in Australia (Paul *et al*., 2002) and 49% for the world (Paul *et al*., 2000).

Lab analysis for soil carbon is another important step after collecting and preparing the soil specimens. Since the beginning of soil carbon research, the Walky and Black (W&B) and the Combustion methods have been used for soil organic carbon (SOC) estimation. Some researchers claim that the W&B method that uses hot chromic acid as an oxidizing agent, is not capable of measuring the total SOC, but only that part which is easily oxidisable (e.g., Rayment, 1992; Arrouays *et al*, 2001), which is 70% to 80% of the total SOC (Piper, 1944 cited in Skjemstad *et al*., 2000). Others claim that the Combustion method overestimates the carbon, as it also burns the other material including organic matter (Rayment, 1992; Frogbroook and Oliver, 2001). Therefore, several modifications are in place for the calibration of the results obtained from those methods.

With the advancement of technology, the LECO combustion method is widely recognised, which determines carbon amounts by converting organic matter into CO_2 at controlled temperatures (1200°C). The LECO CNS-2000 or CHN-2000 can take up to a two gram specimen and allow simultaneous analysis of carbon with other elements such as nitrogen and sulphur or nitrogen and hydrogen (McKenzie *et al.,* 2000). Given the accuracy of this method currently, the LECO CNS-2000 method is widely used in Australia. However, in the past the W&B method was more common.

Therefore, in Australia, to maintain uniformity and accuracy a number of conversion factors (1 to 1.34) are estimated to convert the carbon values generated from various methods to LECO combustion values (Skjemstad *et al.*, 2000).

Another equally preferable hi-tech method in Australia is an Isoprime isotope ratio mass spectrometer coupled to a Eurovector elemental analyser (Isoprime-EuroEA 3000). This method is based on isotopic mass analysis and has the capacity to provide total and delta carbon and nitrogen of specimens (soil, particulate organic matter, surface litter etc.) at the same time. The detailed procedure of this technique is described in chapter three and the general literature is presented here. Understanding the principles of these techniques is necessary for the nitrogen fixation research, physiological process of plant and land use changes.

Atoms that have the same atomic number but different atomic weights are called isotopes (Gross, 2004). Nitrogen has two stable isotopes in nature, ^{14}N and ^{15}N. Since the atmosphere has the lower amount of $\delta^{15}N$ compared to soil N, plants that can fix atmospheric nitrogen should have less amount of ^{15}N (or higher amount of ^{14}N). Researchers are applying this basic principle to study the dynamics of nitrogen in different artificial and natural systems and for the estimation of biologically fixed nitrogen (for detail see Henzell *et al.*, 1967; Peoples *et al.*, 1992; Bell *et al.,* 1994; Rochester *et al.*, 1998; Armstrong *et al.*, 1999; Chu *et al.,* 2004). With respect to naturally abundant stable isotopes of carbon, 98.9% exists as ^{12}C, 1.1% as ^{13}C, and 10-8% as the cosmogenic radioactive ^{14}C (Glaser, 2005).

The mean $\delta^{13}C$ value of C_3 (that follows the Calvin cycle) plants (mean -27‰, range -23 to -34‰) is lower than the mean $\delta^{13}C$ value of C_4 (that follows Slack-Hatch cycle) plants (mean -13‰, range -10 to -15‰) and atmospheric CO_2 (-7.5‰) (Kao, 1997). The differences in $\delta^{13}C$ value in different plants have been extensively utilised for photosynthetic pathways of plants (for detail see Lajtha and Michener, 1994; Ehleringer *et al.,* 1991 cited in Kao, 1997; Glaser, 2005) and to track down the land use changes, as trees are usually C_3 plants and grasses are C_4 plants. However, grasses and trees of some of the woodlands in Southern Australia have common C_3 photosynthetic pathways (CRC for GA, 2004). A precaution is necessary, as carbon isotope analysis of soil organic matter cannot be used as an indicator of previous vegetation change in such areas.

Mass spectrometry is a good method for simultaneous determination of total carbon and nitrogen and their delta values, but care should be taken in the preparation of specimens, as it uses a very small fraction of specimen (in micrograms). Replication of chemical analysis could be a good solution, if the cost is acceptable (Xu *et al.,* 2003). Whatever the methods used, they should use the same laboratory and the same method, otherwise serious errors may occur. For example, while comparing 16 phosphorus extraction methods practiced in Europe, Neyroud and Lischer (2003) found different results. Also, a large variability was observed in the results obtained by laboratories using the same method.

2.4.2 Micrometeorological technique of carbon measurement

The micrometeorological technique is used to predict net ecosystem productivity (NEP) rather than the carbon of an individual pool. It covers both soil and vegetation and estimates the net exchange of carbon between atmosphere and forest ecosystem. One of the micrometeorological techniques is 'eddy covariance', which is used to measure total exchange of CO_2 at the ecosystem level. The number of eddy flux towers has been increased, especially in Europe, during the last decade (Gower, 2003). Its strength is that it allows for modelling of the sensitivity of the carbon fluxes. By using this method, the undisturbed climax forest of Brazil is found to be a net sink (Grace *et al*., 1995; Malhi *et al*., 1998; and Andrea *et al*., 2002 cited in Grace, 2004). It requires turbulent airflow over large flat areas of more-or-less homogenous vegetation, which precludes the use of this technique in many areas of interest. Further, at the regional level there may be disturbances (including fire and harvesting) over a long time, which effectively reduce the carbon sink well below the measure as NEP. Considering the limitation of eddy covariance, recently a multilayer perceptron artificial neural network was applied for multi-ecosystems carbon flux simulation (Melesse and Hanley, 2005).

2.4.3 Model based methods of carbon measurement

Models are widely used for soil carbon measurement. Soil carbon change over time is laborious to measure, and future carbon can only be predicted by models (Liski *et al*., 2005). Measurements taken at a few statistically unrepresentative sites are difficult to scale to larger areas (Peltoniemi *et al.,* 2004) and direct measurements are currently cost prohibitive (Paul *et al*., 2003). Models are important to understand the functioning of soil carbon, to upscale experimental results (both extrapolation and interpolation), to simulate scenarios and to furnish information to scientists, policy makers and consultants (Liski, 2006). A good model should have three characteristics: first, reliability in terms of its structure and parameter values; second, relevance in the sense of model structure; and finally, feasibility in terms of technical possibility to conduct calculations, and calibration and input data availability (Liski, 2006).

After the climate change issue surfaced, many models were developed incorporating carbon. The Annex-I countries in Europe and North America have done a lot in this area, as they have a legal obligation to report to the UNFCCC secretariat, without models these reports would be very limited. Each country may have its own model or at least it may have calibrated a suitable model for the relevant climatic, edaphic and topographic contexts. Describing all models is beyond the scope of this review. Only a few widely used models of Europe and North America are briefly described here.

The first is the CENTURY (Parton *et al.,* 1987) model. It is probably the most widely used and thoroughly validated, process oriented, ecosystem-based, soil carbon model (Liski *et al.,* 2005). This model simulates the long-term dynamics of carbon, nitrogen, phosphorus and sulphur for different plant-soil systems. It was originally developed for grassland and crops in USA but is now widely used in forest and savannah systems as well (Falloon *et al*., 2002; Peng *et al*., 2002). This model estimates lignin to nitrogen ratio of organic matter substrates as an indicator of substrate quality, whereas other models rely on a carbon to nitrogen ratio (Trettin *et al.* 2001). In that sense it is better than other models. In Australia, the modified version of CENTURY, CenW, has been used to model the carbon and water exchange of a sub-alpine native forest at Tumbarumba, New South Wales. A CenW-Tree grass (CenW-TG) model was developed from CenW to include multi-species and multi-plant type capabilities, plant demography and disturbance effects (fire and herbivore). It can apply to heterogeneous systems such as trees and grass and therefore can be used to investigate factors causing woody thickening (CRC for GA, 2004).

The second one is the Yasso model (Liski *et al*., 2005). It is a dynamic forest soil carbon model developed in Finland and is extensively used for boreal forest. It calculates the amount of, and changes in, soil carbon and heterotrophic soil respiration in yearly steps. It requires only basic climate data, litter production and information on litter quality to operate (Liski *et al*., 2005). The third one is the SOILN model (Johnsson *et al*, 1987), which simulates carbon and nitrogen in soils (Topp and McGechan, 2003). Originally, it was developed in Sweden for arable lands but is now widely used in other European countries for various purposes, such as:

- Forest soil carbon and nitrogen modelling in Sweden, Norway, Denmark and Germany (Annemieke, 2006, pers. comm., 8 April);
- Modelling environmental impacts of deposition of excreted N by grazing dairy cow in UK (Topp and McGechan, 2003);
- Simulation of fertiliser and slurry application for nitrogen management in Scotland and Ireland (Lewis *et al*., 2003); and
- Simulation of nitrogen leaching following pig slurry application in northern Italy (Mantovi *et al*., 2006).

The SOILN model has many merits; it is process oriented, dynamically coupled to water and heat balances and well tested and calibrated (Gardenas, 2006). More importantly, SOILN model an option of operating interactively with a crop growth model (McGechan *et al*., 2005). However, this model has some weaknesses as well. This model needs much information and many parameters, it is one-dimensional and it assumes that there is no respiration costs for organic nitrogen uptake (Gardenas, 2006).

The fourth one, the ROMUL model (Chertov *et al*., 2001), is a model of soil organic matter and nitrogen dynamics, which is based on the classical concept of "humus type" (Komrov *et al*., 2003). This model was successfully used for the soil carbon dynamics in primary and secondary forests in The Netherlands (Nadporozhskaya *et al*., 2006) and Jackpine in Canada (Chertov *et al*., 2006). Most of the models work only up to 30 cm depth, but it can model both soil carbon and nitrogen up to 100 cm. This is the strength of the model, as around 30% of soil carbon is retained in B soil-horizon (Pers. comm. Chertov, 2006)[1]. The basis of ROMUL is a set of laboratory experimental data on the rate of decomposition of plant debris and soil organic matter, previously published data, and the results of specially performed experiments in the Lab of Soil Biochemistry, St. Petersburg State University (Chertov *et al.*, 2006). Although lab experiments were in controlled conditions, it is not free from debate, as the decomposition rates in the fields and labs may be significantly different.

The fifth one is the RothC model, which is used worldwide (Liski *et al.*, 2005). It was originally developed from the Rothamsted long-term field experiment (hence the name) for the estimation of turnover of soil organic carbon (0-23 cm or 0-30 cm) of arable lands but is now extensively used in forestry as well (Fallen *et al.*, 2002; Peng *et al.,* 2002). The model divides soil organic matter into four active compartments and a small amount of inert organic mater (IOM) (Figure 2.3). The IOM compartment is resistant to decomposition and therefore has no role. In the model, it is hypothesises that incoming plant carbon splits into decomposable and resistant plant materials (DPM and RPM). DPM and RPM both decompose at different rates and give CO_2, microbial biomass (BIO) and humified organic matter (HUM). The proportion of CO_2, BIO and HUM is determined mainly by the clay content of the soil. Farm yard manure is supposed to decompose faster than normal crop plant material, so, it is treated differently in the model (Coleman and Jenkinson, 1999).

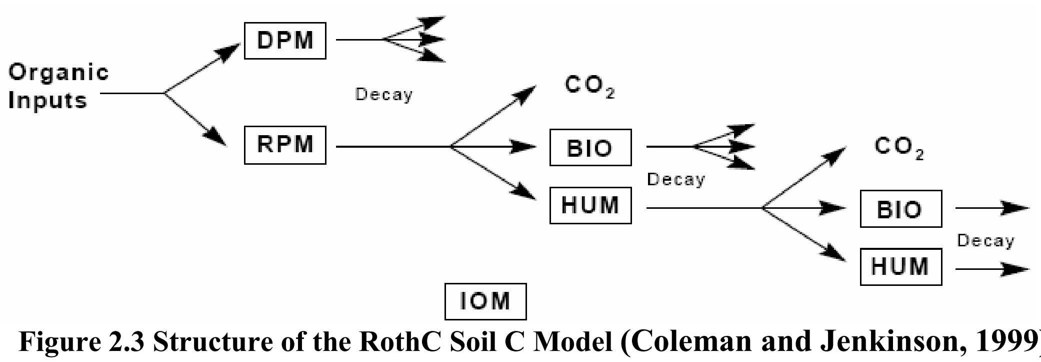


Figure 2.3 Structure of the RothC Soil C Model (Coleman and Jenkinson, 1999)

The parameters needed for this model and the procedure is explained in the methodology chapter. This model has many merits as it is simple, transparent, widely

[1] Biological Research Institute, St. Petersburg State University, 2 Oranienbaum Rd., 198904 St. Petersburg-Peterhof, Russia

tested and all pools are identifiable and measurable. However, it should be used cautiously for soil developed on recent volcanic ashes, soil from tundra and taiga and it is not suitable for soils that are permanently waterlogged or in snow covered areas (Smith *et al*., 2006; Coleman and Jenkinson, 1999). This model needs fewer data and is calibrated for the Australian context (Paul and Polglase 2004a).

Most of the discussed models lack the modelling capability of common phenomena, such as effects of erosion, metal, fire, waterlogging, charcoal, soil disturbances and depth of soil carbon. Models cannot reflect the real world scenario, as they cannot capture all biogeochemical mechanisms going in the soil system. Models could be reliable to some extent, but could not be accurate (examples are discussed in Chapter 1). Extrapolation and interpolation beyond the condition of measurements, default values, assumptions and uncertainty to some parameters make the models less reliable. They may be acceptable for national level communication, but not on a local and species-specific level. Therefore, in this study, RothC model was used only for a supportive role.

2.4.4 The Australian approach to soil carbon measurement

Being in the southern hemisphere and a relatively dry continent, the carbon models developed and applied in the northern hemisphere are not applicable. Australia has developed its own approach to estimating variation in soil carbon over time and space. There are many typical elements of Australian soils. They are dominated by eucalyptus (77%) and acacia (10%) and lack modern herbivores (ABS, 2002). Being old and not stripped by ice-sheets, they are highly weathered (ABS, 2002). There is a relatively higher amount of charcoal and encapsulated carbon due to severe and frequent fires (AGO, 2000), higher soil carbon age (44 years) compared to elsewhere in the world (9-25 years) (CRC for GA, 2003) and a poor organic or 'O' horizon (McKenzie *et al*., 2000).

In Australia, it is estimated that around 12,232 MtC is stocked in soil and 40% of that is in the forest estate (AGO, 2006 cited in Barrett and Kirschbaum, 2000). A soil carbon map (30 cm depth) has been developed by the collaborative work of state and territory governments and the CSIRO. In order to do that, Australia was divided into different climatic zones with the help of the Interim Bio-geographic Regionalisation of Australia (IBRA) (Baldock *et al.*, 2003). The whole country is divided into 85

IBRA regions (Department of Environment and Heritage, 2005). Each IBRA region was divided into major soil types. A spatial coverage of the major soils in each IBRA polygon was compiled from three different sources: the land resources survey database, high intensity soil survey, and the Atlas of Australian Soil where other sources were not available (Smith and Grundy, 2002). The pre-clearing soil organic carbon for each combination of soil type and climatic zone to 30 cm depth was then determined (AGO, 2002).

The map shows that the soil carbon estimates vary from 1-10 tha^{-1} to 300-1000 tha^{-1}. The report shows that the Ferrosols, the soil relevant to this study, tend to have much higher soil carbon than other soil orders in the southeast region (AGO, 2002). The fraction of soil organic carbon in different pools structures (mulch, humus, charcoal etc) was determined by the combination of measurement and estimation using MIR and PLS techniques. The timeline of land use change and the current land use practices for each polygon was determined. A timeline of land use changes and long-term climatic data of all polygons were used and a calibrated RothC model was run to find the soil organic carbon over time (Baldock *et al*., 2003).

There are several reasons for not adopting this approach but the major reason is the reliability for our particular site. First, where there was no information of soil order (major soil types), the value of another soil order or adjacent region was used and adjusted accordingly. Therefore, the results may not reflect local variation. Second, in many soil archives, there was a lack of information about bulk density, and soil carbon below 10 cm. Third, the soil sampling was usually biased towards agriculturally significant soils, low gradient areas and areas with established agricultural land uses (AGO, 2002; Smith and Grundy, 2002). The modelling is not forest and pasture focused. More importantly, the pre-clearing soil carbon map of our study site was developed for the combination of Ferrosol soil and south-east Queensland IBRA region. It can have a broad application (scale problem) for that particular soil order but it cannot reflect the true variation in our site, as our Red Ferrosol soil is one of five sub-orders.

2.4.5 Ferrosol soils: characteristics, distributions and land uses in Australia

Red Ferrosol soils have red colour dominance up to 50 cm depth of B1 horizon (Figure 2.4) (Isbell, 2002). It is more or less similar with Tropeptic Eutrustox (i.e. Oxisol) in the USDA Soil Taxonomy system (Soil Survey Staff, 2003) and Nitisol in FAO systems (B. Harms, 2005, pers. comm., 24 September). It may be either basic or ultrabasic igneous rocks, their metamorphic equivalents, or alluvium derived from them (Isbell, 1996). The depth ranges from one metre to seven metres (tending to be deeper in coastal areas) (Cotching, 1995 cited Isbell, 1994). High contents of 'free iron oxide' (>5%) in fine soil fraction (<2 mm), lack of texture contrast between A and B horizons, moderate to high (40-80%) clay content and low activity clay minerals are their typical features (Cotching, 1995 cited Moody 1994).

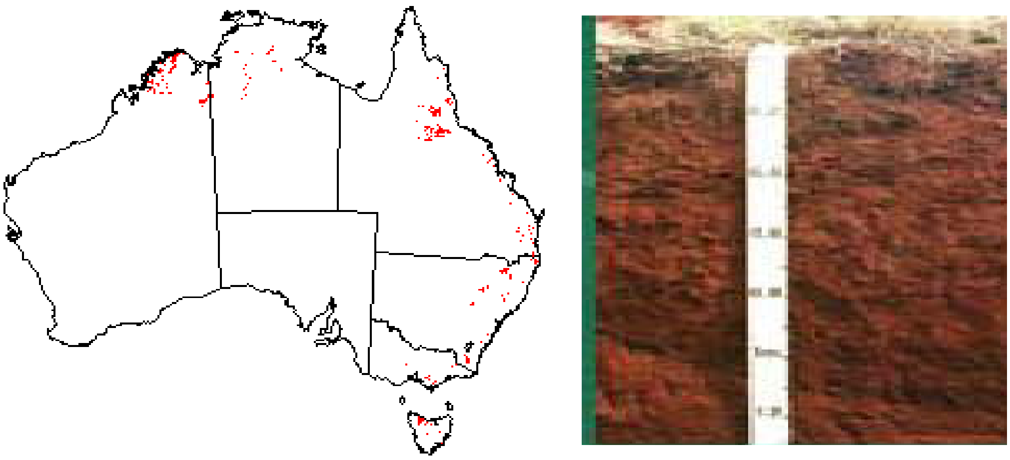


Figure 2.4 Ferrosols area in Australia (left) and soil profile of Red Ferrosol (right) (Isbell, 1996)

Ferrosols in Australia are limited to northern parts of Western Australia, Tasmania and eastern regions from Tasmania to North Queensland (Bell *et al.,* 1997; Cotching, 1995). In the Inland Burnett region, where this research is centred, around 50% (60,000 ha) of the cropped area is in Ferrosols soil (Bell *et al*, 1997). Distribution of this soil in Australia and main land uses in those localities are given in Table 2.1. Higher organic matter content of Ferrosol soil is very important for maintaining better cation exchange capacity (CEC) and sources of nitrogen, phosphorus and sulphur. As it has high percentages of iron and aluminium oxide, the negative charges of Ferrosol soils mainly reside in organic matter. Around 7% of organic matter content of Ferrosol soil is responsible for around 70% of their CEC (Isbell *et* *al*., 1976 cited in Cotching, 1995). Organic matter also minimises the possibility of soil acidification from nitrogen and phosphate fertilisers. However, due to the removal of peanut hay for its higher prices and continuous cropping, this soil is degrading in Kingaroy (Bell *et al.,* 1997). Therefore, it is assumed that soil carbon and peanut production in this area could be decreasing, or at least relative profitability is declining.

Table 2.1 Land use on selected Ferrosols areas of eastern Australia

Locality	State	Main land use
Atherton Tableland	QLD	Peanuts, potatoes, macadamias, mangoes, avocados, grazed pastures, maize, sorghum
South Johnstone	QLD	Sugarcane, bananas, pawpaws
Gympie, Nambour	QLD	Pineapples, dairying, market gardening
South Burnett	QLD	Peanut, maize, sorghum, kiwifruit, stone-fruit, avocadoes, winter cereals, grazed pastures
Eastern Darling Downs	QLD	Forage crops, grazed pasture, navy beans, peanuts
Redlands, Brisbane	QLD	Urban, gardening, pineapples, pawpaws, bananas
Lismore, Richmond	NSW	Vegetables, grazed pastures
Dorrigo, Comboyne	NSW	Potatoes, grazed pastures
Robertson	NSW	Potatoes
Silvan	VIC	Urban, market gardening
Gippsland	VIC	Grazed pastures, potatoes, vegetables
Northern Tasmania	TAS	Potatoes, vegetable, dairying, pyrethrum, forestry
Note: QLD for Queensland, NSW for New South Wales, VIC for Victoria and TAS for Tasmania (Cotching, 1995)		

Ferrosol soil has a high pH buffering capacity (Firth and Loebel, 1987 cited in Cotching, 1995). This means that it needs huge quantities of lime to increase the pH, which adds an extra cost, and production, transportation and application of lime emits some greenhouse gases. Therefore, we assume that peanut cropping may lose its relative profitability, if we consider carbon value.

2.4.6 Changes in soil carbon in different climates, fertilisers and management scenarios

The soil carbon dynamics in different climatic conditions are well researched at the local and regional level. Some of the widely accepted European scenarios are presented here. First, the soil carbon on organic layer, in the long-run, increases with increasing stand age (Paul *et al*., 2003; Peltoniemi *et al*., 2004; Smith *et al*., 2006). Second, increasing temperature increases the soil decomposition rate in most of the colder places (Europe), thereby, reducing the soil carbon. In dry places, increased temperature may increase soil moisture, which may help to increase soil carbon by reducing decomposition rates (Smith *et al*., 2006). Third, the increased temperature,

CO_2 and N_2 increases the growth rate of trees and therefore the carbon storage in stands and soil in the long-run (Makipaa, 1995; Pussinen *et al*., 1997; IPCC, 2000; Smith *et al.,* 2006). The net effect of these factors in sinks carbon in Europe would be positive (Pussinen *et al*., 1997; Smith *et al*., 2006). However, total sequestration will start to decline when the temperature increase exceeds 2.5°C, which is expected in 40 years (Pussinen *et al*., 1997).

Soil carbon could be influenced by carbon and nitrogen fertilisation. Natural deposition (and or fertilisation) of nitrogen was found to be highly effective in promoting growth of forests where the soil carbon level is high but the nitrogen level is low. A recent experiment shows a fourfold increase in the growth of Norway spruce in response of nitrogen fertiliser (75 kg ha^{-1} yr^{-1}) at 64° north over the past 12 years (IPCC, 2000). Another experiment from Sweden (Gardenas and Eckersten, 2006) shows that the soil carbon storage could be increased with nitrogen deposition and fertilisation. However, they also found that the nitrogen deposition could increase the risks for nitrogen leaching but the net effect on carbon sequestration could still be positive. Increasing nitrogen fertilisation could increase soil and forest carbon, but the production, transportation and application of that fertiliser emits a significant amount of CO_2 (Gower, 2003). On top of that, applied nitrogen fertiliser also emits some nitrous oxide during denitrification (IPCC, 2000). In the long run, the quality of litter may be more nitrogenous, which may reduce its decomposition rate. More importantly, the leaching of nitrogen may introduce a new problem of eutrophication in lowland ecosystems. This therefore demands a holistic research in an economic sense, which takes account of all these positive and negative factors.

Management practices also affect soil carbon content. Research at the Hermitage Experimental Station, Queensland showed that the soil organic carbon was 500 kg ha^{-1} higher under no tillage practices than under conventional tillage, 50 kg ha^{-1} higher under stubble retention than under stubble burning and 90 kg ha^{-1} higher under nitrogenous fertiliser application than without that fertiliser (CRC for GA, 2003). Similarly, research done near Warwick, Queensland revealed that the labile soil carbon changed significantly during the summer-autumn period after the wheat harvest. Most of the labile carbon was lost at the time of sowing the next wheat crop. The implication of this finding was that the sampling should be done just before sowing of the next crop. The next section discuss about the soil carbon changes after afforestation.

2.4.7 Changes in soil carbon after afforestation

Murty *et al.* (2002) reviewed 109 global studies and found that the conversion of forest to agricultural land led to an average loss of approximately 22% of soil carbon. However, while considering the transition from forest to pasture there was no significant change, even though reported changes ranged from -50% to + 160%. On the other hand, the Australian Greenhouse Office assumes that the conversion of forest to unimproved pasture decreases carbon by 30% (Kirschbaum *et al*., 2000). Since hardwood forests usually have a higher amount of soil carbon than pasture (Saffigna *et al*., 2004), results from this PhD research could be inclined towards the Australian assumption.

Similarly, there is some literature about the soil carbon dynamics after afforestation on agricultural land. Most of the studies in Australia, with some reservation, report that the soil carbon will increase after afforestation on agricultural land (Paul *et al*., 2002; Paul *et al*., 2003). A similar result was obtained in Hungary (Horvath and Somoyogyi, 2006) and in other countries (IPCC, 2000). However, the conversion of pasture to pine has resulted in a 15% loss of soil carbon (Ross *et al*., 2002; CRC for GA, 2004). It could be caused by a reduction of fine root length of surface area, loss of soil aggregates, and lower input of carbon from fine-root turnover under pines (CRC for GA, 2004). Since most plantations in Australia are established on pastureland (Specht and West, 2003), this change might have created a net loss of soil carbon. On the other hand, afforestation of hardwood is likely to increase soil carbon even in ex-pastureland (Paul *et al*., 2002; Paul *et al*., 2003; Saffigna *et al*., 2004; Maraseni *et al*., 2006).

Paul *et al*. (2003) studied 24 sites of Eucalyptus globules in SEQ and predicted that the soil carbon between 0-10 years deceased by an annual average of 2.35% in general and then from 10-40 years increased by 0.49%. However, soil carbon under the afforestation of the same species in medium-low rainfall zones of Western Australia (rainfall 632mm, mean annual air temperature 15.7°C) decreased by only 0.5% between 0-10 years. From 10-40 years, soil C increased by 1.65% per year and if considered for 0-40 years it increased by 1.05% per year. That means in 40 years soil carbon had increased by 42%. Since Kingaroy has similar climatic conditions (mean daily maximum and minimum temperature of 24.7°C and 11.4°C and mean annual rainfall 781mm, elevation 430m) to that of typical WA sites, our estimation could follow its rate.

The general literature discussed above, however, may not be applicable in our plantation sites for many reasons. First, unlike the plantation discussed in the literature, the plantation in our research site is silvipastoral, in which nitrogen fixing legumes were planted along with grasses as an intercrop. Since accumulation of soil carbon is higher when there is N_2 fixing species (Paul *et al.*, 2002), our site could have more carbon than those cited in the literature. Second, fire management also improves soil carbon (Paul *et al*., 2002), and there is rare cases of fires in the farming and pasture areas in Kingaroy. Third, there are many wild watermelons (weeds) with plenty of fruits, the fast turnover of those fruits may contribute a large amount of soil carbon.

Fourth, initial soil carbon affects much of the soil carbon dynamics after afforestation (Paul *et al*., 2002; Chertov *et al*., 2006; Faubert *et al*., 2006). The decrease in soil carbon during the first 15 years of afforestation on unimproved pasture was four times less than the afforestation on improved pasture (Paul *et al*., 2002). Spotted gum in our study site was planted in semi improved pasture which would have a low amount of initial soil carbon compared to improved pasture. Fifth, sandy soil has a higher decomposition rate than clay soil. A high surface area of clay fractions enhances the formation of organo-mineral complexes that protect carbon from microbial oxidation (Grigal and Bergusan, 1998 cited in Paul *et al*., 2002). Since the review study of Paul *et al.* (2003) was on sandy loam soil, their results are not compatible with these PhD study sites, which have clay loam soil.

Sixth, their result was based on an analysis of soil up to 30 cm depth whereas this PhD research goes beyond that to 100 cm. Most importantly, the soil carbon changes after afforestation depend on the interactive effect of soil carbon amounts before plantation, litter fall rate, partitioning of litter into different carbon pools and their decomposition rates, soil temperature and moisture, rainfall, pan evaporation, solar radiation and frost days (IPCC, 2000; Paul *et al*. 2003). Therefore, it is hard to transfer the research benefit appropriately to particular sites and species. The next section discusses about the carbon accounting model is Australia.

2.5 Full Carbon Accounting Model in Australia

This section discusses different sub-models of a Full Carbon Accounting Model (Richards and Evans, 2000) and its peculiarity and necessity in Australia. FullCAM is the model developed by the Australian Greenhouse Office for full carbon accounting in the land use sector at the project or national level. It has the capacity to estimate and predict all biomass, litter and soil carbon pools, and changes in major greenhouse gases and nitrogen cycling in five systems; forest, agriculture, afforestation and reforestation, deforestation and mixed (e.g., agroforestry) systems. The version referred to here is the latest version of FullCAM (3.0). The nitrogen cycle prediction is being developed at the time of writing (Richards *et al.*, 2005). FullCAM is a comprehensive integrated model, which needs around 1200 different inputs to generate over 800 different outputs. The model has a 25m spatial resolution and a monthly temporal resolution.

Like other models discussed so far, sensitivity analysis in this model is done with Monte Carlo simulation methods. However, this model differs from other models in four main areas. First, it is an integrated continent level model which not only accounts for carbon and nitrogen in soil of all land use types, but can also estimate biomass of standing trees and all types of debris. Second, it has a Data Builder function that allows users to access data archives of NCAS, providing the latitude and longitude of the area of concern, and builds models for individual sites. Third, it has a capacity for optimisation analysis (which is under development) by which it finds optimum values matching closely to the observed values. Fourth, it can generate fossil fuel displacement values for using forest and agricultural products including bio-energy.

FullCAM is an integrated system of five models: (1) the carbon accounting model for forest (CAMFor); (2) the carbon accounting model for cropping and grazing systems (CAMAg); (3) the physiological principle predicting growth (3PG); (4) the general microbial mulch decay model (GENDEC); and (5) the RothC soil carbon model (Richards, 2001). CAMFor and CAMAg are central frameworks developed by the Australian Greenhouse Office and the other three models are independently developed process based models for specific purposes (Paul and Polglase, 2004a). CAMFor models carbon and nitrogen cycling in a forest, including in trees, debris, soil, minerals and wood products (Richards *et al*., 2005). Similarly, CAMAg models carbon and nitrogen cycling in an agricultural system, including in crops, debris, soil, minerals and agriculture products (Richards *et al*., 2005). Within FullCAM, there are both agriculture and forestry versions of RothC and GENDEC models. The CAMFor links 3PG, GENDEC and RothC models, and CAMAg model links GENDEC and RothC models. However, CAMFor has the capacity to work independently (without RothC and GENDEC), but CAMAg always depends on the RothC model (Richard *et al*., 2005).

Here, questions may arise as to why Australia needs integrated (FullCAM) and central framework models (CAMFor and CAMAg) and why it can not work only with process based models (RothC, GENDEC and 3PG). (1) An integrated model (FullCAM) has the capacity to account for the carbon in all pools (soils, vegetation/crops, products and atmosphere) and transfers (to and from atmosphere) between pools. As a result, it avoids double counting or omission in accounting. (2) Integration was necessary to strengthen the capacity of the model to run over the whole Australian continent for fine resolution grid-based spatial application, as it enhances the predictive capability in different potential scenarios (Richards, 2001).

(3) Australia is a dry continent and fire is a common phenomenon. Some of the soils have charcoal and high clay contents, which can encapsulate organic matter for a long-time and protect them from decomposition. Therefore, Australia needs CAMFor or CAMAg in which active soil is modelled by RothC and inert soils are modelled by CAMFor and CAMAg itself (Richards *et al*., 2005). (4), for accuracy, GENDEC and 3PG models are employed in conjunction with CAMFor and CAMAg. In soil, there are many carbon pools, such as debris that include litter and dead roots, mulch (an above ground layer between soil and litter) and soil. GENDEC simulates mulch and passes this information to CAMFor (in forestry) or to CAMAg (in Agriculture). Without DENDEC there is no separate 'mulch' pool, and both debris and mulch will be treated as 'debris' in the CAMFor and CAMAg models (Paul and Polglase, 2004a).

Fifth, also for same accuracy, 3PG is glued with CAMFor as it can generate more accurate net primary productivity (NPP) of forests by simulating many parameters such as slope and aspect corrected solar radiation, digital elevation model, fertility and soil moisture, rainfall, temperature, normalised deviation of vegetation index and frost etc (Richards, 2001). Therefore, where data is available CAMFor uses GENDEC for decomposition of mulch, RothC for turnover of active soil carbon and 3PG for NPP and CAMAg uses GENDEC and RothC for the same purpose in agriculture soils. On top of that, CAMFor has the ability to simulate carbon and nitrogen in case of fire and the wood products. Similarly, CAMAg has the ability to simulate carbon and nitrogen in case of fire, or different management practices and crop products (Richards *et al.,* 2005).

CAMAg is calibrated for many areas, whereas CAMFor is mostly calibrated for *Pinus radiata* and *Eucalyptus globulus* species (Paul *et al*., 2004; Polglase *et al*., 2004). As discussed earlier CAMAg and CAMFor have their own version of the RothC and GENDEC models, they are calibrated for the Australian context (for detail see Janik *et al.,* 2002; Polglase *et al*., 2004a and 2003). The estimation of soil organic carbon fraction in different pools is one of the important tasks for the calibration of RothC and many other models. In Australia, it has been done by mid infrared reflectance (MIR) (Skjemstad and Spouncer, 2003). Recently, Diffuse Reflectance Infrared Spectroscopy Technology (DRIFT) was developed, which can predict soil organic carbon of fractions at a much faster rate (Zimmermann *et al,* 2006). Using DRIFT, Zimmermann *et al.* (2006) found the correlation coefficient of 0.89 to 0.97 between the measured and predicted soil organic carbon fraction in Switzerland. They showed the possibility of using DRIFT, in combination with partial least square (PLS), to estimate RothC pools and utilise them for initialisation of the RothC model at any point, even when historical data are lacking.

2.6 Emissions of N_2O from biologically fixed nitrogen in legumes

This section discusses the literature about biologically fixed nitrogen (BFN) and it argues, based on the a review of relevant literature, that some amount of BFN emits into the atmosphere in the form of N_2O but is not accounted for in land use analysis. Since N_2O is 310 time more global warming potential than CO2, it is necessary to account for in carbon budget.

N_2O is responsible for 6% of observed global warming (Dalal *et al*., 2003). Around 80% of N_2O is produced by the agricultural sector, of which 73% is emitted from the agriculture soil (Dalal *et al*., 2003). N_2O emission comes from nitrogen fertiliser, soil disturbance, general land use and animal waste. Lack of oxygen or limited oxygen supply in the soil or high oxygen demand due to more carbon food in the soil causes micro-organisms to utilise nitrate (NO^-_3) and nitrite (NO^-_2) instead of oxygen. As a result of this de-nitrification, N_2O is released into the atmosphere (Dalal *et al*., 2003). Therefore, even the undisturbed forest may emit N_2O. All these sources and their consequent amount of N_2O emissions in different land uses are discussed in the Methodology chapter. Here, the discussion is mainly focused on N_2O emissions from biologically fixed nitrogen in legumes.

Although nitrogen is not truly an inert gas, it acts as an inert gas for global warming. Legumes can fix nitrogen from the atmosphere and part of that emits into the atmosphere in the form of N_2O. Nitrogen fertiliser use in Australia increased by 325% during the 13 year period (1987-2000) (Dalal *et al*., 2003) but legume based rotations are still commonplace. Around 91.7 Mha of pasture and forage legume fix an estimated amount 4.6 $MtNyr^{-1}$, and two Mha of crop legumes fix 0.31 $MtNyr^{-1}$ (Crews and Peoples, 2004 cited Unkovich, 2001). There is a debate among the scientific community about whether the biologically fixed nitrogen is equally as harmful for global warming as that of nitrogen fertiliser. Dalal *et al*. (2003) suggested that the N_2O emission from legumes crops exceed those from fertiliser due to frequent wetting and drying cycles over a longer period. Crews and Peoples (2004) argued that the biologically fixed nitrogen is ultimately derived from solar energy while nitrogen fertiliser requires significant amount of fossil fuels, thus, legumes should be in a better position. There are several other things to consider, such as the amount of fossil fuel emission while establishing, maintaining and processing of legume crops. Despite this debate, IPCC (2001) consider equal N_2O emission factors of 1.25% (of total nitrogen) for all inorganic nitrogen fertiliser, manures, dungs and biologically fixed nitrogen.

Peanut is a legume crop and it can fix nitrogen by nodulating with diverse strains of the species of *Bradyrhizobium*. Literature around the world shows that peanuts may fix 100-190 $kgNha^{-1}$ depending on soil nitrate conditions, types of cultivar and whether or not peanut is inoculated with rhizobium (Peoples *et al.,* 1992). Nitrogen fixation also depends on the choice of legume species, and crop and soil management practices (Rochester *et al*., 1998). In China, Chu *et al*. (2004) conducted a pot experiment to examine the nitrogen fixation by peanuts and the nitrogen transfer from peanuts to rice at three nitrogen fertiliser application rates using a ^{15}N isotope dilution method. The percentage of nitrogen derived by peanuts from the atmosphere was found to be 72.8%, 56.5% and 35.4% under mono-cropping and 76.1%, 53.3% and 50.7% under the intercropping system at nitrogen application rates of 15, 75 and 150 kg ha^{-1}, respectively. The research showed that the biologically fixed nitrogen increased by growing the crop with rice but decreased by increasing nitrogen fertiliser rates.

Rochester *et al*. (1998) studied the level of nitrogen fixation of several legumes in northern New South Wales, near the Queensland border, where legumes have been rotated with cotton crops. A ^{15}N natural abundance technique was used. Weeds growing adjacent to the area of sampled legume crops were used as the non-nitrogen fixing plants. They found that the peanut crop fixed 258 to 288 kgNha-1 (average 273 kgNha^{-1}), removed 105 kgNha^{-1} in harvested grain and contributed 168 kg Nha^{-1} to the soil nitrogen after harvest. In the case of faba bean, about 2 tDMha^{-1} was required before substantial biologically fixed nitrogen was evident and it was maximised when the dry matter was about 11 t ha^{-1}. Over the range of 2-7 DMha^{-1}, an average of 37 kgN was estimated to be fixed for every tonne of above ground crop dry matter.

Bell *et al*. (1994) estimated the amount of biologically fixed nitrogen of four cultivars of peanuts at the Bundaberg Research Station (152° 26’ E, 24° 50’S) under irrigated conditions. They applied ^{15}N natural abundance procedures using non-nodulating peanut genotypes as a non-nitrogen fixing reference plant. The cultivars differed significantly in terms of dry matter, pod yield and time to harvest after emergence. Virginia Bunch yielded the highest dry matter (11350 kg ha^{-1}) followed by Early Bunch H1 (11050 kg ha^{-1}), Early Bunch H_2 (10480 kg ha^{-1}), TMC-2 (10120 kg ha^{-1}) and Tapir (8870 kg ha^{-1}) continuously. They developed a general regression equation (fixed N= 0.015 DM_{EA}–10.9) for the estimation of biologically fixed nitrogen as a function of energy adjusted dry matter (DM_{EA}) at the accuracy of 98% coefficient of determination (R^2). People *et al*. (1992), in a two year study with Virginia type of peanut in Kingaroy (151° 50’E., 26°, 33’ S), estimated the amount of biologically fixed nitrogen in peanut by ^{15}N natural abundance procedure using a non-nodulating peanut genotype as a non-nitrogen fixing reference plant (Table 2.2).

The results show that there is a direct relation between biologically fixed nitrogen and soil moisture and inverse relation between biologically fixed nitrogen and nitrate fertiliser. There is some positive influence of inoculation of rhizobium in 'continuous rotation of peanuts and winter oats as green manure' but not in 'peanut ─ 4 yr un-grazed Rhodes grass fertilised with 100 $kgNha^{-1}$ as urea each spring ─ peanut'. The greater percent of biologically fixed nitrogen was located to pod and kernel (62-70%) and then in the supporting shoot (13-21%).

Table 2.2 Amount of N-fixation in different peanut cropping systems

Treatments	Year[a]	Condition (Rhizobia inoculated?)	Total DM ($t\ ha^{-1}$)	Pod yield ($t\ ha^{-1}$)	N fixation ($kg\ ha^{-1}$)
Continuous annual peanut with winter fellow since 1983/84	1987/88	Uninoculated	7.7	1.62	32
	1988/89	Uninoculated	7.9	2.99	82
		Inoculated	7.9	3.00	84
Peanuts-2 summer maize 65 $kgNha^{-1}$ ─ peanut	1987/88	Uninoculated	7.0	1.95	57
Peanut ─ 4 yr un-grazed Rhodes grass fertilised with 100 $kgNha^{-1}$ as urea each spring ─ peanut	1987/88	Uninoculated	6.0	1.95	44
	1988/89	Uninoculated	10	4.23	120
		Inoculated	10	4.00	117
Continuous peanuts ─ unfertilised winter oats as a green manure	1988/89	Uninoculated	8.0	3.54	93
		Inoculated	8.0	3.44	102

[a]1987/88: Rain fed condition (355 mm during growing season of 138 days)
1988/89 Rain, 575mm during growing season (144 days), plus 90mm (30x3=90) irrigation. Adopted from Peoples *et al*, (1992)

There are fewer studies about the biologically fixed nitrogen in pasture legumes compared to peanut. Henzell *et al*. (1967) planted the Rhodes grass and Siratro separately and together in pots of soil containing ^{15}N-labelled ground Rhodes and plant material (C : N = 44). Siratro grown alone took up as much ^{15}N as Rhodes grown alone, but Siratro took one-third and Rhodes took two-thirds when they were grown together at 15 weeks. In the case of Siratro, the root had higher ^{15}N than tops, indicating that most of the fixed nitrogen went to the tops (as in other legumes). Their research showed that only 2.4% nitrogen in the Siratro was from the soil at 15 weeks and less than one percent nitrogen transferred from the Siratro to Rhodes grass during that period. This means most of the nitrogen eaten by cattle in Siratro was from biologically fixed nitrogen.

Armstrong *et al*. (1999) studied the dry matter production and nitrogen fixation of several ley legumes including Siratro for four seasons (1994-97) at Emerald (23° 29' S, 148° 09'E, alt 190m), Central Queensland. They used grain sorghum as a non-legume control crop. The proportion of above ground nitrogen fixation in Siratro peaked at 72% in 1995 and then remained at 25-50% throughout the experiment. Siratro accumulated 16160 kg ha^{-1}DM and fixed 176 $kgNha^{-1}$ over the four years. The proportion of biologically fixed nitrogen was negatively correlated (R^2=-0.54) with the amount of soil nitrate. Biologically fixed nitrogen contributed less than 20% of nitrogen, when soil nitrate levels were greater than 40 $kgNha^{-1}$.

The different studies show that a significant amount of nitrogen is fixed by legumes in cultivation and pasture. Part of that biologically fixed nitrogen goes to the atmosphere in the form of N_2O. However, these emissions are largely ignored in land use analysis. Since the above mentioned studies are related to our studies, the most reliable biologically fixed nitrogen data is picked-up for the estimation of N_2O emissions from biologically fixed nitrogen. For detailed information about what study is selected and why, see chapter three.

2.7 Emissions of methane (CH_4) from cattle

Methane (CH_4) is another important gas that need to be account for in carbon budget. Methane is responsible for 20% of the observed global warming (Dalal *et al*., 2003). In 1990, Australian beef cattle were responsible for 24% of the CH_4 emissions from all anthropogenic sources and 6% of Australia's total greenhouse gas emissions. Methane is produced in the rumen of animals by methenogenic bacteria, which uses H_2 produced by protozoa[2]. Methanogens live with the protozoa in a symbiotic relationship. Therefore, ruminants maintaining higher protozoa populations generally have higher CH_4 emissions (Hegarti, 2001). Methane emission in cattle begins when solid feeds are retained in the alimentary canal (about four weeks after the birth) (Hegarti, 2001).

A general analysis showed that the methane emission rate of cattle from developed and developing countries are 55$kghd^{-1}yr^{-1}$ and 35$kghd^{-1}yr^{-1}$ respectively (Crutzen *et al*., 1986 cited in Eckward *et al*., 2000). However, later studies by IPPC from New

[2]The chemical reaction could be written as CO_2+H_2=CH_4

Zealand and Australia shows that there was a big difference in methane emissions between dairy and non-dairy cattle. For example, in New Zealand, mature dairy cows and non dairy cows emitted 80.6 and 69.5 kg $hd^{-1}yr$-1 respectively (Crutzen *et al.*, 1986 cited in Eckward *et al.*, 2000). In Australia, the figures are 68 and 53 $kghd^{-1}yr^{-1}$, respectively (IPCC, 1995 cited in Eckward *et al.*, 2000). For a given species, methane emission depends on its genotype, level of feed intake, feed digestibility and live weight gain. It also depends on feed use efficiency as some cattle consume more feed than expected to achieve a specified rate of growth (low efficiency). Animals with faster passage of feed material and higher feed digestibility greatly reduce daily methane production. This genetically driven variation provides an opportunity to reduce feed consumption and then methane emission without compromising size and growth performance (Hegarti, 2001).

While citing literature about CH_4 emissions, it is better to trace back to Blaxter and Clapperton's predictive equation (1965) that used the most comprehensive set of methane yield data of cattle (138) and sheep (770) offering temperate forage based diets in Scotland. While doing national greenhouse gas inventory in Australia, the methane output from beef cattle estimated based on that predictive equation, which was based on a temperate forage diet (McCrabb and Hunter, 1999). However, a tropical forage diet offered to cattle in Queensland may differ markedly from temperate forage diets. Tropical grasses are generally 13% less digestible than temperate grasses (Minson, 1990). McCrabb and Hunter (1999) reviewed the respiration chamber measurements of daily methane production for Brahman cattle offered three different tropical forages. They found that the methane production (g/kg digestible organic matter) was highest for Angleton grass (75.4±4), intermediate for the Rhodes grass (64.6±1.7) and lowest for the high grain diet (32.1±3.4). For Rhodes grass, which is one of the major grasses in our case, the dry matter intake per day of 7200 gm gave methane output per day of 260 gm and live weight change per day were of 260 gm.

There are potential to reduce CH_4 emissions from cattle. A Queensland CSIRO team is studying the acetate producing bacteria in kangaroos, and to put it in the rumen of cattle so that it would produce acetate and be able to reduce methanogenic bacteria. McCrabb and Hunter (2003) reported that the repeated treatment of beef cattle with hormonal growth promotants (HGP) could lead to a 16% reduction in lifetime CH_4

production and will also lead to a 7-11% reduction in slaughter age. CSIRO is using HGP to quantify CH_4 reduction under grazing conditions in the Northern Territory (McCrabb and Hunter, 2003). However, there are several obstacles to success in these missions. There are several species of methanogens. Direct biological control agents, including vaccines will be effective to some methanogens, but not to others. Since there is a lack of information on the predominant species and types of rumen methanogens in Australian ruminants (Hegarty, 2001), it will be difficult. Similarly, eliminating rumen methanogens without establishing alternate H_2 users will cause the accumulation of H_2 which has catastrophic effects on interrelated organisms, stopping fermentation and causing livestock to stop eating (Hegarty, 2001). Hence analysis is on the basis of conventionally estimated emissions.

2.8 Carbon accounting in biomass

Carbon accounting in standing and harvested biomass is another significant component carbon budgeting, which is discussed in the next section.

2.8.1 Carbon accounting in standing biomass

Standing biomass includes the mass of carbon in roots, stems, branches, barks and leaves. There is no universally agreed upon rule of carbon accounting. Depending on the available technology and methods, various techniques have been used around the world. There are a range of methods (from aerial photography and imagery to destructive sampling) for biomass estimation. Several general and local biomass tables and species-specific allometric equations have been developed for this reason. More than 200 species-specific allometric equations have been developed in Australia. For example, Specht and West (2003) developed six different equations for six popular tree species (*Eucalyptus microcorys*, *E grandis, E. saligna, E. nitens, Grevillea robusta and Pinus radiata*) in New South Wales while Margules (1998) developed 11 equations for 11 morphological groups of tree species found in the SEQRFA region. Similarly, Scanlan (1991) developed an allometric equation for *Acacia harpophylla*, Burrows *et al*. (2002) developed one for *Eucalyptus melanopholoia* and Harrington (1979) developed one for *Eucalyptus populnea*. Some equations are based on diameter at breast height (DBH) as an independent variable whereas others are based on both DBH and height.

There are some limitations to the application of these equations. First, equations developed for the same species in different sites would be different because of different climatic and edaphic conditions (Mohns *et al*., 1989). For instance, there was the cases for *Eucalyptus resinifera* (see Ward and Pickersgill, 1985) and *Acacia aneura* (see Harrington, 1979 and Burrows *et al*., 2002). Second, in some cases, the range of applicable diameters (and/or heights) is not quantified (e.g., Specht and West, 2003), which makes a difficult to use. In others, the range of diameters (and/or heights) is too narrow to apply even for the same species found in the same locality (Burrows *et al.*, 2002). Third, in some cases equations are not reliable, as they are either based on a limited sample or a limited number of independent variables (Snowdon *et al*., 2000). Fourth, the high multicollinearity among the independent variables (biomass predictors) is another problem, which may result in an unreliable equation (Maraseni *et al.,* 2006). For example, the height and diameter, predictors of tree volume, could be hight correlated. These literatures show that the allometric equation (either for biomass or for volume) of the same species varies with sites, management and genetic factors.

Density is the important factor for the indirect estimation of biomass from volume, which is the most common practice throughout the world. Regardless of the age and height of the trees, investigators use the same value of density for each species and sometimes even the arithmetic mean of all known species of similar forest types (for example see Haripriya, 2000). The density of stem increases with height and from pith to outer stem (Raymond *et al*., 1998). However, from the density estimation of 133 *Pinus radiata* (age from 10-47) from 34 sites in South Australia, the age related density pattern was found to be more pronounced than diameter (Mitchell, 1987 cited in Polglase *et al*., 2004). Although the relationship between age and density of *P. radiata* was significant ($P<0.001$) the coefficient of determination was low (R^2 = 49%). It is argued that the R^2 could be improved if site quality is taken into account. Therefore, for the accurate estimation of density of a given species, which in turn is necessary for biomass estimation, age and site factor should be considered.

Biomass largely depends on thinning practices and plantation strategies (monoculture or mixture of species). Bateman and Lovett (2000) combined yield class models with data on carbon storage in Sitka spruce in Wales and plotted a carbon storage curve for yield classes 8, 16 and 24 stands. All un-thinned yield classes produced characteristic S-shaped curves and thinned stands followed this curve until the first thinning. After thinning, the thinned yield curve became much flatter than its un-thinned counter-part. This produced two conclusions: yield class affects the carbon storage in a stand, and un-thinned stands sequester more carbon than thinned ones.

Roots accounts for between 10 and 65% of tree's total biomass, but there is limited understanding of factors that cause these variation. The CRC for GA (2003) used ground penetrating radar to detect and determine the size of the roots so as to support non-destructive estimates of tree biomass and distributions. The IPCC guidelines (2001) suggest a default value of root:shoot ratio of 0.25. In India, the ratio of 0.326, 0.265 and 0.208 were used for tropical, subtropical, and temperate vegetations respectively (Haripriya, 2003). Many factors such as temperature and rainfall changes are occurring towards the alpine region from the tropical region, therefore it is hard to say which factor plays a major role for root:shoot ratio. However, research in three *Eucalyptus populnea* dominated woodlands along a rainfall gradient of 367-1103 mm yr^{-1} found that increasing rainfall results in a significant reduction in the root:shoot ratio (CRC for GA (2004). Types of fertiliser use also play an important role. Preliminary results of research done in *Pinus radiata* in Western Australia (nitrogen effect) and New South Wales (phosphorus effect) show that the poor phosphorus nutrition increases the root:shoot ratio from 0.2 to 0.3, whereas nitrogen did not affect the ratio (CRC for GA, 2004).

2.8.2 Carbon accounting in harvested products

Harvested product can lock up carbon to differing degrees. However, the IPCC (2000) default approach assumes that entire harvested products emit carbon immediately after harvesting. Locking carbon in a wood product that has a long decay period is a better option than that of locking carbon in the standing biomass (unharvested trees). The standing misses the opportunity of sequestrating new carbon in the newly grown plantation. Depending on use the carbon emission rate of harvested product is different. It would be far better if the carbon sequestration rate of a newly planted area exceeds the decomposition rate of harvested products (Jaakko Poyry 2000). The harvesting age of trees determines the size of log which in turn determines the particular use of harvested products. As the different uses have different lifetimes, the amount of carbon retention on each use varies with other uses.

Depending on the duration of time the forest products can retain carbon, the forest products can be classified into different life span categories.

In Australia, Jaakko Poyry (2000) collected the historical data for production, export and import of different kinds of forest products from the Australian Bureau of Agricultural and Resources Economics (ABARE). Of the four carbon accounting approaches (Default, Production, Stock Change, and Atmospheric Flow Approaches) proposed by the IPCC only two approaches (Production and Stock Change Approaches) were found to be feasible in Australia. On the basis of use, they divided forest products into five life span categories (3 yr, 10 yr, 30 yr, 50 yr and 90 yr) and assumed that the decay rate of each category of products remain the same over the life span (for detail see Jaakko Poyry 2000). Forest products may have one of three fates after being used for particular products: reuse into other types of products, burnt for energy or land-filling for decomposition. Since the above mentioned rates assume a constant decay rate over the lifespan of the products, it may need to be redefined again after using them for these purposes. Row and Phelps (1990) have given the over time carbon retention (proportion) formula in harvested products.

The above approach of Jaakko Poyry (2000) and Haripriya (2003) assumed the same life span for the same uses regardless of the species. However, this approach does not give an accurate picture (Maraseni *et al*., 2005). A hardwood species, *Shorea robusta* (a tropical dipterocarp) could have about 300 years of lifespan as a timber in Nepal, whereas in the same country the timber of other hardwood species such as *Alnus nepalensis* could have less than 30 years of lifespan (Maraseni *et al*., 2005). Sometimes, local practices may lengthen the lifetime of timber. For example, in Nepal the smoke in kitchens (from firewood burning) works as a preservative for pine timber that lengthens the lifetime of the timber, whereas the timber of the same species used for other types of construction purposes could have a shorter lifetime (Maraseni *et al*., 2005). Therefore, in order to estimate the lifespan of timber, the types of species and the local practices (treatments) for that particular use should be considered.

2.9 Optimal rotation and affecting factors

In this section, the literature about different types of optimal rotations and factors affecting them are discussed. Optimal rotation is the age at which the trees should be cut to maximise the targeted objective. There are three types of optimal rotation: 1) Maximum Sustainable Yield (MSY) rotation for maximising the physical volume of harvest; 2) Maximum Economic Yield (MEY, Faustmann rotation) rotation for maximising NPV of timber income; and 3) MEY (Hartmen rotation) rotation for maximising the NPV from timber and non timber benefits (von Kooten *et al*., 1995). Current annual increment (CAI[3] or marginal product in economic terms) and mean annual increment (MAI[4] or average product in economic terms) are two important concepts for determining the MSY rotation. The age at which CAI=MAI or when MAI culminates is the age for MSY (Campbell, 1999). This rotation is used to maximise timber volume and is not affected by a demand and supply situation of the market.

The driving force for plantations is economic return. Maximising NPV, taking into account the land rent, from underlying investment is the key objective of all investors; although it is not only objective. This concept is based on the Faustmann rotation. There are two principles to estimating this rotation age: static and dynamic efficiency principles. The static efficiency principle suggests that the MEY (Faustmann) rotation is the age at which the marginal benefit equals the marginal cost. The marginal benefit is the benefit of letting trees remain one more year and the marginal cost is foregone interest which could be earned by cutting trees now, selling the wood and placing the money in the bank. The general rule behind this principle (the famous 'Fisher Rule') is to leave the capital in the forest—the 'tree bank'— as long as the increase in value of the timber exceeds the interest rate in the bank (Campbell, 1999). The principle of dynamic efficiency is based on the general principle of maximising NPV, that is, harvest trees to get maximum NPV. Fortunately, both principles give the same result (Campbell, 1999). Since the MEY (Faustmann) rotation accounts for the time value of money, this rotation is shorter than MSY rotation (Campbell, 1999). The closeness of these two rotations depends on the price of logs, and harvesting and regeneration costs during that time.

Due to growing concern about environmental services from forests and the emergence of a new branch of economics, Environmental Economics, a new dimension of forest non-market values has been brought into the limelight. The

[3] CAI is an increment in a specific year.
[4] The MAI is the total increment up to a given age divided by that age

omission of these environmental services values will give an incorrect optimal rotation, if all benefits are to be considered. In this regard, Hartman (1976) added non marketed values (standing value) into the objective function of the Faustmann rotation (Alaouze, 2001; Ficklin *et al*., 1996). There are three different approaches to predicting the Hartman rotation: (a) by exogenously fixing a market price of non market values and summing the NPV of market and non market values (von Kooten *et al.,* 1995), (b) by producing a production possibility frontier between the NPV of marketed and non-marketed goods (Hoen and Solberg, 1994) and (c) by the optimisation of a utility function over a production possibility frontier of NPV of marketed and non-marketed values (Romero, 1998). The last approach requires the environmental optimum, private optimum and L1 (lower) and L∞ (upper) bound points at the arc of the production possibility frontier. The compromise points on social optima lie in between the L1 and L∞ bound points (Romero *et al*., 1998). This last approach considers the negative externality on the society and gives the most efficient solution, if all external costs to the society are considered.

When the concept of optimal externality is applied, neither total production nor total protection is justified (Ficklin *et al*., 1996). Total protection means zero pollution, which is socially desirable, but undesirable for development. It means some pollution is acceptable for development, but the question is up to what level? In the context of forest rotation, it depends on the type of property and the amount of incentives received from timber and non timber values. A private forest owner with accumulating non-forest assets would never harvest (Ficklin *et al*, 1996) because keeping forest unharvested would be more beneficial. This means that if the standing value of forest is large enough that the rotation age, which satisfied the first order derivatives of value with time (dV (t)/dt=0) cannot be found, then the forest should be preserved (Alaouze, 2001). This may be the case for a habitat of endangered species (Ficklin *et al*, 1996) and ancient growth forest (Kahn, 1998).

With a new monoculture plantations, habitat value is relatively low and with an emerging domestic and international carbon market, carbon sequestration can be considered to be marketed goods. Therefore, the Hartman rotation is no longer necessary; an extension of the Faustmann rotation is enough for the determination of optimal rotation age incorporating timber, stock and carbon values.

As discussed in the previous sections, the plantation in the study area is silvipastoral. Therefore, at the interface of timber, stock and carbon market there are several exogenous factors that may affect the rotation age (most of the factors, except the discount rate, are discussed in chapter one and not repeated here). The discount rate affects the optimal rotation age. There are two reasons for discounting. First, there is discounting due to pure time preferences, a lower value is placed on receiving money in the future relative to the present because in the interim the money could have been used for profitable investment or desired consumption.

The second reason for discounting is due to social time preference, which is related to diminishing marginal utility of income. An extra one dollar income next year is worth less in utility terms than an extra one dollar now (Pearce and Moran, 1994). In the case of forestry, discounting makes the unsustainable use preferable to sustainable use as the future benefits from sustainable use are discounted. That is the reason why MSY rotation is longer than MEY rotation. The higher the rate of discounting the lower will be the MEY rotation and greater will be the difference between MSY and MEY rotation ages (Campbell, 1999).

There are several approaches for fixing discounting rates. One approach to discounting is: $S = P + UC$, where 'S' is social discount rate, 'P' is pure time discounting, 'C' is growth rate of real consumption per head and 'U' is the measure of the rate at which the extra wellbeing (utility) is arising from utility decline as consumption rises (Turner, Pearce and Bateman, 1994). A social discount rate may be applied by a government considering social welfare. The private firm may use the opportunity cost of the best alternative for the estimation of discount rates. In some cases, the risk free discount rate or real rate (net of inflation) may be used as a basis for the discounting rate. The discount rate is further discussed in chapter three.

2.10 Carbon marketing

This section focuses on the demand and supply of carbon credit, carbon market development and prices of different types of carbon credits generated from different sources under the Kyoto mechanism.

2.10.1 Demand and supply of carbon credit

Through the Kyoto Protocol, Annex-B countries are legally-bound to reduce greenhouse gas emissions to an average of 5.2% below their 1990 levels over the first commitment period, 2008-2012 (UNFCCC, 1997). Thus, the demand of carbon credits depends on the overall growth of emissions during the period 1990 to 2012. Until 2000, about 50% of Annex-B countries have positive net emissions with respect to the Kyoto target (UNEP, 2003; Kooten, 2004). However, the projection shows that the demand (191-811 $MtCO_2yr^{-1}$) of emission reduction requirements is lower than the supply (1177-2064 $MtCO_2yr^{-1}$) (UNEP, 2003). This surplus carbon credit would have a demand impact on the carbon market. The main suppliers of carbon credit, through Clean Development Mechanism, are the developing countries of Latin America and Asia (Jung, 2005). The demand for credit for these countries depends on the price offered, the abatement cost of carbon in Annex-B countries, and the market price of carbon from 'hot air' and Joint Implementation (UNEP, 2003).

2.10.2 Carbon finance and market development

Carbon finance catalyses the private sector for carbon market development. The carbon market includes both the generation of emission reductions (ERs) through project based transactions, and the trading of greenhouse gas emissions allowances allocated under existing cap-and-trade regimes (Lecocq and Capoor, 2005). For the first category, the World Bank, the EU, and Dutch, Japanese and Swedish governments are playing leading roles. Among them the World Bank's Prototype Carbon Fund (PCF) and the Dutch Government's Certified Emission Reduction Unit Procurement Tender (CERUPT) are the main buyers (UNEP, 2003). The CERUPT tender approved 18 Clean Development Mechanism (CDM) projects in nine developing countries in 2003 and aimed to cut emissions by more than 16 $MtCO_2e$ (Point Carbon, 2003). Similarly, as of 2002 the PCF approved a total of 16 Clean Development Mechanism projects with emissions reduction potential of 24 $MtCO_2e$ (UNEP, 2003). Regarding the trading of emissions allowances, as of May 2005, there are four active markets: the European Union Emission Trading Scheme (EU ETS), the UK Emission Trading Scheme, the New South Wales Trading System and Chicago Climate Exchange (Lecocq and Capoor, 2005). These markets have been accelerating carbon trading. As a result, project based emissions reached to 107 Mt in 2004— an increase of 38% compared to 2003 (Lecocq and Capoor, 2005).

The price of carbon varies substantially depending on the size of the project, type of projects (technology used), buyer risk and type of actors involved (Point Carbon, 2003). Larger projects would have offered a higher price due to economies of scale of production and reduction in transaction costs. As at April 2005, Hydroflurocarbon[5] (HFC23) is the dominant type of emission reduction project in terms of volume (25% increase from January 2004 to April 2005) followed by capturing CH_4 and N_2O from animal waste (18%) (Lecocq and Capoor, 2005). The price offered by CERUPT for biomass and energy efficiency projects, and fuel switching and methane projects are respectively priced 20% and 40% lower than renewable energy projects, except biomass (UNEP, 2003). The Joint Implementation and Clean Development Mechanism are both project-based. However, PCF pays higher prices for the carbon credit from Joint Implementation projects, because it is supported by the host country (Annex-B countries) agreement, which reduces the risk of the project (UNEP, 2003). Similarly, due to higher registration and delivery risks, the carbon price in Joint Implementation and Clean Development Mechanism is lower than the carbon price of the European Union Emissions Tradition Scheme. There are low risk as these are government issued compliance-grade assets (Lecocq and Capoor, 2005). If the actors involved are reputable and reliable, the risk to business will be lower. Similarly, a reliable institution and investment environment can be helpful for carbon prices. This is why China, India and Brazil are the most promising Clean Development Mechanism host countries (Jung, 2005).

Transaction costs are another deciding factor for carbon price. These are the costs of arranging contracts to exchange property rights ex-ante and monitoring and enforcing the contract ex-post (Matthews 1986 cited in Cacho *et al*., 2003). Carbon costs of a sink project can be classified into seven categories: search costs, negotiation costs, verification and certification costs, implementation costs, monitoring costs, enforcement costs and insurance costs (Cacho *et al*., 2003). The transaction cost will reduce the attractiveness of the carbon market (Michaelowa *et al*., 2003; Michaelowa and Jotzo, 2005). Jung (2003) estimated the transaction costs

[5] One ton of HCF_{23} is equivalent to 11,700 ton of CO2 in terms of global warming potential

of 0.55 U$$t^{-1}CO_2$ for Clean Development Mechanism in non Annex B countries and 0.27U$ $t^{-1}CO_2$ for Annex B countries. Under the current circumstances, projects with annual emission reductions of less than 50,000 $t^{-1}CO_2e$ are unlikely to be viable (Michaelowa *et al*., 2003). In order to reduce transaction costs and encourage small scale projects, simplified rules and regulations have been adopted for the project which sequestrate up to 8 $ktCO_2eyr^{-1}$, but this rule is only applicable to Clean Development Mechanism projects.

The market price of carbon is not stabilised yet (Lecocq and Capoor, 2005). Policy and regulatory factors have a huge impact on demand and supply situations and market de-stabilisation. In the context of the Kyoto Protocol (KP), rules and regulations are well defined but still there are huge uncertainties. Includes such as what will be the position of Annex-B countries after the first commitment period (2008-2012)? will the developing countries (non-Annex-B) be legally bound to emission reduction obligations after 2012? will those avoiding deforestation be eligible for the Kyoto mechanism? will the United States and Australia, which are outside the Kyoto Protocol, ratify the Kyoto Protocol or develop some different sort of carbon trading mechanisms? even if they develop a market will the carbon credit produced by them be fungible with the carbon credit of the Kyoto Protocol? what policy will Russia and the Ukraine adopt about the selling of 'hot air'? will there be any breakthrough in new technology? These uncertainties are playing a vital role in market destabilisation.

If Annex-B countries are more stringent in their obligations for the post 2012 period and if some of the economically emerging non Annex-B countries (China, India, Brazil, Korea, Mexico and South Africa) shoulder some responsibility, the demand for carbon will increase and price rise. Avoiding deforestation is the cheapest source of carbon credit (IPCC, 2001; Jung, 2003; Maraseni *et al*., 2005; Osborne *et al*., 2005) but it is not eligible for Clean Development Mechanism. There is mounting pressure to include deforestation because it is cost effective, compatible with several bilateral and multilateral environmental agreements (such as Convention of Biological Diversity and Combating Desertification) and also preferable for many community based forest management systems (Scheulze *et al*., 2003; Maraseni *et al*., 2005). If this approach is included, a cheap supply of carbon will flood the market and the price would be lowered.

USA and Australia have not ratified the Kyoto Protocol. However, they have developed a non-Kyoto compliance market. If this market becomes a reality and the carbon credits are interchangeable with Kyoto credit, the demand side will increase which could increase the market price. Similarly, the policy adopted by 'hot air' countries (Russia, Ukraine and Eastern European countries) will have a huge impact on the market price of carbon (Jung, 2003; Lecocq and Capoor, 2005). If they decided to sell all their surplus emissions (1300 $MtCO_2$) at a price lower than the current market price, the market will be dominated by 'hot air'.

Future technological breakthroughs on emission reduction in any sector will bring the carbon price down. Several new approaches and techniques have been discussed in the international arena. Carbon capture and storage in deep oil wells (40-400 GtC), exhausted gas wells (90-400 GtC), unminable coal measures (40 GtC), saline aquifers (90 to > 1000 GtC) and ocean disposal (400 to >1200 GtC) are getting increased attention (Kraxner *et al*., 2003). However, at the current state of knowledge, it has some technical and legal complexities. First, the cost is in the range of U$200-300 per tC, which is quite expensive (Kraxner *et al*., 2003). Second, ocean disposal can increase acidity which could affect marine flora and fauna (Kraxner *et al*., 2003).

Third, the stored carbon could release at any time and therefore is non-permanent in nature. Moreover, it is incompatible with the current UNFCCC rules and definitions and there is a great chance of inter-Annex leakage (for detail see Bode and Jung, 2004; Bode and Jung, 2005). Currently, nuclear energy and an ocean carbon sink are being cited as important options. Nuclear energy may have negative externalities due to radioactive radiation and also because the total greenhouse gas emissions for the installation and functioning of a nuclear plant are seven times less cost-effective at displacing carbon than the cheapest alternative energy efficiency project (Hertsgaard, 2005). Countries like Australia, Denmark, France, Iceland, New Zealand and Portugal could benefit from the ocean carbon sink. Like the forest management activities, an ocean carbon sink applies zero cost, but unfortunately it is not eligible for the Kyoto Protocol (Rehdanz *et al*., 2005).

2.10.3 Market prices of different types of carbon credits

During the period between January 2004 and April 2005, the major buyer of project based emission reduction is Europe (60%) and the major seller is Asia (45%). Project abating non-CO_2 gases account for 57% of the volume supplied, and Land Use Land Use Change and Forestry account only for four percent (Lecocq and Capoor, 2005). The price of carbon has greatly varied on the basis of the extent of the risk. Carbon prices from Joint Implementation projects are higher than the carbon price from Clean Development Mechanism projects (UNEP, 2003), but are lower than from the European Union Emissions Trading Scheme (Lecocq and Capoor, 2005). Prices for different types of carbon credit from January 2004 to April 2005 are given in Table 2.3. The lowest price was offered for non Kyoto compliance Emission Reduction (ER). It commands a price between \$0.65 and \$2.65 $t^{-1}CO_2$.

Table 2.3 Prices for non-retail project based carbon credit (ER, VER, CER & ERU) and the market price of EUA from January 2004 to April 2005

ER (U\$$t^{-1}CO_2e$)		VER (U\$ $t^{-1}CO_2e$)		CER (U\$ $t^{-1}CO_2e$)		ERU (U\$ $t^{-1}CO_2e$)		EUA (€$t^{-1}CO_2e$)	
Range	WA	Range	WA	Range	WA	Range	WA	Range	WA
0.65-2.65	1.2	3.6-5.0	4.2	3-7.15	5.63	4.6-7.3	6.1	7-17	15

Adopted from Lecocq and Capoor, 2005
Note: ER-Emission Reduction, VER-Verified Emission Reduction, CER-Certified Emission Reduction, ERU-Emissions Reduction Unit, EUA-European Union Allowance and WA-weighted average

Similarly, prices for Verified Emission Reduction (registration risk on the buyer) are higher than ER, but lower than Certified Emission Reduction (registration risk on the seller). ER, VER and CER are related to the Clean Development Mechanism projects, but the Emission Reduction Unit is related to Joint Implementation projects. The reasons why prices of carbon credits are different in different projects are already discussed (section 2.10.2).

2.10.4 Market development and carbon price in Australia

Since the Australian government did not ratify the Kyoto Protocol, it cannot participate in the Kyoto market. However, federal and state governments in Australia are developing some policies for market development. In 2005, the governments of Australia, China, India, Japan, the Republic of Korea and the United States released a joint vision statement for a new "Asia-Pacific partnership on clean development and climate" (Sarre, 2005). The area of collaboration could include market development among other things (Sarre, 2005). Australia has implemented a mandatory target for electricity retailers to obtain an additional 9.5 $TWhyr^{-1}$ of electricity from renewable sources by 2010 (Fung *et al*., 2002). The enacted Electricity Supply Act of NSW requires electricity retailers and large electricity users to reduce their greenhouse gas emissions to 5% below 1990 levels on a per capita basis (Booth, 2003). These types of policies and other national policies such as the Greenhouse Friendly Scheme[6] and, 'GGAP and Greenfleet[7]' may create some demand for carbon credit, which could be supplied from the forestry sector. The Bush Tender initiative in Victoria and the Environmental Service Scheme in New South Wales (Cacho *et al*., 2003) are other examples of forest ecosystem market development. The joint decision of the NSW and Victorian state governments in 2005 for greenhouse gas emissions reduction were important steps which could foster a market for carbon credits. Similarly, Emission Traders Pty Ltd and CO_2 Forest Sinks Pty Ltd are offering to arrange for the acquisition of rights to any greenhouse gas credits associated with investment in timber plantations (Binning *et al*., 2002). There is further discussion of the market price and transaction costs in Australia in chapter three.

2.11 Cost benefit analysis and gross margin

Cost-benefit analysis (CBA) is the most widely used project appraisal technique to choose the most profitable option. CBA uses the distribution and amount of costs and benefits streams and brings them back to the present values, by using specified discount rates, to compare with other alternatives. Several criteria, such as net present value (NPV), internal rate of return (IRR), benefit cost ratio (BCR), and payback period, could be used for comparison, and NPV is the preferred option. This is because the other criteria do not reflect the size of the project, and IRR can give multiple solutions (Antony and Cox, 1996). The project that gives a higher NPV or IRR or BCR, is usually selected[8]. On the basis of the nature of costs and benefits, there are two types of CBA analysis: Financial CBA and Economic CBA. Financial analysis is taken from the perspective of a private investor, who is interested in actual costs and benefits based on market prices. It does not account for policy and market failures. Externalities, non-marketed costs and benefits that impact on others are

[6] See www.greenhouse.gov.au/greenhousefriendly/index.html
[7] See www.greenfleet.com.au
[8] However, there could be some private reasons in which investor may not choose with the highest forecasted NPV.

excluded, but tax and subsidies are included in the financial CBA (Ive and Abel, 2001).

As the market price may not reflect the economic value, economic analysis goes beyond this and uses adjusted market prices. For this, it adjusts price distortion in traded and non-traded items and direct transfer payments (Bann, 1998) and uses shadow prices (Antony and Cox, 1996). The National Planning Commissions or the Central Bank of each country have estimated the conversion factors to convert market prices to the shadow prices of different goods and services based on their own economy (Wickramanayake, 1994). The economic CBA is a method of checking whether a project is viable from a social point of view. In economic CBA, equity issues are also incorporated for better distribution of income. Some projects are more beneficial to certain groups of society, therefore, the cost and benefit streams may also be weighted, depending on who owns them (Antony and Cox, 1996). However, all types of CBA do not usually take account of the multiplier effect of investment (Ive and Abel, 2001).

Gross margin is another option for estimating land use return. It is a widely used tool for farm management, budgeting and estimating the likely returns or losses of a particular enterprise (Jack, 2004; Harris, 2006; Victoria DPI, 2006). It is the difference between the gross income and the variable costs of an enterprise. It is not a measure of profit, as it does not include any capital (land, buildings, machinery, irrigation equipment etc) or fixed costs (building and machinery depreciation, permanent labour, administration, insurance, rates, taxes, etc.) that must be met regardless of the enterprise (Victoria DPI, 2006). While estimating the gross margin, some costs are not included but all revenues are included. Therefore, the gross margin will be greater than the net returns. Gross margins for a range of crops are currently available from a variety of sources (for details see Jack, 2004; Harris, 2006; Victoria DPI, 2006).

When using pre-prepared average annual gross margins, we need to adjust them to suit our own situation, as both income and expenses can vary significantly with location, time of year, crop variety and so on (Victoria DPI, 2006). It can be used for a comparison of the relative profitability of alternative enterprises that have similar land, machinery and equipment requirements (Hassall & Associates Pty Ltd, 2005).

However, when making comparisons between enterprises, we have to keep in mind the resources used by them (Harris, 2006). For further discussion see Harris (2006), Victoria DPI (2006), Hassall & Associates Pty Ltd (2005) and Jack (2004).

This PhD project is financial in nature. The focus is on how land holders might respond to different incentives. All variable costs (the cost of machinery operations, agrochemicals and other operations) of all land use systems were evaluated by a consisted method (i.e. same amount or form). For the same reason, overhead costs, such as owner labour, rates and rents, insurance, living costs, taxation and lease payments were not included in all land use systems. Similarly, the market price for fuel was not used; a subsidised value was used. Therefore, the NPVs estimated in this study are neither profit nor economic benefit. However, the external cost of carbon (negative externality) is included, even if the carbon market is not fully developed. It is assumed that, if carbon market becomes reality, farmers may be rewarded for carbon sequestration or taxed for greenhouse gas emissions. Therefore, it has financial nature.

2.12 Conclusions

From the review and discussion of the literature, it is apparent that there are some research gaps both at the global and local levels. At the global level, five major problems are identified. (1) Greenhouse emissions associated with production, transportation and application of agrochemicals, fuels and machines are not sufficiently considered. (2) Emission of N_2O from biologically fixed nitrogen is largely ignored. (3) Harvested products could be a sink of carbon for a long time, but the fates of harvested products are poorly accounted for. (4) While estimating the optimal rotation of plantations, all sources and sinks of greenhouse gases in individual years are not sufficiently considered. Finally, all greenhouse gases are not accounted for in one place. As a result of omissions of one or the other gases, results are incomplete and therefore not reliable.

Similarly, at the local level, three major problems were identified. (1) Forest clearing is a major environmental problem. Therefore, the Queensland government is encouraging hardwood plantations especially of spotted gum, on the basis of their early age performances and local and international markets, but the optimal spacing and optimal rotation of spotted gum is unknown. The major problem for this is the lack of full rotation experimental data. (2) The Red Ferrosol soil was thought to be one of the most productive soils for various crops, but due to continuous cultivation practices it is highly degraded and therefore probable that cultivation practices have resulted in higher greenhouse gas emissions compared to other land use systems.

(3) The Queensland government, through the SEQRFA program, is giving incentives to farmers for planting trees on ex-pasture and cultivated land in low rainfall rain-fed Red-Ferrosols areas. Research shows that the economic viability of timber-alone-plantations in such areas is questionable. Since the major motivating factor for farmers is economic return, the government is not getting the expected response from farmers. However, there is a knowledge gap about whether plantations could be comparable with other land use systems, if carbon and stock values are considered. Since carbon is payable in domestic and international markets, there is a chance of implementing this idea and maximising net benefit by selecting appropriate land use types. A comprehensive field based study which addresses all these issues would increase knowledge for policy refinement.. This was the main reason this research was conducted. Considering the identified research issues and specified objectives, the next chapter will develop a conceptual research framework and detailed methodology.

Chapter 3

Research Design and Methods

3.1 Introduction

In previous chapters, different types and scales of research problems have been identified. This chapter discusses different methods to address those research problems in general and to address the research objectives in particular. The research compares the peanut-maize cropping, beef-pasture and timber-plantation[1] in Taabinga, Kingaroy, Queensland by incorporating carbon and stock values. In addition to an in-depth case study of those land use systems at Taabinga, three other related land uses in other locations were also studied for inferential data. This research is comprehensive in nature, as it has covered all variable costs and benefits and different sources and sinks of three major greenhouse gases: carbon dioxide, methane and nitrous oxide. The data for the study was also supplemented by formal and informal interviews with respective landholders, agronomists, sawmill staff and extension officers. In particular, forest inventory, biomass and soil sampling and stakeholders' interviews were used as sources of primary data. Collected data were modelled using different software to predict a long-term scenario.

The conceptual framework of the study is given in Figure 3.1. The optimal spacing and optimal rotation was determined by modelling. A triangulation of timelines of different land use systems was used to predict the soil carbon trend of all land use systems. The amount, types and time of primary farm inputs (agrochemicals, machines and fuels) used in these land uses were determined to estimate the emissions associated with them. Stocking rates used on pasture and in plantation in different years were determined by modelling. The resulting stocking rates were used for the estimation of greenhouse gas emissions from urine, dung and burping of cattle. The amount of biologically fixed nitrogen in cultivation, pasture and plantation was determined using field measured and literature-based data, and the emissions associated with them were estimated.

[1] Throughout the thesis, the words cultivation and maize-peanut cropping are used interchangeably. Similarly, the words spotted gum plantation and plantation are used interchangeably.

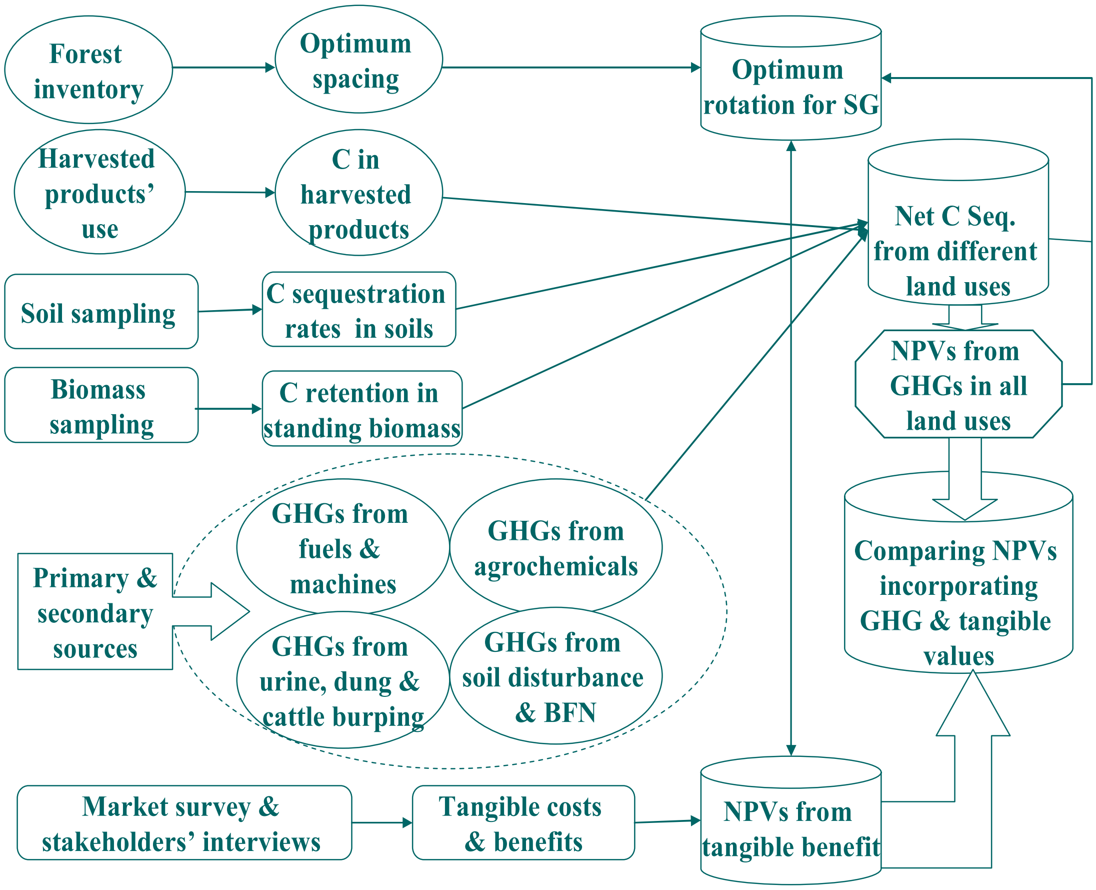


Figure 3.1 Conceptual framework of the study

This chapter is divided into several sections. An overview of the study area with reasons for selecting the research sites are discussed first, which is followed by a brief description of the concerned species and the methods used to meet the study's objectives.

3.2 Study area overview

While selecting the research sites, three criteria were considered: 1) sites where plantations are to be encouraged under the Southeast Queensland Regional Forest Agreement (SEQRFA) program; 2) sites where both pasture and cropping has been practiced for a long-time; and 3) sites which lie in low rainfall areas of Southeast Queensland (SEQ), have Red Ferrosol soil and have been practicing rain-fed cropping for a long time. It was assumed that the plantations could be a viable competitive land use in these areas if carbon and stock values are considered.

The South Burnett district meets most of these criteria. Around 11% (113,163 ha) of the total area (1,020,397 ha) in the South Burnett district has been classified as a Red

Tablelands soil (B. Harms[2], 2005, pers. comm., 27 May). At least 34,788 ha of them have Red Ferrosol soils, which may be higher since 34,533 ha of the area has been left unclassified (B. Harms[3], 2005, pers. comm., 27 May). The Red Ferrosol soils were considered to be good soils for different types of crops, but due to traditional continuous cultivation practices they have been losing their fertility (Bell *et al*., 1995; Cotching, 1995; Bell *et al.,* 1997; Bell *et al*., 2001). Mean monthly rainfall is always lower than mean monthly evaporation in this district (Mills and Schmidt, 2000). More than 95% of the cropping land has been rain-fed (Smith and Kent, 1993). Plantations could be a viable competitive land use in these areas if carbon sequestration is considered. This was the main reason why the SEQRFA program had targeted these areas and the Queensland government (DPI&F) had encouraged research in these areas.

3.2.1 An overview of the Kingaroy region

The Taabinga sub-region of the Kingaroy shire was selected, as a representative of the South Burnett district. In this section, an overview of Kingaroy shire is presented first, and then the reasons for selecting Taabinga are given.

The first post-European use of the land in the Kingaroy was for sheep (1846) followed by peanuts (1924) and these quickly became synonymous with Kingaroy. Later, land use was diversified for different agricultural industries such as dairying, beef, fisheries, maize, navy beans, sorghum and other crops. In particular, the sheep industry was replaced by the beef industry due to changing preferences and prices, and because of attacks of sheep by dingoes (C. Marshall, 2005, pers.com., 7 April). In the early 1990s, farmers further diversified into wine production and native hardwood plantation, as peanut growers feared an uncertain future (Nunn, 2004). Agriculture and forestry is the second industry in terms of proportion of employment (12.9%) after the retail trade (16.1%) (Parratt *et al.,* 1998).

Only around 3000 ha of Kingaroy is classified as State Forest and Timber Reserve (Smith and Kent, 1993). Non-modified (virgin) vegetation is rare. Originally, around 80% of the area was dominated by eucalyptus whereas 'softwood scrub' species as closed forest and scrubs accounted for 10% (Vandersee and Kent, 1983). Most of the remaining forest is native hardwood, predominantly spotted gum and ironbark (Bell

[2] Soil Scientist for CRC for Greenhouse Accounting, GPO Box 475, Canberra, ACT 2601, Australia
[3] Soil Scientist for CRC for Greenhouse Accounting, GPO Box 475, Canberra, ACT 2601, Australia

et al., 2000; Vandersee and Kent, 1983; Smith and Kent, 1993). The nearest sawmill is the Wondai Saw and Planing Mill Pty Ltd, which was established in the Wondai shire in 1906. The implementation of the Southeast Queensland Regional Forest Agreement (SEQRFA) in 1999 has provided some timber production security. The mill has a current annual turnover rate of $10 million and is the major employer in the region. It became the first mill ever to receive assistance from government on a dollar-for-dollar basis for its $3 million upgrade plan for both green and dry mills in 1999 (DPI&F, 2005). In 2006, the mill sourced 50% hardwood from state-owned native forest and the balance from freeholders. Although it processes many species, around 90% is accounted for by spotted gum.

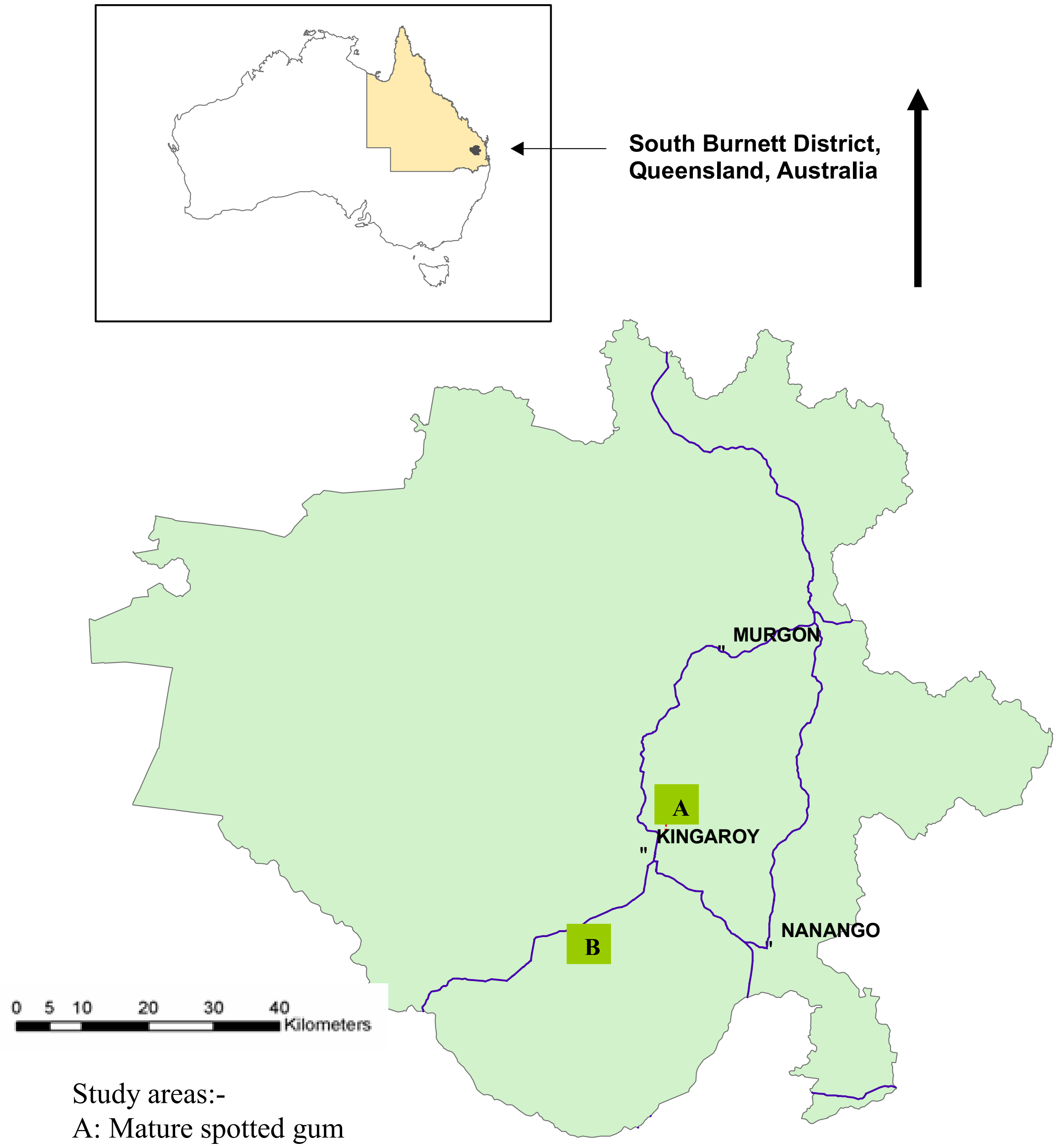
The climate of Kingaroy is classified as subtropical, with long summers and mild winters. Annual rainfall varies from 339 to 1430 mm, with an average of 781 mm, which is summer-dominant with about 70% falling between October and March. The evaporation rates are highest between October and March and in every month it exceeds the average rainfall. Frosts also occur during winter, with low-lying areas having the highest number of severe frosts. June, July and August are the coldest months and on average Kingaroy has 24 heavy and 22 light frosts each year. Occasional frosts can also occur in May and September. Kingaroy does not have the high summer temperatures of many other regions in Queensland with December and January - the hottest months – averaging only 10 days between them over 32°C and usually only one day on an average over 38°C (100°F). The yearly average maximum temperature is 24.7°C, while the yearly average minimum temperature is 11.4°C.

Drought is a regular feature in this region. Between the period of 1963 and 1993 alone, the State government had declared the Kingaroy as a drought stricken area for over four periods (1965; 1969/70; 1970/71; and 1977/78) (Smith and Kent, 1993). Still around 98% of the total cropping area in Kingaroy (43,200 ha) is rain-fed (Smith and Kent, 1993). Therefore, the soil moisture is the major limiting factor in land use decisions and considered to be the margin of suitability for plantations.

3.2.2 Site selection

The three sites studied were on the Marshall, Raibe and Perrett properties, located near the Kingaroy township. They are situated approximately 215 km North West of

Brisbane and some 130 km inland from the coast. Elevation is around 500 m above sea level. The map of the study areas is given in Figure 3.2.



Study areas:-
A: Mature spotted gum
B: Pasture, cultivation, native scrub and spotted gum plantation

Figure 3.2 Location of South Burnett district in Australia (upper) and the study areas in the South Burnett district (lower)

The GPS readings (coordinates) of all sample sites are given in the Annex (Table C-1)[4].The soil at each site is classified as a Red Ferrosol according to the Australian Soil Classification of Isbell (2002), or a Tropeptic Eutrustox (i.e. Oxisol) in the USDA Soil Taxonomy (USDA Soil Survey Staff, 2003). Raibe and Marshall's properties are adjacent at Taabinga and the owners have been practicing dry land farming since the beginning of farming systems in the region. At Taabinga (Figure 3.2 point B) the plantation was only up to four of years age, so a mature spotted gum at Perrett's property (Figure 3.2, point A), where the same temperature, rainfall and soil type as Taabinga was found, was analysed for the proxy value of soil carbon for a mature plantation.

There were many reasons why the Taabinga sub-region of Kingaroy shire was selected. First, it satisfied all the above-mentioned conditions (being in the South Burnett district, Red Ferrosol soils and rain-fed cropping), and especially the newly planted spotted gum species in 2001 on the Marshall Property was under the SEQRFA program. There was a rental agreement between the owner and DPI&F, in which tree crop was legally separated from the land, thereby the dual ownership was legally accepted (*profit a prendre*).

Second, there was a debate at the time about the economics of plantations versus peanut production. Third, the timeline of land use transformation in this area was promising so that the soil carbon trends could be predicted efficiently and effectively (Figure 3.3). Both the Raibe and Marshall properties had scrub until 1950. Since then, Marshall's property was cultivated to peanut-maize until 1983 and then became grazed pasture; however, there are also pockets of remnant native scrub. The Raibe property has been cultivated with a peanut-maize rotation since 1950. Perrett's property is located around 20 km from Raibe's and Marshall's and was planted with spotted gum approximately 50 years ago on land previously used as pasture. Since the spotted gum in the Marshall property was started in 2001, Perrett's property has been studied for modelling the proxy value of soil carbon in Marshall's property.

[4] In order to differentiate table number in the main text to the table number in appendix, the symbols 'Table C1, C2 are used. Since appendix table start from Chapter 3, the first appendix table appears as Table C-1, and then Table C-2, Table C-3 etc. Similarly, in chapter four, Appendix table start from Table-D1, Table D-2 etc.

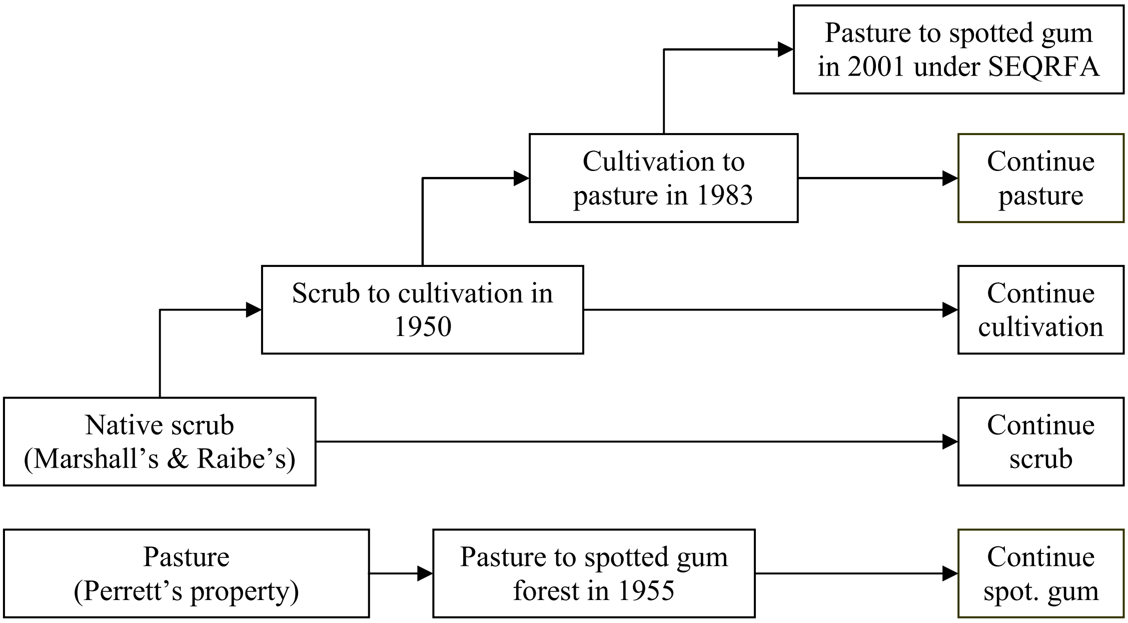


Figure-3.3 Land-use changes at Kingaroy

Fourth, access to these properties was granted and the request for formal and informal interviews with landowners was accepted. Fifth, this area met some of the overlapping research interests between the author and the Queensland Department of Natural Resources and Mine (DNRM) so as to derive more information from sharing the limited financial resources, with regards to soil testing. The next section discusses the relevant species in this research.

3.3 Species description

The land uses in the selected sites are cropping, pasture and spotted gum plantation. For economic and environmental reasons, peanuts are usually alternated with maize. Since both are summer crops, the land is fallowed for around seven months in every winter season. The main grass species in pasture and plantation on the study sites were varieties of native grasses and Rhodes grass *(Chloris gayana)* and the dominant legume species were burr medic (*Medicago polymorpha)* and Siratro *(Macroptilium atropurpureum*).

Spotted gum is one of the recommended species in the research area. Spotted gum is a trade name of the group of four species: *Corymbia maculata, Corymbia citriodora* subsp**.** *variegata*, *Corymbia citriodora* subsp**.** *citriodora*, and *Corymbia henry.* Prior to 1995 they were placed in the genus *Eucalyptus.* Hill and Johnson (1995), while making taxonomic revisions, placed them in a new genus Corymbia, series Maculatae and section Politaria under the Family Myrtaceae. Politaria is derived from the Latin word *politus,* which means made smooth or polished, as all species under politaria have smooth decorticating bark throughout (Asnate *et al.,* 2001). *Corumbia variegata*, the species of concern in the research site, has more frost resistant capacity than others and is most popularly known by the common name of spotted gum (Larmour *et al.,* 2000). The detail description of peanuts, maize, grasses, legumes and spotted gum is given in Appendix J (at the end of thesis)

3.4 Research methods

This section develops the methods to address the specific research questions discussed in chapter one. After conceptualising the research idea, there were a series of visits and meetings, that helped the researcher to become familiar with the study region and production and to build rapport with landholders and other key stakeholders. These include officers from DNRM, DPI&F and Gympie Forest Institute. The visits were critical for sharing, discussing, re-shaping and screening the research issues and for searching and short listing the potential research sites.

3.4.1 Estimating and predicting soil carbon quantities

This section describes the methods for the soil sampling and analysis and prediction of long-term soil carbon trends in different land use systems.

3.4.1.1 Preliminary soil analysis for site selection

In South Burnett, soil types vary even within a short distance. Therefore, a detailed site investigation was done to confirm that any changes in soil carbon attributes among the land uses were due to changes in land use rather than natural variation. On 2nd February 2005, the research team (including soil experts)[5] visited the sites for preliminary soil analysis. The team took several soil cores by soil augers (in scrublands and native forest) and by a vehicle mounted hydraulically operated soil sampling rig machine in other land use types. Part of the sample from each core was tested in the field for soil pH (using pH Kit, indicators and colour charts), and hue, value and chroma (using Munsell Soil Colour Chart) and soil texture (Ribon

[5] The team included soil scientists Nicole Mathers and Ben Harms from the *Department of Natural Resources and Mines* and Geoff Cockfield from the University of Southern Queensland

Method). The rest of the sample of each core was brought to the Brisbane lab to measure particle size, pH and electric conductivity (EC) analysis. Sites for in-depth soil sampling and analysis were selected on the basis of field and lab tests. All the selected sites were across the one slope and as close to each other as possible, given the spatial distribution of the required land uses. The mature spotted gum was far from other sites. However, the climatic and edaphic properties of the mature spotted gum site verified that the site could be quite comparable.

3.4.1.2 Soil sampling

For soil sampling and analysis (see Figure 3.4) following guidelines were adopted: (1) Technical Report Number 14 from the Australian Greenhouse Office (McKenzie *et al.,* 2000), (2) the Australian Laboratory Handbook (Rayment, 1992) and the Soil Physical Measurement and (3) Interpretation for Land Evaluation from CSIRO (McKenzie *et al.,* 2002). In order to capture the variance within a land use type, several replicates should be used. The required number of replicates can be obtained using a formula, but with even in a small variance, samples sizes are often larger than people can afford (Rayment, 1992; McKenzie *et al.,* 2000).

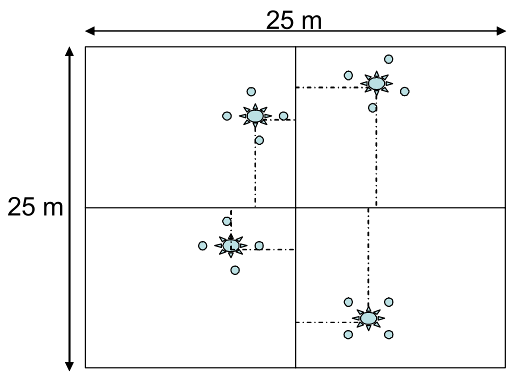


Figure 3.4 Field soil sampling layout

The number of required replicates in each land use depends mainly on three factors: cultivation practices, lime application rate and species composition (Rayment, 1992). The preliminary field test and lab analysis found that there was a reasonable homogeneity of soil attributes within each land use. From informal interviews with landowners it was found that the cultivation practices and amount of lime application in different parts of the same land use type were almost identical. In the case of scrubland, more than 90% of trees and shrubs were of the same species. Similarly, most of trees in the mature spotted gum forest were of *Corymbia citriodora* *variegata.* Thus, four replicates are enough to capture the variability within each land use type (Figure 3.4). Financial limitations of the study had also played some role in this conclusion.

Soil samples were taken using a 44.23 mm soil coring tube driven by a hydraulically operated soil rig. However, in the native scrub a hand auger was used because the vegetation was too dense for access with the soil rig. Each plot was divided into four quadrats and within each quadrat a sampling point was randomly located (Figure 3.4). At each sampling point, one core was taken to 110 cm soil depth, and then four adjacent cores were taken to 30 cm. Each main core was divided into 0-5, 5-10, 10-20, 20-30, 30-50, 50-70, 70-90 and 90-110 cm depths and bagged in the field. The smaller cores were divided into 0-5, 5-10, 10-20, and 20-30 cm depths and bulked with the main core samples.

3.4.1.3 Surface litter and particulate organic matter sampling

In order to sample surface litter and particulate organic matter (POM), a 5 m radius plot was marked from the central point of the 25 m × 25 m soil plot. At three points within the plot, where litter was ranked light, medium or heavy, two quadrats of 50 cm × 50 cm were selected randomly and the litter collected in paper bags. The area of each litter type was also estimated. Surface litter was collected and weighed in the field using a calibrated spring balance and bucket. The fresh weight of surface litter per ha was calculated as follows:

$$\text{Fresh weight (kg ha}^{-1}) = \sum (A_i \times W_i \times 20{,}000) \quad \ldots\ldots 1$$

where ‘A’ is the fraction of area (if 50% then use 0.5) and ‘W’ is fresh weight of surface litter (kg) of two quadrats from a given surface litter type (i).

All litter materials were again weighed in the laboratory, both fresh and oven-dried. In some areas, particularly the native scrub and mature spotted gum forest, partially decomposed litter was discovered between the surface litter layer and the soil and termed particulate organic matter (POM). The same procedure used to sample surface litter was also used for the POM samples.

3.4.1.4 Chemical analysis

All samples (soil, surface litter and particulate organic matter) from all land uses studied were air-dried, while the oven-dry mass was determined after drying at 105°C. The soil was sieved using a 2-mm sieve, stones and roots were separated and their mass recorded. Sub-samples of the soil and litter samples were fine-ground for soil carbon and delta (δ) ^{13}C analysis. Total carbon and ^{13}C natural abundance ($\delta^{13}C$) of soils, litter and POM were determined using an Isoprime isotope ratio mass spectrometer (IRMS) coupled to a Eurovector elemental analyser (Isoprime-EuroEA 3000) with a 10% replication. The basic principle of elemental analyser (continuous flow) IRMS is given in Fig-3.5. Samples containing approximately 50 μg N were weighed into 8 × 5 mm tin (Sn) capsules and analysed against a known set of standards.

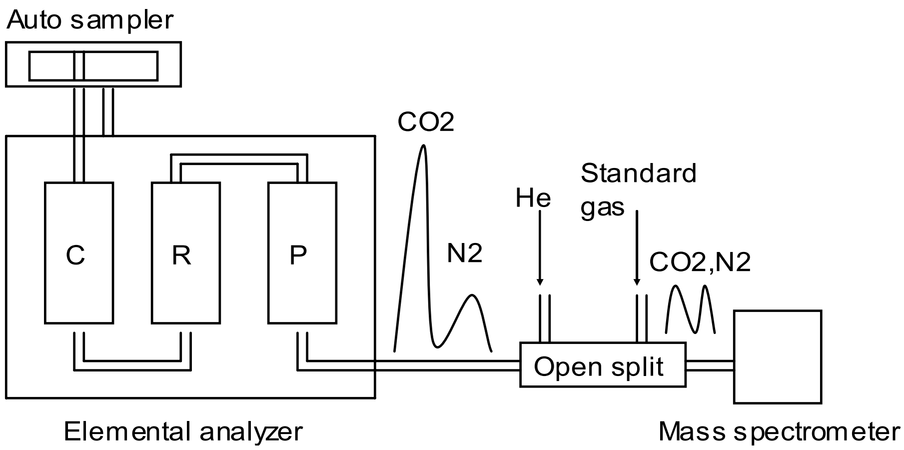


Figure 3.5 Principle of elemental analyser (continuous flow) IRMS (adopted from Glaser, 2005).

Samples were dropped from the auto sampler into the combustion furnace (C), nitrous oxides were reduced to nitrogen in the reduction furnaces (R), and molecular sieving (P) reduced the CO_2, and both gases reached the isotope ratio mass spectrometry (IRMS). The reaction products were separated by gas chromatography to give total carbon together with stable isotope ratios (see Zhihong *et al.,* 2003; Saffigna *et al.,* 2004 for detail). The isotope ratios were expressed using the 'delta' notation (δ), with units of per mil or parts per thousand (‰), relative to the marine limestone fossil Pee Dee Belemnite (as described in Craig, 1953) for $\delta^{13}C$, using the following relationship:

$\delta^{13}C(‰) = (R_{sample} / R_{standard} - 1) \times 1000$……………………….….2

where R is the molar ratio of the heavy to light isotope (i.e. $^{13}C/^{12}C$) of the sample or standard (Ehleringer *et al.* 2000).

The next section discuss the ways of estimation of soil carbon amount.

3.4.1.5 Calculation of soil C stocks

The amount of soil organic carbon (A, in g m^{-2}) was calculated as follows (Garten, 2002):

$A = B \times C \times D$…………………………….................................3

where 'B' is the bulk density of soil (kg m^{-3}), 'C' is the soil carbon concentration (g kg^{-1} soil) and 'D' is the soil depth in metres.

The cumulative soil carbon ha^{-1} and percentage of soil carbon of all land use systems was determined and compared. However, because there were differences in bulk density between land-uses, soil carbon comparisons based on cumulative depth may be misleading. If soil carbon stocks are given in t ha^{-1} to a certain depth across different land uses, then any apparent increase in soil carbon in more compacted soil (high bulk density soil) could be due to the greater mass of soil sampled (Murty *et al*., 2002). If results are expressed as a percentage basis of soil carbon, an opposite bias could be encountered (Murty *et al.*, 2002).

For accuracy in comparing land use effects on soil carbon, all calculations were also referred to a fixed dry mass of soil per unit ground area as recommended by Gifford and Roderick (2003). As an alternative to the standard depth of 30 cm, soil carbon in the top 0.4 t dry soil m^{-2} is adopted. As an alternative to the standard 1 m soil depth, the top 1.2 t m^{-2} of dry soil is suggested. Similarly, soil carbon to 0.4 t m^{-2} and 1.2 t m^{-2} was calculated from the cumulative soil carbon and soil mass relationships by graph interpolation. In order to run the RothC soil carbon model and to predict long-term changes in soil carbon, the cumulative soil carbon stocks to 1.2 t (dry soil) m^{-2} were used.

3.4.1.6 Estimation of long-term soil carbon trend

The soil carbon content under the native scrub was assumed to have been at equilibrium since 1950. The trendline for soil carbon under cultivation since 1950 was developed from current soil carbon contents of the native scrub and cultivation. The validity of this trendline was tested by running the RothC model, as this is the most important trendline on which all other trendlines are dependent (as in Coleman and Jenkinsen, 1999). In order to run the model, the current soil carbon content of the native scrub was taken as an estimate of the soil carbon content under the cultivated area in 1950. Average weather data (mean monthly rainfall, mean monthly open pan evaporation and mean monthly air temperature) for Kingaroy from 1968 to 2003 was used in the model. Regarding the land management data for a scrub to peanut cropping transformation, two scenarios were developed: (a) all months covered by vegetation until 1950; and (b) five months per year covered by vegetation when cultivation was in place.

Monthly input of plant residues in the cultivated area was assumed to be zero, as there was no practice of leaving residues on the ground. Similarly, the monthly input of farmyard manure (FYM) was assumed to be zero, as there was no practice of FYM application. The native scrub was allocated a clay content of 33%, and the ratio of decomposable to resistant plant material was 1.44. The soil carbon content of the native scrub was assumed to be constant for the last 20 years (Coleman and Jenkinsen, 1999), so the total soil carbon content was divided by 20 to get an estimate of the annual plant residue carbon inputs (228.6/20 = 11.4 t C ha^{-1}) in the native scrub. After that, the monthly incoming plant residue was estimated to be 11.4/12 = 0.95 t C ha^{-1} $month^{-1}$. The accurate monthly input of plant residues, radiocarbon content (^{14}C), inert organic matter and biomass carbon for 1950 were estimated by running the RothC model in reverse mode. The initial data was then replaced by the model-generated data (1.26 t C $month^{-1}$) for further modelling (for detail see Coleman and Jenkinsen, 1999).

Using the cultivation trendline, soil carbon content in the pasture for 1983 was estimated (for reference see Figure 3-3). This value and the measured soil carbon content for 2005 under pasture was used to develop a soil carbon trendline for pasture, which in turn was used to estimate the soil carbon content of the spotted gum plantation in 2001 when it was established. The soil carbon content of the mature spotted gum forest was assumed to be the soil carbon content of the plantation at 50 years of age[6]. The soil carbon content of the mature spotted gum forest and the estimated soil carbon content of the plantation in 2001 (from the trendline of pasture) were used to develop the long-term soil carbon predictions for spotted gum plantations.

Carbon dioxide (CO_2) emission rates after land-use change from native scrub to cultivation could initially be high, declining over time (Dalal and Carter 2000). Conversely, land use change from pasture to plantation can be expected to increase soil carbon content, slowly (even decreasing immediately after plantation) at first and then at a faster rate as time progresses. Therefore, the carbon trendlines with land use change could be a slightly exponential line, not linear. Therefore, two trendlines were developed: one from extrapolation of past measured data and the other from the RothC model.

Finally, statistical tests were undertaken. The STATISTICA software was used for the soil data analysis and one-way ANOVA. Significant tests are given in terms of p-values wherever necessary. Two appropriate statistical tests (t-test and correlation test) were applied to test whether there was any statistically significant difference between the extrapolated and RothC predicted soil carbon trend lines within the same land use system. However, since the plantation had just started in 2001 and the objective was to compare this plantation with pasture and cultivation, the RothC predicted soil carbon values for 2001 to 2035 were used for comparison.

3.4.2 Estimation of grass and legumes biomass

This includes the biomass of grass and legumes species in pasture and a four year plantation. In order to make it economically attractive, the plantation was intentionally developed as a silvipastoral system, a type of agroforestry system which integrates the woody perennials with livestock production. Therefore, the plantation contains varieties of grasses and legumes.

[6] It is acknowledge that the soil carbon under the MSG could not accurately reflect the plantations over 50 years, as the agricultural soil may be so degraded it could never return to its original condition. This is thoroughly discussed at the end of Chapter 4.

Grass was quite homogenous in distribution in each land use. Therefore, there was no need for stratification. Biomass sampling of grasses was done in the same sample plot where soil sampling was done. In each quadrant (12.5 m × 12.5 m) of the main sample plot (25 m × 25 m), three points (coordinates) were selected randomly by throwing a 50 cm × 50 cm steel rod. Three major grass species and legumes were recorded. All the grasses and legumes were dug out very carefully and were separated from the soils. Both roots and shoots were washed, dried and weighed. The weight of legume species was taken separately. A sample of each species was taken to the lab to identify the species (in case of unknown species), and to measure the fresh weight dry weight ratio and carbon density.

Biomass content was calculated by using sampling area expansion factors. For example, in pasture, samples were taken at 12 spots so the sampling area expansion factor for one ha was ($10,000m^2/12 \times 0.25m^2=3,333.33$) about 3,333. The same method followed for the chemical analysis of soil, surface litter and POM, and was also used for the estimation of carbon content of grasses and legumes.

3.4.3 Estimation of nitrous oxide (N_2O) emissions

Nitrous oxide (N_2O) contributes 6.3% of Australia's greenhouse gases emissions, however, it is increasing rapidly as its contribution was only 4.3% in 1990 (Mitchell and Skjemstad, 2004). In the context of land use systems, N_2O emissions occur from general land use, nitrogen fertiliser, soil disturbance, animal waste and biologically fixed nitrogen (Dalal *et al.,* 2003).

Micrometerological techniques are used for the continuous measurement of methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O), but are expensive. Moreover, it requires skill to analyse and interpret the data, so they are not deployed widely (Mitchell and Skjemstad, 2004). Similarly, DNDC and DAYCENT models could be used to simulate N_2O production from soil after parameterisation with local data (Dalal *et al,* 2003). The latest version of DNDC has better support for a grazing system, but it has not been tested (Andrew *et al.,* 2003). EcoModel, a biophysical agricultural model, is being developed jointly by Australia and New Zealand (Johnson *et al.,* 2003). This model may give daily and annual summaries of all the principle components including CH_4 and N_2O emissions, and nitrate leaching and ammonia volatilisation, which could contribute further off-farm emissions (Johnson *et al.,* 2003).

Considering the limited time, research funds and research aim, the most relevant N_2O emissions value from past studies were borrowed. As the major objective was economic analysis, the minor variations in emission would have been captured by sensitivity and scenario analysis. While searching the literature, the amount of N_2O emissions found were significantly different in different land uses and also varied significantly within the same land use in different management conditions (Table 3.1).

Table 3.1 Nitrous oxide emissions from different land uses

Land use	N-fertiliser ha^{-1}	Emission of N $kgNha^{-1}yr^{-1}$	Sources
Unfertilised pasture, Northern Hemisphere	NA	1-2	Bouwmann, 1994
Dairy pasture NSW	0-200	6-11	Eckward *et al*., 2001
Unfertilised pasture, Australia	NA	0-5	Barton *et al.,* 1999 cited in Eckward *et al.,* 2000
Fertilised pasture, Australia		17-25	
Legume based pasture, Australia		6-60	Ellington, 1986 cited in Eckward *et al.,* 2000
Tropical rainforest[1]	NA	1.7	Bouwman, 1998
Northeast QLD forest	NA	<1.8	Kiese & Butterbach 2002
Northeast QLD rainforest[2]	NA	3.2 to 6.7	Dalal *et al.,* 2003

[1] Median value
[2] Three months of wet season in a year was assumed to predict the value

Considering the conditions applied in the research sites, the following nitrogen emissions figures in different land uses have been used. However, it does not cover nitrogen emission due to soil disturbance factors, nitrogen fertiliser, cattle excretion and biologically fixed nitrogen, which are described separately below.

(i) Pastureland: 2.5 kg N $ha^{-1}yr^{-1}$ (average of 0-5 kg, Barton *et al.,* 1999 cited in Eckward *et al.,* 2000). Since the area is legume based fertilised pasture, initially there was a tendency towards fertilised or legume based pasture values, but on reflection it was decided to use those values as the amount of N_2O emissions from nitrogen fertiliser and biologically fixed nitrogen was estimated separately.

(ii) Plantations, scrubland and native forest: 2.52 kg N $ha^{-1}yr^{-1}$, an average value from Bouwman (1998), Kiese and Butterbach (2002) and Dalal *et al.* (2003).

3.4.3.1 Estimation of Nitrous Oxide (N_2O) emissions due to soil disturbance

The following N_2O emissions factors were used for estimating N_2O emissions due to soil disturbance (Nussey, 2005):

- Pasture land: 0.29 $kgNha^{-1}$ in every eight years (soils disturbed in every eight years)
- Peanut cropping land: 0.29 kg $Nha^{-1}yr^{-1}$ (soils disturbed in each year)
- Plantation: 0.29 $kgNha^{-1}$ in every 34 years[7] (soils disturbed in every 34 years)

3.4.3.2 Estimation of N_2O emissions due to animal urine and faeces

Animal urine and faeces are source of nitrous oxide. Rotational grazing has been practiced in the pastureland and plantations. We could estimate total N_2O emissions on faeces on the basis of the amount of grass taken by animals and their digestibility. However, it is too complicated to find the digestibility of so many different varieties of grasses and legumes. Therefore, we recorded the types and number of cattle grazed, and their grazing days and seasons in that particular land use from the grazing calendar. The amount of nitrogen excreted by different types of cattle in different seasons in urine and faeces was taken from Nussey (2005) and the total amount of nitrogen excreted by cattle during the grazing time was calculated from those figures (details of calculation are in chapter 5).

3.4.3.3 Amount of biological nitrogen fixation in legumes

Cropping land, pastureland and plantation contain legumes. Peanuts are a legume crop in cultivation and can fix atmospheric nitrogen nodulating with diverse strains of bradyrhizobium species. There are several studies, discussed in the literature review, about the amount of biological nitrogen fixation (BNF) by peanuts in Australia (Peoples *et al.,* 1992; Bell *et al.*, 1994; Rochester *et al.,* 1998).

The most applicable in our case is the Peoples *et al.* (1992) study in Kingaroy (151^o 50'E., 26^o, 33' S). They studied for two years and estimated the amount of BFN by ^{15}N natural abundance procedure using a non-nodulating peanut genotype as a non-nitrogen fixing reference plant. There were several treatments in terms of water use

[7] As per the findings of the research 34 years is considered the optimal rotation of plantation incorporating both timber and carbon benefits.

and rotational crops. Because of rain-fed cropping, only the 1987/88 year data were applicable to this research. However, none of the treatments was exactly matching with this case, as there was a rotation of summer peanut ─ winter fallow ─ summer maize ─ winter fallow ─ summer peanut. The 'continuous annual peanut with winter fallow' treatment has a lower amount of BFN (32 kg ha^{-1}) compared to the 'summer peanuts ─ 2 summer maize ─ summer peanut' treatment (57 kg ha^{-1}). This means, the amount of BFN in the peanuts could be in between the two values. Therefore, for the purpose of the analysis an average of both figures 44.5 $kgNha^{-1}$ {(32+57)/2} was used. In the research site, all residues were removed for cattle feeds. The dung of cattle could take a few months to a few years to decompose. Therefore, the greenhouse gases could release slowly in the atmosphere. However, as with other land use products, it was assumed that the N_2O would release into the atmosphere immediately after harvesting.

Pasture and plantation contain Burr Medic Siratro and Wincassia legumes. There are some studies about the BFN in pasture (Henzell *et al.,* 1967; Armstrong *et al.,* 1999), but Armstrong *et al.* (1999) and Bell *et al.* (1994) are the most applicable. Armstrong *et al.* (1999) studied the dry matter production and nitrogen fixation of several ley legumes including Siratro for four seasons (1994-97) at Emerald (23° 29' S, 148° 09'E, alt 190m), Central Queensland. They used grain sorghum as a non-legume control crop. Siratro accumulated 16160 kg ha^{-1} dry matter and fixed 176 kg N ha^{-1} over the four years.

Therefore, there were two options for estimating BNF in pasture legumes. First, estimating dry matter and then converting it into the BFN following Armstrong *et al.* (1999) (16160 kg dry matter = 176 kg N). Second, following the regression equation (fixed N= $0.015 \times DM_{EA} - 10.9$) developed by Bell *et al.* (1994). The first method is only applicable to Siratro and cannot be applied to other legumes found in the pasture. Therefore, the second option was preferred. For that, energy adjusted dry matter (DM_{EA}) of legumes was necessary, which was calculated as Equation 4 (Vertregt and De Vries, 1987).

$$PVI_{dm}=5.39\ C_{dm} + 0.80\ ASH_{dm} - 1191 \quad \ldots\ldots\ldots\ldots 4$$

where 'PVI_{dm}' is the quantity of glucose required (gram) to produce one kg of end product or biosynthesis (on the dry weight basis), 'C_{dm}' is the mass of carbon in gram per kg of dry matter and 'ASH_{dm}' is the mass of ash in gm per kg of dry matter.

The amount of carbon (g/kg of dry matter) and ash (g/kg of dry matter estimated using 550°C drying temperature) of each specimen was estimated. Then, the above equation was used to find out the PVI_{dm} (gm/kg of dry matter). The total PVI_{dm} was used for an energy adjusted dry matter (total) and then the Bell *et al.* (1994) formula was applied to find the BFN for each pasture legume.

3.4.4 Estimation of methane (CH_4) emissions

The literature discussed in chapter two reveals that there are several studies which may be adopted for the estimation of CH_4 emission from cattle. However, there are several limitations. For instance Blaxter and Clapperton (1965) predictive equation. needs the dry matter digestibility of the feed at the maintenance level of feed intake and also the level of feeding as a multiple of the maintenance level of feed intake. This was difficult to get, as the pasture had different varieties of grasses and legumes. Similarly, McCrabb and Hunter (1999) would have followed as their research species, Rhodes grass, which was one of the major species in the site. However, the pasture was a mixture of several grasses, which made the case more complicated to estimate digestible organic matter in the grasses.

A major complexity in this case was posed by the unique system of grazing. Cattle were grazed on a rotational basis. As a result, they were grazed for a short period of time during the year in the pasture and plantation paddock. As methane is produced by cattle not by the grasses as such, calculating methane on the basis of dry matter and their digestibility was quite unrealistic, and there would be a chance of overestimation. Therefore, the types and number of cattle grazed were recorded, and their grazing days and seasons in pasture and plantation from the grazing calendar. The amount of daily methane emissions by different types of cattle in different seasons were taken from Nussey (2005) and then the total amount of methane emissions by cattle during the grazing time was calculated from those figures.

3.4.5 Estimation of greenhouse gas emissions from primary farm inputs

The primary farm inputs include agrochemicals (fertilisers, pesticides, herbicides, fungicides and insecticides), fuels and machines. For all major production processes creating the inputs for forestry, pasture and agriculture, greenhouse gas emissions that released directly, or as a result of energy use, were calculated. In order to make the methods clear, this section is divided into four subsections.

3.4.5.1 Emissions of major greenhouse gases for the production of one KWhr electricity

The estimation of emissions from energy use is based on coal as the source of energy. About 0.41 kg CO_2 is emitted for each kilo watt hour (KWhr) of electricity production from coal (URS, 2001). While producing electricity from coal, other greenhouse gases (methane and nitrous oxides) produce as well. The amount of methane and nitrous oxides were calculated on the basis of the total amount of these gases and the electricity produced in Australia from black coal, a major type of coal in Australia (AGO, 2002). The calculation shows that around 0.411 kg of carbon dioxide equivalent (CO_2e) greenhouse gases are emitted into the atmosphere while producing one KWhr of energy (Table 3.2).

Table 3.2 Emissions of major greenhouse gases for the production of one KWhr electricity

Activity	CO_2	CH_4	N_2O	CO_2e
Emissions of GHGs (Giga gram) while producing 1193 PJ of electricity[1]	-	1.05	0.98	
Emissions (gram) while producing 1KWh of electricity	410[a]	0.0032	0.003	
Carbon dioxide equivalent (CO_2e) while producing 1KWh of electricity	410	0.067	0.93	0.411kg

[1] AGO (2002), [a] URS (2001)
Note: One Kilo watt hour (KWhr) = 3,600 KJ, global warming impact of 1 kg of N_2O=310 kg CO_2 and 1 kg of CH_4=21 kg CO_2.

3.4.5.2 Emission from farm machinery

On average, approximately 83.7 MJ of energy is required to produce a kilo of farm machinary (Stout, 1990). Since 1 KWhr = 3.6 MJ, 23.25 (83.7/3.6) KWhrs are required for each of those machinery kilos. Hence, the CO_2e greenhouse gas emitted into the atmosphere while producing each kg of machinery must be 9.6 kg (0.411 x 23.25). Some greenhouse gases would be emitted while transporting the machines but it is negligible on a per ha basis and is not considered in this study.

Data for peanut and maize cropping machinery operations were taken from state agriculture agency notes (DPI&F, 2000) and other sources (Harden, 2004; Harris, 2004; Peanut Company of Australia, 2005) and verified by the relevant landholders and state extension officers. Pasture establishment data were taken from a landholder's interview, data for plantations came from the local state agency plantations extension officer. The working life span of machineries and accessory equipment were taken from Harris (2004) and the weight of machines and accessories were taken from production companies (John Deere and AMADAS). The fraction of time a particular machine used for a particular operation was derived from crop production publications noted earlier and independently verified by landholders and extension officers. From that information, the following equation was developed to estimate the greenhouse gas emissions for using particular machinery for particular land use.

Greenhouse gas emission ($kgCO_2eha^{-1}$) = weight of machine (kg) x 9.6 $kgCO_2e\ kg^{-1}$ x fraction of lifespan of that machine used for a hectare of that land use……………………………………………………….….5

3.4.5.3 Production, packing, transportation and application of agrochemicals

Production, packing, transportation and application of agrochemicals emits some greenhouse gases. In later stage cropping areas, input requirements increase, especially fertiliser and plant protection chemicals. The Red Ferrosol soils at the study sites have been farmed for at least 50 years and so nitrogen (N) fertiliser is used to boost crops and some pastures. Relative to other fertilisers such as phosphorus and potassium, N requires more energy for its production (Helsel, 1992; Vlek *et al.,* 2003). Furthermore, crops such as peanuts require considerable crop protection from disease and pests and more energy is required in the production of insecticides, herbicides and fungicides on a per unit basis than any other input into agriculture (Helsel, 1992; Government of State of Sao Paulo, 2004). Hence, an increase in agrochemical inputs is likely to mean an increase in emissions at some point in the production chain.

There are two common procedures for estimating greenhouse gas emissions from agrochemical inputs: estimating the amount of energy for all the processes of production, packing, transportation and application; and then estimating greenhouse gas emissions from that energy (3.6 MJ=1 KWhr=0.411kgCO_2e GHGs); or estimating the global warming potential of each agrochemical. The Government of the State of Sao Paulo (2004) has estimated the amount of energy required for producing different agrochemicals in Brazil. Mudahar and Hignett (1987) estimated the energy requirement for production, packing, transportation and applications of fertilisers. Shapouri *et al.* (1995) estimated the energy required for the production of fertilisers and pesticides in USA. Kim and Dale (2003) independently estimated the amount of energy required for the production, packing, transportation and application of fertilisers.

However, the estimation of net greenhouse gas emissions from these studies seemed quite difficult. Because some chemical reactions are exothermic, they release energy during the reaction. Since there is no information about how much energy was released during each reaction, it is hard to find the actual amount of external energy needed during their production. Although the total energy figure gives some clue about the relative emissions of different agrochemicals, it was not appropriate to use as such. Therefore, the second option, the global warming potential of all agrochemicals was preferred for this study.

Kim and Dale (2003) estimated the global warming impact value (gm CO_2 equivalent kg^{-1}) of most of the agrochemicals (Table 3.3). The global warming impact value (GWIV) included all three greenhouse gases (CO_2, CH_4 and N_2O) and their impact due to their production, packing, transportation and application. Not only this, GWIV also includes the emission of N_2O during the process of denitrification after applying nitrogen fertilisers (Kim and Dale, 2003). As it covers broad impact, we used these values for the estimation of emission by the agrochemicals. The GWIV for insecticides and fungicides is not available in their estimation. For them, I used the value of pesticides as it covers both insecticides and fungicides. In the case of mixed fertiliser, the value of the main fertiliser was used, if there was only one element among the N, P and K, and if there were two main elements an average was taken.

Table 3.3 Global warming impact (GWI) (gm CO_2 equivalent kg^{-1}) of agrochemicals

Chemicals	GWI[1]	Chemicals	GWI	Chemicals	GWI
Nitrogen	3270	Herbicides	22800	Lime	42.1
Phosphorus	1340	Pesticides	24500		
Potassium	642	Boron	335		

Source: Kim and Dale (2003)

The amount of different types of agrochemicals used in peanut and maize cropping were taken from the Crop Management Notes (DPI&F, 2000) and were then independently verified and qualified where necessary by landholders and experts (Mike Bell[8] and Peter Hatfield[9]). This information on plantation and pasture was taken from different literature and later verified by the plantation officer and landowner. The total amount of each type of agrochemical used and the GWI (gm CO_2 equivalent kg^{-1}) of each kg of agrochemical was used to find the total amount of greenhouse gas emissions due to the use of agrochemicals.

3.4.5.4 Production, transportation and combustion of Fuel

There are a number of studies of the production, transportation and combustion of petroleum products. In the Australian context, AGO (2001), Beer *et al.* (2002) and Nussey (2005) estimated the total carbon emissions during the production and combustion of fossil fuel. According to Bear *et al.* (2002), each litre of diesel produces 0.45 kg and 2.59 kg of CO_2 during production and combustion, respectively. The respective values estimated by AGO (2001) are 0.46 and 2.69 kg. Combustion of fossil fuel also emits methane and nitrous oxide. Nussey (2005) estimated that each litre of diesel combustion gives off 2.66 kg CO_2, 0.000383 kg methane (0.00802kg CO_2e) and 0.0007645 kg nitrous oxide (0.237kg CO_2e). Since all studies are quite reliable the average value {(0.45+0.46)/2=0.455} of two studies (AGO, 2001; Beer *et al.,* 2002) was used for the estimation of greenhouse gas emissions during the production of diesel and the average of all three studies was taken for the estimation of CO_2 emissions during combustions of diesel {(2.59+2.69+2.66)/3=2.65kg L^{-1}). Therefore, the total greenhouse gases emissions during the production and combustion of one litre of diesel is 3.35 kgCO_2L^{-1} (0.455+2.65+0.00802+0.237=3.35kgCO_2 L^{-1}).

[8] An expert working at Department of Primary Industries, Kingaroy
[9] An expert agronomist at Kingaroy

Some amount of greenhouse gas emissions also occurred during the transportation of fuels, but this would be negligible if we consider transportation from the petrol station at Kingaroy to the farm. For example, if we use a 160 KW power tanker for 1 hour (round trip) with 17,000L capacity the total fuel consumption per litre for transportation would be around 0.0023L (160*0.25/17000), which would produce around 0.008 kgCO_2e. Therefore, for the purpose of this study greenhouse gas emissions due to transportation of fuel was not considered.

The amount of fuel consumed in the establishment, production, harvesting and transportation of all land use products of different land use types was derived from Harries (2004) and was then independently verified and qualified where necessary by landholders and extension officials. The total amount of fuel consumption and greenhouse gas emissions from each litre of fuel was used to find the total amount of greenhouse gas emissions due to the use of fuel.

3.4.6 Assessing the optimum spacing for spotted gum plantation

The following sections discuss about the data sources and growth modelling procedures.

3.4.6.1 Data sources

The age of the plantation in the study site was around four years. Estimation of the optimum spacing (density) level from that plantation data was not possible. Warril View Experiment Site (WVES), near Ipswich, was the oldest spotted gum experimental site in South East Queensland[10]. The soil of the WVES was of lower fertility than the Taabinga plantation, while the rainfall was bit higher than in the study site. Therefore, we assumed that the optimum spacing level of WVES approximated the optimum spacing level of the study site.

The spotted gum in the experimental site was planted on 31st May 1990 at five different spacing levels— ‘A’ (11.3 m x 11.3 m=78 trees ha^{-1}), ‘B’ (7.4 m x 7.4 m =182 trees ha^{-1}), ‘C’ (5.4 m x 5.4 m=343 trees ha^{-1}), ‘D’ (3.6 m x 3.6 m =771 trees ha^{-1}) and ‘E’ (2.9 m x 2.9 m=1189 trees ha^{-1}). Each treatment had three replicates. No artificial thinning was done but natural thinning has probably been occurring in all

[10] Personal communication with David Taylor, Senior Research Scientist, Native Forest Horticulture and Forestry Science, Department of Primary Industries and Fisheries, Gympie, Queensland, Australia

spacing levels except spacing level 'A', where there was no mortality. The number of trees at the last measurement (after 15.16 years) at spacing level 'B', 'C', 'D' and 'E' was reduced to 161 (by 21), 302 (by 41), 724 (by 47) and 1093 (by 97) trees per hectare, respectively.

Diameter at breast height (DBH at 130 cm) and height of all trees were measured at the age of 0.07, 0.51, 1.01, 1.51, 2.01, 3.12, 4.02, 5, 6.02, 7, 8.04, 11.01, and 15.16 years. However, because of the relatively small height there was no DBH measured until the age of 4.02 years. A 1.3 m stick and diameter tape was used for the DBH measurement. Before taking DBH, all dead bark was removed. A Vertex Hypsometer was used for height measurement and a Husky Hunter 16 was used for data entry[11].

3.4.6.2 Data analyses and growth models development

The mean DBH and mean height of all trees and the 50 largest trees ha^{-1} in different spacing levels were compared. Since the main objective of plantation in the research site was to maximise merchantable log volume in the minimum time frame, a series of growth models were developed to see the merchantable log volume of each spacing level at different ages.

For the development of the growth model of this study, the Von Bertalanffy growth equation was used (a description is given in Vanclay, 1994; Williams *et al*, 1991; Fekedulegn *et al.*, 1999). As suggested by Fekedulegn *et al.* (1999) the formula can be re-written in a simple form as follows.

$$\text{DBH} = \left[b_0^{(1-b_3)} - b_1 * \exp(-b_2 * T) \right]^{1/(1-b_3)} \quad \text{.................................(6)}$$

where, DBH is the dependent growth variable, T (age of tree) is an independent variable, and 'exp' is the base of a natural logarithm. Similarly, b_0, b_1, b_2 and b_3 are regression parameters to be estimated. The b_0 refers to the asymptote or potential maximum of the response variable (DBH), b_1 is the biological constant, b_2 is the parameter governing the rate at which the DBH (or volume) approaches its potential maximum, and b_3 is the allometric constant.

[11] The researcher was involved only on the last measurement. All the other measurements were done by the Gympie Forest Research Institute, Gympie.

The regression parameters (b_0, b_1, b_2 and b_3) were determined iteratively. However, for the iteration to be initiated starting values for b_0, b_1, b_2 and b_3 were needed. Finding starting values for iteration was the most difficult part in modelling (Draper and Smith, 1981; Lei and Zhang, 2004). For the estimation of starting values Fekedulegn *et al*. (1999) was followed as they have made a useful contribution in this direction (Lei and Zhang, 2004). In order to demonstrate the procedure, the starting values for spacing level 'C' (5.4 m x 5.4 m=343 trees ha^{-1}) were calculated as follows. Time series data of age and mean DBH of spacing level 'C' is given in Table 3.4. As per a suggestion of Fekedulegn *et al.* (1999), a negligible value of DBH (0.0001 cm) for age 0.001 year was assumed, which significantly improved the predictive power of the model. The same method was applied for all spacing levels.

Table 3.4 Age and mean DBH of spacing level 'C'

Age (yr)	0.001	4.02	5.00	6.02	7.00	8.04	11.01	15.16
DBH (cm)	0.001	5.690	7.720	10.060	12.180	13.650	18.230	23.21

$b_0 = \text{MaximumDBH} = 23.21$ cm

b_3=0.5 (positive, less than 1 value assumed)

Calculation for b_1:

$$\text{DBH (at 0 yr age)} = b_0\ (1-b_1)^{1/(1-b_3)} \quad \text{...(7)}$$

DBH for '0' age is also assumed to be 0.001cm, b_0 =23.21 and b_3=0.5 then b_1= 0.9934

Calculation for B2:

$$b_2 = \frac{\{\text{DBH(last)} - \text{DBH(first)}\}/\{\text{Age(last)} - \text{Age(first)}\}}{b_0} \quad \text{..........................(8)}$$

$$b_2 = \frac{\{(23.21\ \text{cm} - 0.001\ \text{cm})/(15.16 - 0.001)\}}{23.21\ \text{cm}} = 0.06596$$

After entering these starting values for b_0, b_1, b_2 and b_3 regression parameters, the non-linear estimation module of STASTICA software was run. The model produced more appropriate values for these parameters. The starting values were replaced by the model's produced values and the same process was repeated until the lowest and constant root mean square error (RMSE) and highest value of proportion of variance were accounted for (R^2). The RMSE was used because it is easier to interpret and explain and is also the most compatible with the statistical concepts of standard deviation (Makridakis *et al*, 1998; Wilson, 2001). While doing so, the step size, convergence criterion and iteration number were adjusted until they produced the best model. The final (best) model was used to predict the DBHs. Then the DBHs were converted into volume by using the allometric equation developed for the spotted gum by Margules Poyry (1998).

$$\text{Volume } (m^3) = [\{(9.1944 * \pi * (\text{DBHcm})^2)/4\}-0.1167]/10000 \ldots\ldots\ldots (9)$$

After selecting the best spacing level among the five treatment levels, thinning scenarios were analysed for that spacing level to know which one was the most profitable option: keeping all the trees for the whole rotation or thinning some trees at some stage. In order to resolve this problem, similar analyses were repeated taking the time series data of a mean DBH of the 200 and 250 largest trees (ha^{-1}) from the optimum spacing level.

3.4.7 Assessing the optimum rotation for spotted gum plantation

The conceptual framework for the determination of both rotations is given in Figure 3.6. Optimal rotation is the age at which the trees should be cut to maximise the targeted objective. The targeted objectives could be maximising the physical volume of harvest (maximum sustainable yield or MSY), maximising the net present value of timber income (maximum economic yield (MEY) or Faustmann rotation), and maximising the present value of timber and non timber values (Hartman rotation) (Kooten *et al.,* 1995).

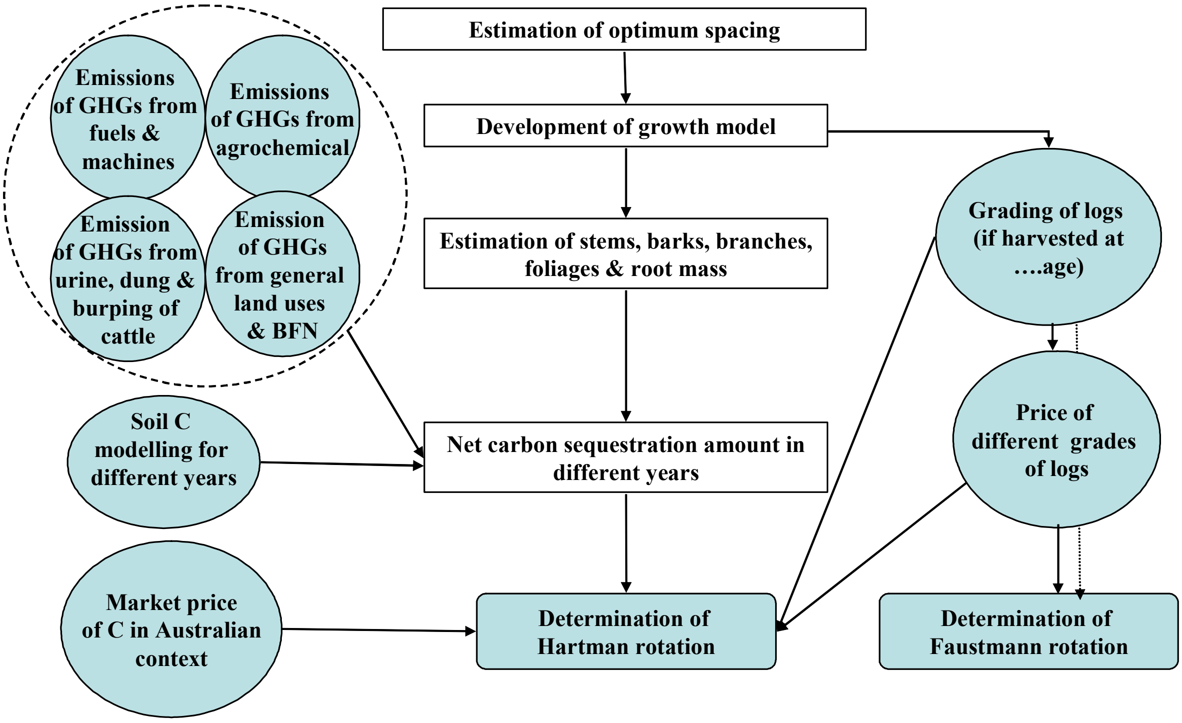


Figure 3.6 Conceptual frameworks for the determination of optimal rotation ages

Just a decade ago, carbon sequestration was considered to be a public good and there was no incentive for sequestrating carbon. Therefore, the Hartman rotation was necessary for the incorporation of carbon benefit (non-timber), as there was a big gap in the private and social optima. Recently, carbon is being traded in the market, thus, the price of carbon credit narrow down the private and the social optima[12]. Therefore, the Hartman rotation is no longer necessary and an extension of the Faustmann rotation is enough for the inclusion of carbon benefit (Diaz-Balteiro and Romero, 2003). However, since this study is for the comparison of different land uses with and without including carbon benefits, two rotations are dealt with separately. A detailed discussion of different methods and other relevant issues is given in chapter two. As discussed previously, the optimum rotation age depends on in-/decreasing the rate of soil carbon, carbon retention in standing biomass, emissions associated with primary farm inputs and different types of costs and benefits. The different steps followed for the determination of an optimal rotation are given below. The method of estimating soil carbon has already been described in earlier sections.

[12] Even if carbon credits are included, the analysis falls far short of a social analysis, because of the difference in treatment of cash flow variables in the two contexts, and because the analysis would still not take account of, for example, ecosystem services and landscape amenity benefits of forestry.

3.4.7.1 Growth model development for spotted gum in Kingaroy (research site)

Growth is a function of different factors including climatic, edaphic, genetic and management factors. While transferring the benefits from policy sites (Warril View) to research sites (Kingaroy), the author was mindful of all those factors. Therefore, as far as possible, the growth data were collected from the research site and collated with some data from nearby, which have similar climatic factor, genetic material and soil types to the research sites. The actual data from the research site and nearby sites were only up to 6.5 years age (Table 3.5), from which time producing a full rotation growth model was not possible. Moreover, these growth data would have incorporated only three factors: climatic, edaphic and genetic and do not incorporate the management factor (thinning scenario). In order to incorporate the thinning scenario the basic growth model developed for optimum spacing level at the Warril View site was used. The growth performance of trees up to 6.5 years of age from the research site was found to be better than the Warril View site. The difference in mean DBH between the Warril View site and the research site at age 3.1 was 1.8 cm (6 cm vs. 7.8 cm) and the difference increased to 2.8 cm (12 cm vs. 14.8 cm) at 6.5 years.

Table 3.5 Actual mean DBH (cm, over bark) of spotted gum at different ages (yr)

Age (yr)	DBH (cm)	Location	Soil type	Stocking no/ha^{-1}	Source
3.1	7.8	Barron block, Boonenne, 10 km south west of Kingaroy	Red Krasnozem	1111	Huth *et al.,* 2004
4.0	9.8	Marshal property, Taabinga, Kingaroy	Red Krasnozem	Largest 400	Field measurement
6.5	14.8	John Mangan's property, 12 km north Yarraman	Red Krasnozem	Largest 400	Huth *et al.,* 2004

Initially, it was thought that the divergence of mean DBH goes further at the same rate. However, after discussion with an expert (N. Halpin, 2006, pers. com., 2 February) it was concluded that the higher DBH in a younger stand at the research site may be due to the relatively better soil, but the same pattern would not follow in the long run, as the rainfall at the research site was slightly lower than at the policy site. Since the soil moisture is the major limiting factor in the research site, in order to be more realistic, the constant difference of 2.8 cm after the age of 6.5 years was assumed. After having the time series data of age and mean DBH, the growth model of spotted gum was developed for the research site following the same procedures as described in earlier sections.

3.4.7.2 Estimation of underbark DBH, tapering factor and stem volume

In order to estimate the underbark volume, and biomass of stem, bark, foliage and branches, the underbark DBH was needed. Margules Poyry (1998) did an intensive survey of 101 different sizes of spotted gum trees and found the average bark thickness of 0.5 cm. Therefore, one cm was deducted from the overbark DBH to get the underbark DBH. After that, Equation 10 was used to get the underbark volume of stem from the underbark DBH.

$$\text{Volume (m}^3\text{)} = [\{(9.1944 * \pi * (\text{DBH cm})^2)/4\}-0.1167]/10000 \ldots(10)$$

Equation 10 estimates the merchantable volume of log up to a 10 cm top diameter. However, discussion with Wondai Sawmill staff[13] (a sawmill in the region), where more than 90% sawing is of spotted gum, found that they were buying logs only up to 25cm top (small end) diameter. Processing of logs below that size would not be profitable due to high processing costs. Therefore, the volume of logs between 10 and 25cm diameter need to be deducted from the above estimated volume. For this, we took both end diameters and length of 45 spotted gum log between 12.5cm and 29cm diameter (Annex Table C-2). Our assumption of taking these sizes of log was that there would be a significant difference in the tapering factor of larger (bottom part) and smaller (upper part) log. Our analysis shows that the tapering of spotted gum log from 10 to 25cm diameter is around 0.97 cm per metre. It means, around 0.37 cubic metres of log between 10 and 25 cm diameter would be lost from each tree of harvestable age. This was deducted from the above volume to get a saleable volume of spotted gum.

3.4.7.3 Estimation of stem, bark, foliage, branches and under ground biomass and carbon mass

The most sensitive factor for the biomass of a tree is the density of the stem (Polglase *et al*, 2004), which is calculated by dividing the oven-dry mass of a specimen by its green volume. Initially, it was believed that the density depends on the size (DBH) of

[13] Personal communication with Mr Ron Bergman (Site Manager) and Jason Worling (Training Officer) on 1st of June 2006.

the given species, but later it was found that it is more strongly correlated with the age than size (Raymond *et al*., 1998; Borough 1993 cited in Polglase *et al*., 2004). Density depends on site as well (DPI&F, 2004). Therefore, 'biscuits' were cut from the stem of the spotted gum using a pruning saw and were used to estimate the density for one year (496 kg m^{-3}) and four year old (613 kg m^{-3}) trees. The density of planted spotted gum at age 11 (643.8 kg m^{-3}) and 41 (802 kg m^{-3}) was taken from DPI&F (2004). As the density increases with age, the other density figures at different ages were interpolated from a graph of these four known values (Figure 3.7). The density of timber after age 41 was assumed to be constant (that is 802 kg m^{-3}).

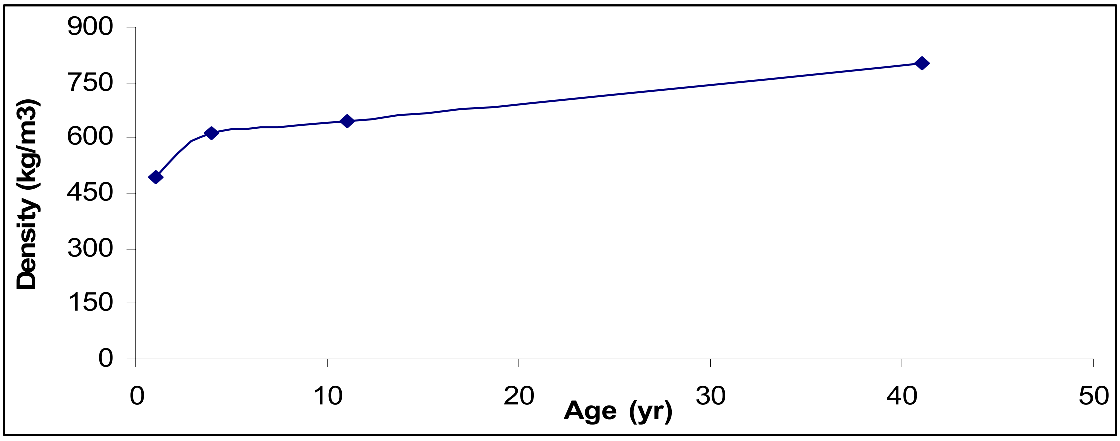


Figure 3.7 Density of spotted gum at various ages, Southeast Queensland

After calculating the volume and density of stem, the stem-mass was estimated using a simple formula (density=mass/volume). Once having stem biomass, there were two alternatives for estimating total biomass of a tree, either follow Cacho *et al.* (2003) or Polglase *et al.* (2004). While simulating the Australian farm forestry system, Cacho *et al*. (2003) assumed that the stem wood is approximately 70% of the total aboveground biomass. It means the total aboveground biomass is around 1.43 times the stem biomass. If author followed Cacho *et al*. (2003) he should assume the same proportion of stem and non-stem aboveground biomass (that is 70%) throughout all the rotation ages. This is quite inappropriate, as the proportion of stem and aboveground biomass for a given species and for a given site depends on age (Cacho *et al.,* 2003). Moreover, that value is for the general application of all hardwood species, and not for specific species.

Polglase *et al.* (2004) developed a model for the estimation of bark, foliage and branches biomass for *Eucalyptus globules*. The research species (spotted gum) was classified under genus *Eucalyptus* until 1995. Although the general form and appearance of *Eucalyptus globules* and spotted gum is not similar, the proportion of stem mass to bark mass and stem mass to foliage mass of *Eucalyptus globules* may be similar to the proportion of the same attributes of spotted gum. This was also acknowledged by David Lee[14]. Given the comparison of two alternatives Polglase *et al.* (2004) was preferred. This is because this method would give aboveground biomass for different ages, which is necessary for the estimation of biomass carbon in different ages and thereby the optimal rotation of spotted gum.

The mass of bark (K, ton DM ha^{-1}), foliage (F, ton DM ha^{-1}) and branches (B, ton DM ha^{-1}) were estimated by using the following relations (Table 3.6).

Table 3.6 Equations for estimation of bark, branches and foliage biomass

Relationship	Parameter	N	R^2
K=d{1-exp(f.S)	d = 32.0, f = -0.005	73	0.86
F=(h.i.SK)/(h + i.SK)	h = 16.0, I = 0.300	176	0.82
B=k{1-exp(m.SK)}	k = 14.9, m =-0.003	179	0.89

Note: 'K' is mass of bark (t DM ha^{-1}), 'F' is mass of foliage (t DM ha^{-1}), 'B' is mass of branches (t DM ha^{-1}), 'S' is mass of stem (t DM ha^{-1}), 'SK' is mass of stem plus bark (t DM ha^{-1}), 'N' is number of samples and 'R^2' is coefficient of determination.

Adopted from Polglase *et al,* 2004

The underground biomass is another important part of standing biomass. Researchers usually use 25% of the above ground biomass as an underground biomass (IPCC, 1996; Haripriya, 2001; IPCC, 2001; Haripriya, 2003). In this regard, Specht and West (2003) felled five common tree species in New South Wales, Australia and took fresh and oven dried weight (at 80°C) of foliage, branches, stem wood, stem bark and roots with a diameter of five mm or greater. From those data, they found a pooled value of root shoot ratio of 0.259. They did not find a significant relationship between the ratio of biomass of roots and shoots with the diameter at breast height. Nor was there any significant difference between the mean ratio (roots and shoots) of the five species. Given this, they recommended that the root biomass could be predicted as being 25.9% of the above ground biomass. Since this research was done for hardwood species in NSW, which is near relatively nearer to the research site, this figure was used to find the below ground biomass of spotted gum.

[14] Dr David Lee, Department of Primary Industries and Fisheries, Email communication on 21 September 2005

3.4.7.4 Conversion factors

For the purpose of getting a common value of greenhouse gases (in terms of CO_2e) conversion factors are necessary and are equally applicable to all land use systems. Carbon content of all grasses, legumes and forest biomass was assumed to be 50% of their biomass (IPCC, 2001; Paul *et al*., 2004). All carbon (including soil) was converted into CO_2 multiplying by 3.67 (molecular weight of CO_2/atomic weight of C = 44/12). Similarly, after estimating the amount of N in fertiliser, animal excretion and biological fixation, the emission factor of 1.25% was used for calculating the amount of N emissions into the atmosphere (IPCC, 1997). This was because the agreed uncertainty around this emission factor was only plus-minus one percent (National GHG Inventory Committee, 2004). The conversion factor of 1.57 {molecular weight of N_2O /molecular weight N_2 = (28+16)/28=1.57} was used for the conversion of N to N_2O. The total amount of N_2O was converted to CO_2 equivalent (CO_2e) multiplying by 310. Similarly, the total amount of CH_4 was converted to CO_2e multiplying by 21 (IPCC, 2001).

3.4.7.5 Carbon price

The market price of carbon has not stabilised yet (Lecocq and Capoor, 2005). Policy and regulatory factors have had a huge impact on demand and supply situations and therefore on carbon price and market stabilisation. For a detailed discussion of demand and supply of carbon credit, transaction costs and international market prices of different types of carbon credits see the literature review (chapter 2). Since the study area lies in Australia, the discussion in this section is based on the Australian context.

In the international arena, Australia is one of the major buyers of carbon credit (3% by volume). The New South Wales Greenhouse Gas Abatement Scheme plays a vital role in this (Lecocq and Capoor, 2005). This Scheme was commenced in January 2003. It requires all electricity retailers and other concerned parties to reduce greenhouse gases to their benchmark by offsetting their excess emissions through the surrender of abatement certificates. At the end of a commitment period, non-compliance attracts a penalty of U$10.50 $t^{-1}CO_2e$. A total of five $MtCO_2e$ of NSW Greenhouse Gas Abatement Certificate have been exchanged in 2004 and 2.2 tCO_2e

in the first three months of 2005. The average 'price' was around U8.1t^{-1}CO_2$e over the past 15 months (Lecocq and Capoor, 2005).

The transaction costs are important costs in order to get the certified carbon cedit. In comparison to other Annex-B countries, Australia has few carbon market institutions. Therefore, the transaction costs in Australia could be higher than in other Annex-B countries. Since the Queensland Government is committed to increase to 320,000 ha plantations by 2020 (DPI&F, 2000), there is a chance of creating a bubble project[15] (carbon pooling), which could be helpful to reduce transaction costs. The involvement of government will encourage the buyers to purchase carbon credits at higher prices as it creates a low risk environment. If the carbon credit is fungible in an international market, the price of Australian produced carbon allowances could be comparable to the European Union's allowances (Euro 7-17 t^{-1} CO_2e).

Prices of carbon vary widely in different Australian studies, but the best estimate is assumed to be U$9 $t^{-1}CO_2$e (CRC for GHG Accounting, 2003). However, for the purpose of this study, the current market price of a NSW Greenhouse Gas Abatement Certificate (U$8.1 $t^{-1}CO_2$e) was used. For the purpose of a transaction cost, the Annex B countries figure US$0.27 $t^{-1}CO_2$e (Jung, 2003) was used. Therefore, the carbon price used for this study was A10.5t^{-1}CO_2$e. However, given the uncertainty the sensitivity of NPV to changes in the carbon prices was tested.

3.4.7.6 Valuation of carbon credits

Because of the non-permanent nature of some sequestration, the value of carbon credits from a sink project is not the same as that of carbon credit from an energy project (or permanent emission reduction or avoidance project), Therefore, carbon from sink projects needs to be adjusted so that the temporarily sequestrated carbon could be equivalent to the permanently sequestrated carbon. There are many greenhouse gases in the atmosphere, but CO_2 is the major one. In order to find the multiplier factor and convert all greenhouse gas into CO_2e, global warming potential of all greenhouse gases were estimated based on an arbitrary timeframe of 100 years. This time horizon was determined by policy (not technically), but is commonly used to derive an equivalence factor. This equivalent factor represents the amount of time

[15] Carbon pooling is a way to group individual sequestration projects and manage them on a larger 'pooled' basis

temporary carbon must be stored in a sink in order to be considered equivalent to a permanently avoided emission (Moura-Costa and Wilson, 2000 and Fearnside 2000 cited in Cacho *et al.,* 2003).

The decay pattern of carbon of CO_2 is complex, as it decays quickly over the first 10 years and then gradually over the next 100 years and then very slowly over hundreds of years before ending in the ocean sediments. Because of this pattern, it is necessary to find the age at which the area under the decay curve of CO_2 up to 100 years (which gives the total amount of carbon staying in the atmosphere in 100 years) is equivalent to the sequestration of the same amount of CO_2. This age, which is called equivalence time (Te), is found to be 46 years (Cacho *et al.,* 2003). Therefore, the C stored in each year was divided by 46 in order to get the same credit (value) of permanently avoided emissions.

There are four methods of carbon accounting. Each method has pros and cons. The Ex-ante method provides the greatest incentive to landholders as they receive full payment (non-discounted) before starting the project, but this is risky for the investor. The Ex-post method has a low risk for investors as they will pay once the project reaches equivalence time (Te=46 years), but there will be no incentive for growers, as the payment is heavily discounted. The Ideal method (payment occurs when carbon sequestered and debit occurs when carbon is released) assumes all carbon is released after harvesting; therefore, it is hard for the investor, as they need to find an alternative project to retain the carbon credit. In the Tonne-year method payment is made annually, but only the fraction of ($1/46^{th}$) of the carbon is stocked in that year. This method is good for the investor, but has little incentive for the grower (Cacho *et al*., 2003).

Considering the risk factor, we selected the tonne-year method. Australia is a relatively dry continent and there are many events of fire and drought. Pests and diseases are common problems as well. Therefore, Australian sink projects are relatively risky. Investors want to minimise the risk of their investment. The tonne-year approach has lower risk, and the enforcement and insurance cost is lower than other approaches (Cacho *et al.,* 2003). It was decided to use this approach in this study, in which carbon stocked in that year was divided by 46 and an annual payment was assumed. However, the emission of greenhouse gases from agrochemicals, machinery, fuels, cattle excretions and burping, nitrogen fixation and soil disturbances are permanent in nature, and so they were not discounted.

3.4.7.7 Grazing value for plantation and pasture

A plantation was developed as an improved silvipastoral system, thus, after three years, grazing was permitted. The grazing value of plantation and pastureland was determined from actual stocking rates. The number of cattle and their grazing days in pastureland and plantation was taken from a grazing calendar. According to the landholder, the average gross live weight gain of weaners in 12 months was around 250 kg and the price was between $1.8 and $2.2 per kg live weight. Therefore, the average price of $2 and annual gross weight gain of 250 kg was used for this study. The total cost in pasture, and additional cost due to the inclusion of the pasture in the plantation were taken from the landholder and independently verified by experts where necessary. Since the cattle in the given land uses were grazed only for a limited time each year, the total cost and benefits were divided proportionally to get the real cost involved and benefit received from the research sites.

The number of trees in the plantation was reduced from 1000 to 400 trees ha^{-1} at the fourth year in the first thinning. The canopy cover has a huge impact on grass biomass. The biomass of grass would be decreasing at different rates in different ages of trees. We assumed that the stocking rate would be directly proportional to the grass biomass. Considering this, the stocking rates in the plantation were assumed as follows: (a) for fourth year, the actual number of cattle grazed (from cattle grazing calendar), (b) fifth to tenth year, decreased by 2.5% per year, (c) at eleventh year, same as that of fourth year and (d) from twelfth year decreased by 5% per year up to the 25th year and then constant until harvesting. The amount of greenhouse gas emissions from cattle burping and excretions in different ages was modelled as per these stocking rates. Moreover, the same rates were applied for an estimation of grass biomass. However, in the case of pasture, it was assumed constant for all years.

3.4.7.8 Estimation of costs and timber benefit

In the study area, hardwood plantation has a short history. Getting all the cost data from the research site was not possible. However, there are two highly relevant studies (Cockfield, 2005; Venn, 2005) from the same region. Therefore, different types of costs up to three years of plantation were derived from them and were assessed independently by the plantation officer. Thinning and harvesting had been done by contractors (or sawmillers) and farmers were getting a stumpage price and so the costs were not disclosed. The issue of not disclosing forest market information have been described elsewhere (ANU, 2005). However, for the estimation of greenhouse gases from thinning, harvesting and transporting operations, tentative working hours of different machines and their fuel consumption rates were needed. Moreover, it was worthwhile to see the potential benefit to farmers, if they harvest forest and sell it themselves. This was essential, as plantations going towards commercial scale and farmers were organising into farm forestry collectives and looking at possible options for more benefits.

Therefore two different scenarios, business-as-usual and an optimistic (ideal), were analysed. For a business-as-usual scenario, the number of plants at the time of planting and after first thinning was taken from the plantation officer. The number of trees after the second thinning was derived from modelling (for optimum spacing). The size (DBH) and volume of the trees at different ages was derived from the growth model. The proportion of different grades of logs at different ages and their stumpage prices were taken from Wondai Sawmill staff. On top of the above mentioned data, other data were necessary for the optimistic scenario and estimation of greenhouse gas emissions from thinning, harvesting and transportation operations. The working hours of all those operations and their tentative costs are modelled in the following sections. The basic concepts of all formulae used in modelling were derived from FAO Forestry (1992). However, values of different coefficients of the different formulae were decided on the basis of real information and discussion with experts. The contract rates of machines were taken from different experts and average value of all was taken for the studies.

First thinning (manual work with power chain saw): Initially, around 1000 trees (ha^{-1}) were planted. They were reduced to 400 trees (ha^{-1}) in the first thinning (4 yrs of age). If the mortality of trees up to 4 years was around 20%, 400 trees would have been removed in the first thinning. Equation 11 was developed for the estimation of cutting time per tree.

$$T = a + b\,D^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

where, 'T' is the cutting time per tree in minutes, 'b' is the cutting time minutes (in our case 0.005) per unit diameter (cm) and the 'D' is the diameter (cm). The coefficient 'a' is the time per tree that is not related to diameter, such as walking between trees or preparing for felling. It was assumed to be 1.25 minutes, as it was easy terrain and trees were near to each other. The average diameter of trees at age 4 would be around nine centimetres at the

$T = 1.25 + 0.005\ (9\ \text{cm})^2 = 1.655$ minutes/tree

Total time for felling and bucking 400 trees = 662 minutes = 11.03 hr (ha^{-1})

Second thinning (manual work with power chain saw): It was assumed that no tree would die after the first thinning. The total number of felling trees in this thinning would be around 150 ha^{-1}(400 to 250 trees ha^{-1}). Marking 150 trees before thinning would cost $50 (Venn, 2005). Equation (12) was used for the estimation of thinning time. All notations except 'c' are already discussed in the first thinning section. Here, 'c' is de-limbing and one bucking cut time per tree (including the time to walk from the bottom of the tree to the buck point), which would be around 1.5 minutes. Similarly, 'a' would be around 1.5 minutes (higher than the first thinning due to increased distance), 'b' would be 0.005 minute per cm diameter. The diameter of the tree would be around 24cm at the cutting point (from modelling). Therefore,

$T = a + b\,D^2 + c$ ……………………………………………(12)

$T = 1.5 + 0.005\ (24\ \text{cm})^2 + 1.5 = 5.88$ minutes/tree

Harvesting and bucking for 150 trees = 882 min = 14.7 hr (ha^{-1})

Final harvesting (mechanical feller, Boucher): From modelling, it was found that the optimal spacing for spotted gum after a second thinning would be around 250 trees ha^{-1}. Therefore, all the calculations are based on 250 trees ha^{-1}. Equation 13 was developed for the estimation of harvesting time.

$T = a + 2\,b\,D$ ………………………………………………(13)

where, 'T' is the harvesting time per tree in minutes, 'b' is the minutes per unit diameter (cm) and the 'D' is the diameter (cm).

The coefficient ‘a’ is the time interval between two cuts (that is, time for preparing the next cut). This assumed that the cut-time and time to fell the cut tree in an appropriate position would be equal. Therefore, 2bD (bD + bD) was needed. In this case, the research had to model harvesting costs of trees for different ages. As there was DBH information for all ages (from growth modelling), it was easy to do so by using the above formula. For example, if harvesting spotted gum at age 29, the average DBH (at 1.37m height) and volume of trees would be around 44.7 cm and 1.07 m^3 respectively. From calculations, it was found that the tapering of a spotted gum tree is 0.97 cm diameter per metre. Therefore, the diameter (D) at the bottom felling part would be around 46cm. We assumed that ‘a’ would be around 0.25 minutes and ‘b’ would be 0.005 minute per cm diameter. Therefore;

T = 0.5 + 2 * 0.005 (46 cm) = 0.71 min/tree = 2.96 hr (ha^{-1})

De-limbing and bucking of final harvest (using a power chain saw): Equation 14 was developed for the estimation of de-limbing and bucking time (T).

T = a + c ……………………………………………………..(14)

where, ‘T’ is the de-limbing and bucking time per tree in minutes, ‘a’ is assumed to be one minute (time for walking between two felled trees and preparing to cut) and ‘c’ is de-limbing and one bucking cut time per tree (including the time to walk from the bottom of the tree to the buck point), which is assumed to be two minutes. Therefore, the total de-limbing and bucking time for 250 (ha^{-1}) trees would be around 12.5 hr.

Skidding: This includes the time (T) for travel unloaded, hooking, travel loaded and unhooking time. Equation 15 was developed for the estimation of skidding time.

T = a N + b x…………………………………………………..(15)

where ‘a’ is the combined time for hooking and unhooking per log (assumed 1.5 minutes), ‘N’ is number of logs carried at a time (assumed four), ‘b’ is the minutes per round trip distance (minutes/metre) and ‘x’ is the one way distance (the average distance from harvesting point to log yard). Considering the area of plantation, ‘x’, is assumed to be 200 metre. Equation 16 was used to calculate ‘b’ as per the unitary method.

$b = (V_1 + V_2)/(V_1V_2)$..(16)

where 'V_1' is travel speed loaded and 'V_2' is travel speed unloaded. In this case, 'V_1' is assumed as 75 metres/minute (4.5 km/hr) and 'V_2' as 150 metres/minute (9 km/hr). Therefore, 'b' would be around 0.02 minutes/metre and total skidding time for 250 logs (ha^{-1}) would be around 10.42 hr.

Crosscutting of log using a power chain saw at log yard (one cut): Equation 17 was developed for the estimation of logs crosscutting time.

$T = a + c N$…………………………………………………...(17)

where, 'T' is the cross cutting time per log in minutes, 'a' is the time per log that is not related to its diameter such as walking between logs and preparing to cut another log and 'c' is the time per cut and 'N' is the number of cuts in each log. We assumed 'a', 'c' and 'N' as 1 minute, 0.5 minutes and 1 cut respectively. Therefore, the total crosscutting time for 250 log (ha^{-1}) would be around 6.25 hr.

Loading, transporting and unloading: The John Deere D-series Forwarder (1710D model) was used for these activities; loading from log yard and transportation and unloading to Wondai Sawmill (35 km distance). The round trip travel time (T) was calculated by using Equation 18.

$T = a + b x$ ……………………………………………………(18)

where 'a' is combined time for loading and unloading and 'b' is the hour per round trip km and 'x' is the one-way distance. The coefficient 'b' is calculated as Equation 19.

$b = (V_1 + V_2)/(V_1 V_2)$………………………………………(19)

where 'V_1' is travel speed unloaded and 'V_2' is travel speed loaded.

Calculation for loading, transporting and unloading time: A D-series truck (D1710) can carry 17 t (or 23 m^3) per trip (23 m^3 x 739 kg/m^3 = 17 t). The haul distance from Taabinga to Wondai Sawmill is around 35 km. It was assumed that the unloaded truck can travel 90 km per hour and a loaded truck can travel 60 km per hour. The combine sorting and loading time is 30 minutes and combined unloading and piling time is around 20 minutes per load. So the time taken for each trip (or for 23 m^3) is around 1.972 hr {T = (40 + 20)/60 + {(90 + 60)/(90*60)}35= 1.972 hr).

3.4.7.9 Discount rate

In order to bring all future costs and benefits to the present values discounting was necessary. Two types of discount rates are common in practice; (a) risk free discount rate and (b) real rate (net of inflation). In Australia, the risk free discount rate is calculated by subtracting the consumer price index from the annual yield of Australian Treasury Bonds of that year. Taking the mean value of the past few years Alaouze (2001) found this value to be 5% in Australia. Another commonly adopted discount rate is real rate (net inflation rate), which is around 7% (Spencer *et al.,* 1999 in Venn, 2005; DPI, 2000). For the purpose of this study, a private, pre-tax, constant price and nominal discount rate is applied. This is because, it is assumed that all costs and prices are change at the same rate over time, and also this rate is easiest to use (no need for building inflation factors into costs and returns). The nominal rate applied for this study is six percent, which is also an estimate of a real rate of return that could be achieved by alternative uses of firm capital (Cockfield, 2005).

3.4.7.10 Determination of optimal rotation ages

In addition to the above mentioned costs and benefits several other costs and benefits for different years were estimated. The year and amount of greenhouse gas emissions associated with agrochemicals, fuels, machines, biologically fixed nitrogen, and cattle urine, dung and burping were converted into a monetary value and was considered as a cost of that year. Similarly, the value of carbon sequestered in the soil, surface litter, particulate organic matter, and grass and forest biomass were considered to be the benefit of plantation. After calculating the year-wise costs and benefits database, the Equation 20 was applied and net present benefit and cost were estimated and then the net present value (net present benefit – net present cost) was determined. From all this information, the Hartman rotation (the age at which the total NPV from greenhouse gases and timber benefit was maximised) and the Faustmann rotation (the age at which the total NPVs from timber, and timber plus grazing were maximised) were determined.

$$V_0 = \frac{V_n}{(1+i)^n} \text{-------------------------} (20)$$

where, 'V_n' and 'V_o' are value (cost or benefit) at present and future (after 'n' years), respectively, and 'i' is the discount rate (that is 0.06).

3.4.8 Estimating net present values from cultivation and pasture

The costs and benefits of maize and peanut cropping were initially derived from the latest version of the Crop Management Notes of the South Burnett region (DPI&F, 2000). The CMN provided an average figure for the whole region. Therefore, in order to get a more accurate figure for the research sites, the data were modified by the respective landholders and Kingaroy DPI officer Dr Mike Bell and agronomist Peter Hatfield. In the case of pastureland, all types of costs and benefits were provided by the landholder. In order to make the comparison more realistic, the cost of similar machinery operations, agrochemicals and other operations were streamlined into the same amount (form) in all land use systems. Because the analysis is performed in with respect to incremental cash flow, overhead costs such as owner labour, rates and rents, insurance, living costs, taxation and lease payments were not included in all land use systems. Similarly, the market price for fuel was not used; the farm business subsidised value was used. In that sense, the NPVs estimated in this study are neither profits nor economic benefits, but indicators of the comparative benefit of different land use systems.

The study period was extended up to the optimum rotation age of the spotted gum plantation (incorporating timber, stock and carbon values). As explained in earlier sections, greenhouse gas emissions from different sources were converted into monetary terms and were noted as a cost of that year. Similarly, carbon sequestrations in different sinks were converted into monetary terms and noted as benefits of that year. Finally, the NPVs from traditional tangible benefits and greenhouse gases were estimated separately and these NPVs were compared with the NPVs from plantation.

3.4.9 Sensitivity analysis

The process of determining the sensitivity of the results by changing its key parameters is called sensitivity analysis. It was discussed elsewhere that the study period of all land use systems was extended up to the optimal rotation age of plantation. In such a long period, there is likely to be a large number of risks and uncertainties. It demands critical analysis of several key factors that may affect the NPVs of land uses. The possibilities of variable parameters were discussed with experts and were scaled as per their suggestions.

The ranking of different key parameters was done by using the concept of a sensitivity index or the elasticity of NPV. This concept is similar to the concept of price elasticity of demand or supply that is a percentage change in quantity (demand/supply) due to a percentage change in price. Here, the elasticity of NPV was determined by dividing the percentage change in NPV by the percentage change in different key parameters. The percentage change in NPV was estimated by the mid point method using the NPV of a base case scenario and predicted NPV due to change in any given key parameter. Similarly, percentage change of a given parameter was estimated by the mid point method using the value of a given key-parameter in a base case scenario and new scenario.

3.5 Summary

This chapter has described and developed different methods to address the research objectives. It has presented and justified the data collection, analysis and interpretation techniques for each objective. Growth modelling of spotted gum was done using non-linear estimation module (NLEM) of STASTICA software. Grass and tree biomass of pasture and plantation was determined by sampling and modelling. Emissions of nitrous oxide from biologically fixed nitrogen in legumes was estimated by sampling, and analysis of past literature. Soil, surface litter and particulate organic matter carbon was estimated by isoprime isotope ratio mass spectrometer, and long-term soil carbon trend was estimated by RothC model. Stocking rates in plantation and pasture was taken from grazing calendar, and in plantation long-term stocking rates was modelled with crown cover change over time. Both primary and secondary data were used for the estimation of greenhouse gas emissions from primary farm inputs, cattle burping, excretion and faeces. In many cases, this chapter has presented the critical analyses on why some current methods are not enough and how new methods have developed.

Chapter 4

Carbon Sequestration in Soil and Biomass of Different Land Use Systems

4.1 Introduction

The aim of this chapter is to estimate and predict the soil carbon and biomass trends in different land use systems. This chapter addresses the hypothesis that the soil and biomass carbon in plantations is higher than the soil and biomass carbon in cultivation and pasture. The results from this chapter are used to address other objectives in later chapters.

In land use, there could be several carbon pools: (1) soil (including surface litter and particulate organic matter), (2) vegetation and (3) harvested products. Depending on the types of land use and their treatments, soil can be a source or sink of carbon. Similarly, vegetation remains a sink until its gross primary product from photosynthesis is higher than the loss of photosynthesised products from autorespiration (i.e. by the growth and respiration of new tissues and growth and maintenance of existing tissues). The harvested products start emissions immediately after harvesting and the proportion of carbon retention (over time) in them depends on its life span, which in turn relies on the type of end uses.

This chapter is further divided into four sections (4.2, 4.3, 4.4 and 4.5). In section 4.2, the soil carbon amount and trends over time under cultivation (peanut-maize rotation), pasture, mature spotted gum and scrubland are analysed. In section 4.2 standing biomass of pasture and plantations are discussed. In the final two sections, chapter conclusion and implications of the study are presented.

4.2 Soil carbon quantities and trends under different land use systems

In the past, there were two popular ways to compare the soil carbon in different land use systems, percentage basis and mass per unit area or cumulative depth basis (tha^{-1}). Since there are differences in bulk density among the land uses, soil carbon comparisons on the basis of cumulative depth could be misleading. Therefore, comparisons are now made on the basis of fixed dry mass per unit ground area

(Gifford and Roderick, 2003). However, in order to apply the latest approach, soil carbon percents are necessary. This section compares the soil carbon amount of different land use systems from three different approaches initially and then the long-term trend of soil carbon is estimated using the RothC model.

4.2.1 Comparison of soil carbon (%) and ^{13}C natural abundance (‰)

Soils under the mature spotted gum (MSG), pasture, cultivation and scrubland were analysed from the Kingaroy shire of the South Burnett district. Scrub was used as a reference, as it was the original land use system in the research area.

The percent of soil carbon reflects the amount of carbon per 100 unit (may be gm, kg etc) of soil. The MSG had the highest carbon percentage up to a 50 cm depth (Figure 4.1). However, after 50 cm depth the differences were narrowed down. MSG was followed by native scrub up to a 50 cm depth. After that, the soil carbon under scrubland was marginally higher than spotted gum. The cultivation had the lowest carbon concentration in each layer, and unlike other land uses the difference between the successive layers were not much pronounced. Maximum fluctuation of carbon content between successive layers was found in MSG. It had higher differences in soil carbon content values even within the same soil depth, which is justified by a higher standard deviation compared to other land use systems (Annex Table D.1). The higher percentage of soil carbon in the surface-soil of MSG could be due to the presence of plenty of under-storey Rhodes grass.

The $\delta^{13}C$ value for soil under the MSG forest was significantly lower ($p<0.001$) than the cultivation and the pasture in the top 20 cm (Annex Table D.1). However, there was no statistically significant differences between the $\delta^{13}C$ values of soil under the mature spotted gum forest and the native scrub ($p>0.05$) as both had C_3 plants[1]. The marginally higher $\delta^{13}C$ under the MSG forest compared to scrubland could be due to the presence of Rhodes grass, a C_4 grass species. Due to poor penetration of sunlight to the ground, grasses were not evident in the native scrub, as grasses are light demanding species. The $\delta^{13}C$ value for pasture was significantly greater ($p<0.05$) than that under peanut cultivation. This was expected because of the presence of C_4 grasses (Rhodes and different native grasses) in the pasture. In comparison to the

[1] The C_3 and C_4 plants follow the Calvin cycle and Slack-Hatch cycle for photosynthesis respectively

original land use (native scrub) the $\delta^{13}C$ values in the pasture and peanut cultivation were much greater. The small increase in $\delta^{13}C$ under peanut cultivation, compared to that under pasture, was due to the presence of the C_3 peanut crop.

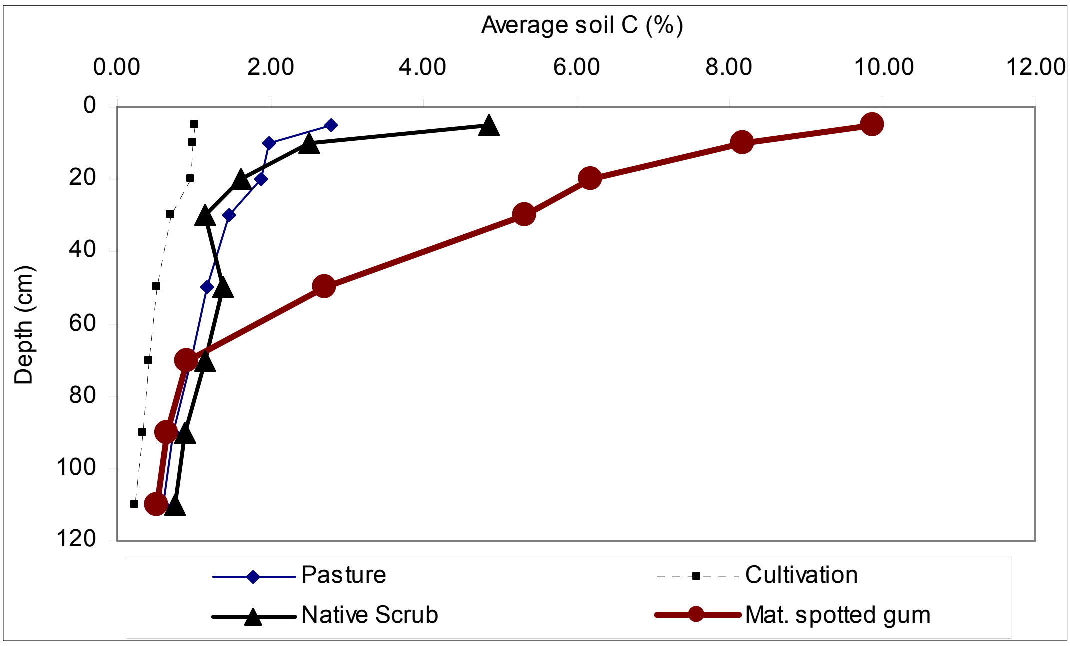


Figure 4.1 Average soil carbon (%) in different land uses and at different depths

4.2.2 Comparison of soil carbon stock

The soil carbon percent does not take into account the differences in bulk density in different land use systems whereas the soil carbon stock (t ha^{-1}) does. Therefore, bulk density is a necessary parameter for the comparison of different land systems. Bulk density measures the soil compactivity; the higher the bulk density the greater will be the soil compactness. In the study site, the highly compacted soil under cultivation made deeper soil collection difficult. In spite of repeated efforts, we had only one sample for 90-110 cm depth. Therefore, I did not have average value for 90-110 cm depth. The results suggest that the bulk density of all land uses increased with depth. Up to 30 cm depth the bulk density of the soil under the MSG was found to be much lower than others. The highest bulk density of soil was found under cultivation (Fig 4.2 and Annex Table D-2), which was linked with long-term continuous traditional mechanised cultivation practices.

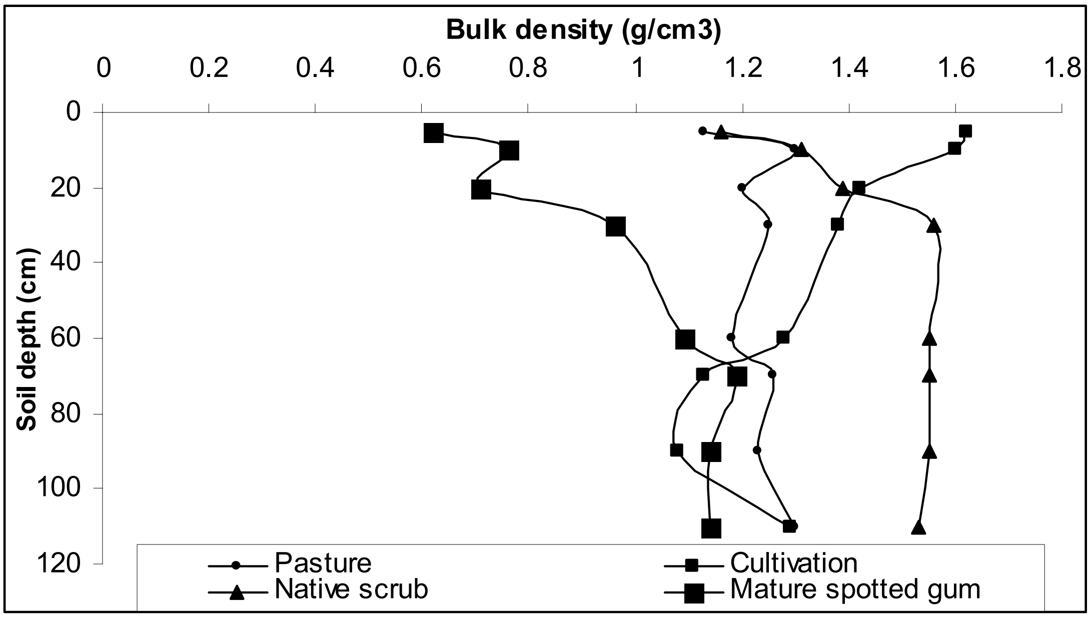


Figure 4.2 Average bulk density (gcm^{-3}) of different land uses at different depths

In the 0-5 cm layer, the bulk density of MSG was 61% lower than that of cultivation, and the difference was reduced to 28% in the 20-30 cm layer. The difference in bulk density among the different land use systems up to 30 cm was quite remarkable, however, in deeper layers the difference was narrowing down. It was expected, because the effect of different land uses to the soil compaction at deeper layers is not pronounced. The difference in bulk density between the forest and cultivation soil (28%) up to 30 cm depth was much higher than the world average (13%) from 109 studies (Murty *et al.,* 2002). This suggests that the compaction of cultivated soil in Kingaroy is relatively high.

The soil carbon stock decreased with depth in all land-uses (Table 4.1). The MSG forest had the greatest soil carbon content down to 50 cm depth followed by the native scrub. The cultivation had the lowest soil C content at all soil depths. For the entire soil profile, down to 110 cm depth, the MSG forest had the greatest soil carbon content (264 t C ha^{-1}), which was 3.5 times (or 188.7 t C ha^{-1}) greater than in peanut cultivation and 1.7 times (or 109 t C ha^{-1}) greater than in pasture. The total soil carbon content in the native scrub was lower (by 50.2 t C ha^{-1}) than that in MSG forest.

Table 4.1 Average soil carbon and cumulative average soil carbon and soil mass in different land use systems

Land use	soil depths (cm)	average soil C (t ha^{-1})	cumulative depth (m)	cumulative soil C (t ha^{-1})	cumulative average soil C (kg m^{-2})	cumulative average soil mass (tm^{-2})
Pasture	0-5	15.82	0.05	15.82	1.58	0.06
	5-10	13.00	0.05	28.82	2.88	0.12
	10-20	22.44	0.10	51.26	5.13	0.24
	20-30	18.38	0.10	69.64	6.96	0.37
	30-50	27.61	0.20	97.25	9.73	0.60
	50-70	24.44	0.20	121.69	12.17	0.85
	70-90	18.20	0.20	139.89	13.99	1.10
	90-110	15.60	0.20	155.49	15.55	1.36
Cultivation	0-5	8.18	0.05	8.18	0.82	0.08
	5-10	8.00	0.05	16.18	1.62	0.16
	10-20	13.77	0.10	29.95	3.00	0.30
	20-30	9.94	0.10	39.89	3.99	0.44
	30-50	13.57	0.20	53.46	5.35	0.70
	50-70	9.27	0.20	62.73	6.27	0.92
	70-90	7.13	0.20	69.86	6.99	1.14
	90-110	5.93	0.20	75.79	7.58	1.40
Scrubland	0-5	28.19	0.05	28.19	2.82	0.06
	5-10	16.38	0.05	44.57	4.46	0.12
	10-20	22.52	0.10	67.09	6.71	0.26
	20-30	17.94	0.10	85.03	8.50	0.42
	30-50	43.09	0.20	128.12	12.81	0.73
	50-70	35.96	0.20	164.08	16.41	1.04
	70-90	27.28	0.20	191.36	19.14	1.35
	90-110	22.95	0.20	214.31	21.43	1.65
Mature spotted gum	0-5	30.66	0.05	30.66	3.07	0.03
	5-10	31.08	0.05	61.74	6.17	0.07
	10-20	43.95	0.10	105.69	10.57	0.14
	20-30	51.17	0.10	156.86	15.69	0.24
	30-50	59.08	0.20	215.94	21.59	0.45
	50-70	21.90	0.20	237.84	23.78	0.69
	70-90	14.59	0.20	252.43	25.24	0.92
	90-110	12.08	0.20	264.51	26.45	1.15

The estimated soil carbon content up to 30 cm depth in the pasture was 69.6 t C ha^{-1} which was close to the average of 68 t C ha^{-1} for 24 pasture sites across South East Queensland (Paul *et al.*, 2003). This shows the consistency of our predicted results with other similar sites.

4.2.3 Comparison of soil with equivalent mass unit

An apparent increase in soil carbon in highly compacted soil could be due to the high amount of soil sampled. An opposite bias would occur if soil carbon compared on a percentage basis. For accuracy in comparing land use effects on soil carbon, different land uses were compared using equivalent mass units (fixed mass of dry soil per unit ground area). As an alternative to the standard depth of 30 cm and 100 cm, soil carbon in the top 0.4 t dry soil m^{-2} and 1.2 t m^{-2} of dry soil was used, respectively (Gifford and Roderick, 2003). The cumulative soil carbon under different land uses could be interpolated by graph (Fig 4.3). The graph was developed by using the cumulative average soil carbon (kg m^{-2}) and cumulative average soil mass (t m^{-2}) as calculated in Table 4.1.

When soil carbon for the different land uses is compared using equivalent mass units (0.4 t dry soil m^{-2}) the MSG forest had the highest soil carbon, which was more than five times higher than in cultivation (38 vs. 202 t ha^{-1}). However, when soil carbon was compared using equivalent mass units of 1.2 t dry soil m^{-2} the difference between the two land uses was reduced to 3.7 times (72 vs. 267 t ha^{-1}). But even in this case, the MSG forest had the greatest soil carbon content (267 t ha^{-1}), compared to 178, 145 and 72 (t ha^{-1}) for the native scrub, pasture and MSG forest respectively.

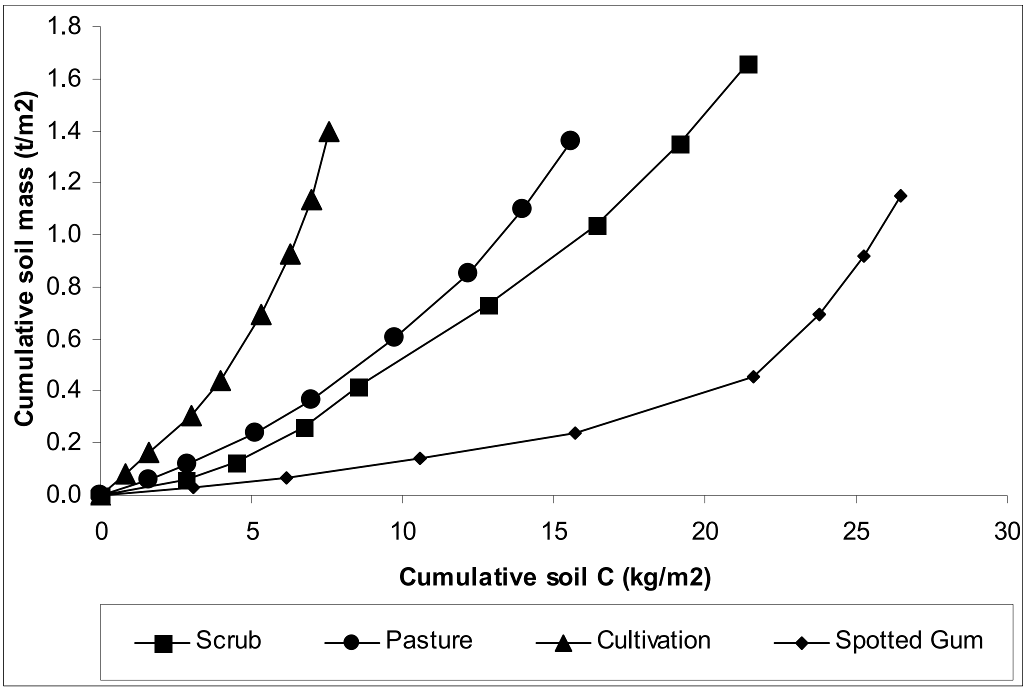


Figure 4.3 Cumulative soil C and soil mass in four different land uses at Kingaroy

Many national and international soil carbon studies have compared the soil carbon changes due to land-use change up to 30 cm depth (Murty *et al*., 2002; Paul *et al*., 2002; Paul *et al*., 2003a). However, a special report of the Intergovernmental Panel on Climate Change (IPCC, 2000) estimated the total land and total soil carbon (up to one metre depth) of all prominent land-use systems in the world. The global average soil carbon to one metre soil depth for cultivated areas is 80 t ha^{-1} (IPCC, 2000), whereas the cultivated area in this study had the slightly lower value of 72 t ha^{-1} to approximately one metre depth. The estimated soil carbon content at the pasture site of 74 t ha^{-1} (to 30 cm depth or 0.4 t dry soil m^{-2}) is similar to the average of 68 t ha^{-1} for 24 pasture sites across SEQ (Paul *et al*., 2003).

The soil carbon content up to one metre depth in tropical forests, temperate forests and boreal forests were 123, 96 and 343 t ha^{-1}, respectively (IPCC, 2000). The soil carbon content of the mature spotted gum forest in this study was 267 t ha^{-1}, although it was expected to be somewhere in between the values for tropical and temperate forests. In fact it was much greater than both these regions and unexpectedly closer to the world's richest ecosystem, the boreal forests. Saffigna *et al.* (2004) quote similar concentrations of soil carbon for a native scrub site in the same region of south east Queensland. This indicates that remarkably high levels of soil carbon are achievable in these ecosystems. However, as there was a higher percentage of carbon:nitrogen ratio in spotted gum (Table 4.2), especially up to 50 cm, there is a need to research further whether the high soil carbon recorded in spotted gum may be due to a higher proportion of non-labile carbon (such as lignin). Tropical savannas and temperate grasslands up to one metre depth had 117 and 236 $tCha^{-1}$, respectively (IPCC, 2000). Soil carbon under the pasture area of this study was in between these two figures at 145 $tCha^{-1}$.

Table 4.2 Carbon and Nitrogen ratio of different land use systems at different depths

Depth (cm)	Pasture		Cultivation		Scrubland		Mature spotted gum	
	Av soil N (%)	Av (C/N)	Av soil N (%)	Av (C/N)	Av soil N (%)	Av (C/N)	Av soil N (%)	Av (C/N)
0-5	0.24	11.7	0.09	11.2	0.35	13.9	0.55	18.0
5-10	0.17	11.8	0.09	11.1	0.19	13.2	0.45	18.2
10-20	0.16	11.7	0.08	12.1	0.13	12.5	0.40	15.5
20-30	0.12	12.3	0.06	12.0	0.10	11.5	0.30	17.8
30-50	0.09	13.0	0.04	13.3	0.11	12.6	0.14	19.4
50-70	0.06	16.2	0.03	13.7	0.09	12.9	0.05	18.4
70-90	0.05	14.8	0.02	16.5	0.06	14.7	0.04	16.0
90-110	0.04	15.0	0.02	11.5	0.05	15.0	0.03	17.7

Note: In order to calculate average C/N average soil C (%) was taken from Table 5.1

Murty *et al*. (2002) reviewed around 109 global studies and found that the conversion of forest to agriculture land lead to an average loss of approximately 22% of soil carbon. The Australian National Greenhouse Gas Office, for the purpose of national inventory and national communication, assumes that the conversion of forest to unimproved pasture decreases carbon by 30% (Kirschbaum *et al.,* 2000). The analysis shows that the conversion of scrubland to cultivation lost around 60% of soil carbon in 55 years. This again suggests that cultivated land has been deteriorating faster than the global average for similar land uses.

4.2.4 Surface litter and particulate organic matter (POM)

Surface litter (dead plant material) and particulate organic matter (partially decomposed litter in between the surface litter layer and the soil) are important sources of soil carbon. Surface litter was present in all land uses except cultivation (Annex Table D-3). The greatest amount of surface litter was found in native scrub (119.2 t ha^{-1} dry weight, DW), which was 7.3 times greater than the mature spotted gum forest (16.4 t ha^{-1} DW). Particulate organic matter (POM) in the mature spotted gum forest (30.1 t ha^{-1} DW) was approximately 24% less than that for POM in the native scrubs (39.5 t ha^{-1} DW). The carbon content in all surface litter and POM components was less than 50% (Annex Table D-3).

The greatest carbon content in POM was found in the mature spotted gum forest with 8.12 $tCha^{-1}$ (Table 4.3), almost double that in the native scrub (4.18 $tCha^{-1}$). However, the greatest surface litter carbon content was found in the native scrub (46.5 $tCha^{-1}$), which is more than seven times that in the mature spotted gum forest (6.21 $tCha^{-1}$).

When calculating total carbon (including soil, POM and surface litter), the greatest carbon content was found in the mature spotted gum forest (281.3 t ha^{-1}) followed by the native scrub with 228.6 t ha^{-1} (Table 4.3). The cultivated area had the lowest total carbon content (72 t ha^{-1}), most probably a result of removal of the crop biomass at harvest, lower soil carbon contents, a distinct lack of surface litter and POM and no fallow or plant residues remaining between crop rotations.

Table 4.3 Total carbon content under different land use systems up to 1 m depth

Land use types	POM, t C ha^{-1}	Surface litter, t C ha^{-1}	Soil C, t C ha^{-1}	Total C, t C ha^{-1}
Cultivation	0	0	72	72
Pasture	0	1.01	145	146
Native scrub	4.18	46.46	178	228.6
Mat. spotted gum	8.12	6.21	267	281.3

4.2.5 Long-term prediction of total soil carbon stocks

The previous results show that the initial total soil carbon under cultivation in 1950 was estimated at 228.6 t ha^{-1}. After continuous cultivation of peanut and maize for 55 years, it was reduced to 72 t ha^{-1} in 2005, decreasing annually at a rate of 2.1% (Figure 4.4). Similarly, the total soil carbon of pasture was estimated at 114.3 t ha^{-1}, when it was established in 1983 at cultivation. After 22 years of continuous pasture the total soil carbon content was 146 t ha^{-1} in 2005, a net annual increase rate of 1.1%. The total soil carbon of the plantation in 2001 was estimated as 139.6 t ha^{-1}, and could reach approximately 280 t ha^{-1} after 50 years with an annual increasing rate of 1.4%.

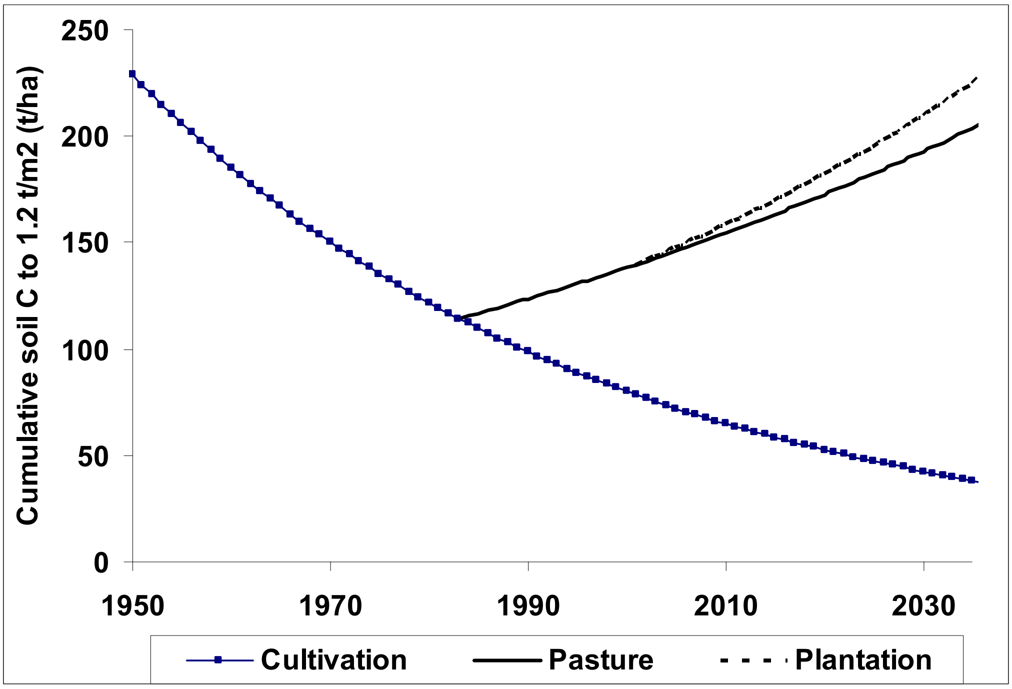


Figure 4.4 Long-term prediction of total soil carbon extrapolated from past trends

The predicted results indicate that total soil carbon in the pasture and spotted gum plantations will increase, while under cultivation soil carbon will continue to decline (Figure 4.4). Until the first rotation is harvested there will not be a large difference in soil carbon between the pasture and the plantation, but larger differences are expected in the long-term. However, if spotted gum is planted on previously cultivated land there may be a large difference in soil carbon even in the first rotation.

The literature on soil carbon dynamics after afforestation of ex-agricultural and forest lands are quite diverse. Studies show that the soil carbon could be decreased when pine species were planted as its litters decompose slowly, whereas contrary results were reported when ex-agricultural lands were forested with native hardwood species. Paul *et al.* (2002) reported that soil carbon was lost when *Pinus radiata* plantations were established on ex-improved pastureland in temperate regions. Similarly, Turner *et al.* (2005) found declining soil carbon when changing land use from native eucalyptus species to pine plantations in eastern Australia.

Studies on hardwood native species indicate that the soil carbon is likely to increase after afforestation of native hardwood species (Paul *et al*., 2002; Paul *et al*., 2003; Saffigna *et al*., 2004). For example, Paul *et al*. (2003) predicted that after afforestation with *Eucalyptus globulus* in the low rainfall zone of Western Australia soil carbon would increase by 1.05% per year over a 40-year period. In this case, the soil carbon content in planted spotted gum was predicted to increase by 1.4% per year over 50 years. The higher percentage of the spotted gum could be due to clay loam soil in the site (sandy soil the site of Paul *et al*), as higher surface area of clay loam soil fractions enhances formation of organo-mineral complexes that protect carbon from microbial oxidation (Grigal and Bergusan, 1998 cited in Paul *et al.,* 2002). There are some other reasons for this (see section 4.2.8). For a detailed discussion of soil carbon change after afforestation, see chapter 2.

4.2.6 Comparison of RothC predicted soil carbon and measured soil carbon

The RothC model was applied to predict the long-term soil carbon trends under cultivation and pastureland. The RothC predicted values and estimated values (inter-/extrapolated measured values) were compared. Following the procedure in chapter three, trendlines were developed for soil carbon in the cultivated land and pastureland. Soil carbon in cultivation as predicted by RothC was 73.2 t ha^{-1} in 2005, which was similar to the measured value of 72 t ha^{-1} (Table 4.3). Similarly, soil carbon in pastureland as predicted by RothC in 1983 and 2005 was 105.81 t ha^{-1} and 147.41 t ha^{-1}, respectively, which were close to measured values of 106 t ha^{-1} (in 1983) and 145 t ha^{-1} (in 2005) (Figure 4.4 and Figure 4.5). This result suggests the assumption that soil carbon has remained relatively constant in the native scrub for the last 75 years. It also suggests the assumption that soil carbon decline or incline is exponential and not linear.

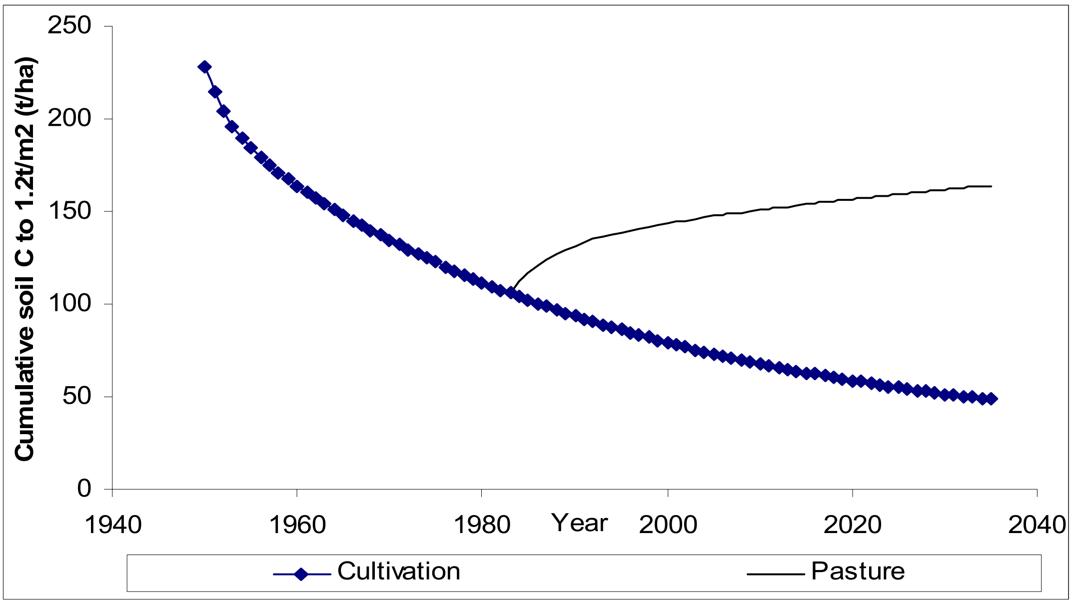


Figure 4.5 Long-term prediction of soil carbon simulated using the ROTHC model

There was a very high correlation ($r = 0.99$) and there was no statistically significant difference between the estimated and RothC predicted data sets in both cultivated and pasture lands ($p = 0.000$). Similarly, while applying an independent t-test it was found that the null hypothesis was true ($p > 0.05$); indicating that there was no significant difference between their mean values and therefore the mean of the two data sets are statistically similar. However, a paired t-test suggests that the two data sets are different ($p < 0.001$), in that the mean difference of two datasets is statistically not equal to zero. Since two sets of data of the same land use are being compared, one predicted by inter/extrapolation of estimated value and other by the RothC model, the paired t-test is the only way of testing the mean difference (equity of means) in this data environment.

Analysis of both time paths, predicted by extrapolation (Figure 4.4) and the RothC model (Figure 4.5), shows that the annual decreasing and increasing rate of soil carbon are similar in the long run, however, it was not similar in all years. In the case of cultivation, the annual soil carbon decreasing rate in earlier years (1950-1955) was 4.4%, but this rate dropped to 1.48% yr^{-1} during 1990-2000. Similarly, in the case of pasture, in the first five years (1983-1988) the annual soil carbon increasing rate was 3.74%, but reduced to 0.45% during 1995-2000.

4.3 Biomass of pastureland and plantation

Biomass is a photosynthetic product, which has around 50% carbon mass. Both pastureland and plantation contain grass and legume permanently. Plantation contains tree biomass as well. This section compares the measured grass (including legume) biomass of both pasture and plantation and then predicts the long-term trend of grass and tree biomass in plantations.

4.3.1 Grass biomass in pastureland and plantations

The amount of dry matter (including roots) found on pastureland (7.45 t ha^{-1}) was around 37% higher than for a four-year plantation (4.72 t ha^{-}1) (Table 4.4). More than 96% of the dry matter in both cases was grass biomass, the legume biomass was negligible. In both sites, the dominant grass species were varieties of native grasses and Rhodes grass *(Chloris gayana)*, whereas the dominant legume species were Burr Medic (*Medicago polymorpha)* and Siratro *(Macroptilium atropurpureum*).

Table 4.4 Biomass and carbon mass of grass and legume found on pastureland and four year plantation

	Dry weight (t ha^{-1})	Carbon (t ha^{-1})	Grazing history
Pastureland (total area 12.15 ha)			
Grasses	7.20	3.60	27 cattle grazed for 92 days
Legumes	0.25	0.11	in 2004 (21 May to 9 Aug
Total	7.45	3.61	& 23 Aug to 2 Sept)
4-year plantation (total area 24.3 ha)			
Grasses	4.58	2.29	27 cattle grazed for 94 days
Legumes	0.14	0.06	(2 May to 10 June 2004 &
Total	4.72	2.35	26 Jan to 20 March 2005)

Note: Carbon in legume and grasses was found as 42.9% and 49.48% of dry weight respectively.

The lower amount of the pasture biomass in the plantation could be mainly due to two reasons. Firstly, the biomass of both a four year plantation and pastureland was measured at the same time, in April (during the end of growing season). However, the plantation had already been grazed twice in that calendar year (trees were planted in April so a calendar year is assumed to be April to April). The 24.3 ha four year plantation was grazed by 27 cattle for 40 consecutive days in 2004 (2 May to 10 June 2004) and 54 consecutive days in 2005 (26 January to 20 March). However, the pastureland (12.15 ha) was grazed more than seven months before the field work, 81 days from 21 May to 9 August and 11 days from 23 August to 2 September in 2004. Secondly, the four year plantation would have developed some canopy, which would have filtered the sunlight and affected the growth of grass species. Thirdly, as soil moisture is limiting factor, there may be some competition between plant and grass for moisture.

Using the measured grass (includes legume) biomass for comparison of pasture and plantation is not realistic. To make it realistic, it is necessary to add the amount of grass grazed in plantation, at least after the growing season. Twenty-seven cattle were grazed in 24.30 ha of plantation for 54 days (26 January to 20 March) after the growing season; all of them were weaners having an approximate live weight[2] of 150-300 kg. On an average, each weaner would take around 5.5 kgDMday^{-1} (Department of Natural Resources and Environment, 2002). Therefore, the 27 cattle would have eaten around 0.33 t dry matter per hectare during that grazing time. Therefore, the total amount of grass in plantation before the last grazing could be around 5.05 t ha^{-1}.

It is necessary to estimate permanently retained grass biomass for biomass carbon estimation. The estimated amount of biomass on pastureland and plantation could not be maintained throughout the year. The stocking rate (ha^{-1}) in pastureland[3] and in plantation was around 0.56 (27 cattle * 92 days/365 days /12.15 ha) and 0.286 (27 cattle * 94 days/365 days/ 24.30 ha), respectively. Every year approximately 1.12 t DM from pastureland and around 0.57 t DM from plantation would be eaten by cattle. Therefore, on average around 6.33 t DM (7.45 – 1.12 m = 6.33 t ha^{-1} = 3.15 t C ha^{-1}) in pastureland and around 4.48 t DM (5.05 – 0.57 = 4.48 t ha^{-1}) in plantation (2.24 t C ha^{-1}) would be retained after grazing. Thus, for the prediction of a long-term trend, the pasture biomass was assumed to be constant at 6.33 tha^{-1} (3.16 t C ha^{-1}) in each year.

4.3.2 Long-term trend of grass biomass in plantation

Unlike pastureland, the grass biomass of a plantation would decrease over time due to growing crown cover (for a detailed discussion, see chapter 3). At age ten, the total grass biomass would decrease to 3.85 t ha^{-1} from 4.48 t ha^{-1} at age four. However, due to a second thinning at 10 years, the canopy would be re-opened and

[2] Interview with Colin Marshall, cattle farmer
[3] The average stocking rate of pasture in different years is almost the same. Therefore, the same rate is applied for all years.

the grass biomass could be increased significantly in the eleventh year. After that canopy cover would decrease to 2.18 t ha^{-1} at age 25. The canopy cover and the grass biomass would be constant after this age (Figure 4.6).

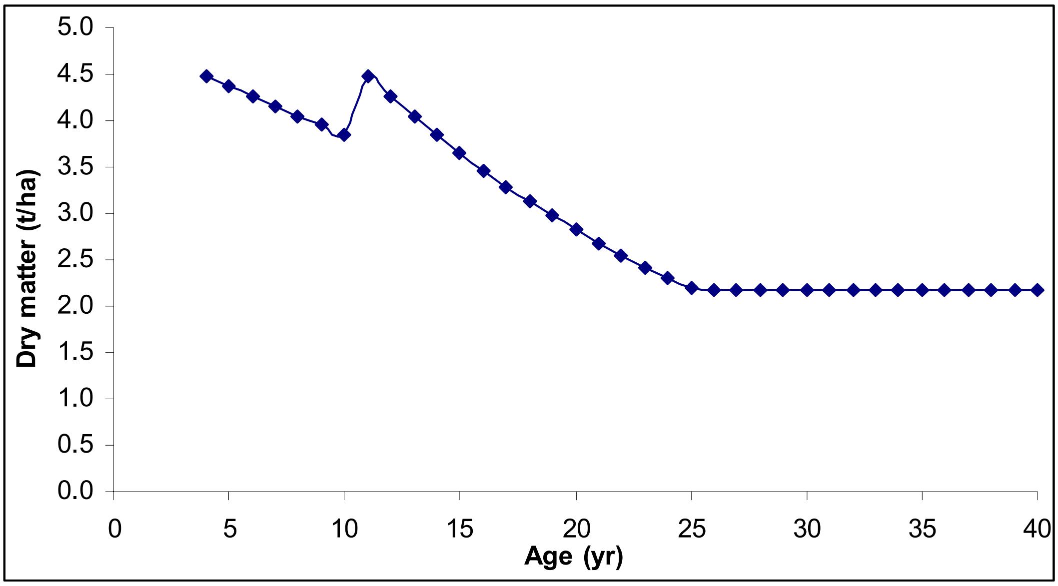


Figure 4.6 Long-term trend of grass biomass under spotted gum plantation

Since the grass biomass is almost constant over the year in pastureland, the stocking rate would remain the same. In the plantation, the stocking rate is assumed to fluctuate in proportion with the grass biomass. It is around 0.286 at age 4 and would reduce to 0.24 at age 10. It would regain to 0.286 at age 11 and then would decline to 0.14 at age 26 and then would remain constant until final harvesting (for detail see forthcoming chapters).

4.3.3 Long-term trend of tree biomass of a spotted gum plantation

Tree biomass is a major component of a carbon pool. The individual year's biomass of spotted gum is necessary for carbon biomass estimation and optimal rotation determination. The biomass of trees comprises the aboveground (stems, barks, foliages, branches) and belowground biomass (roots). The biomass of some of the important parts are given in Figure 4.7 and biomass of individual parts is given in the Annex (Table D-4). All types of biomass including total biomass, decreases twice (fourth and tenth years) due to thinning. Of the 1000 (ha^{-1}) trees planted, around 200 trees are assumed to have died before age four. In the first thinning, at age four, the total number of trees was down to 400 trees from 800 (ha^{-1}). In the second thinning, at age 10, it was further reduced to 250 (ha^{-1}).

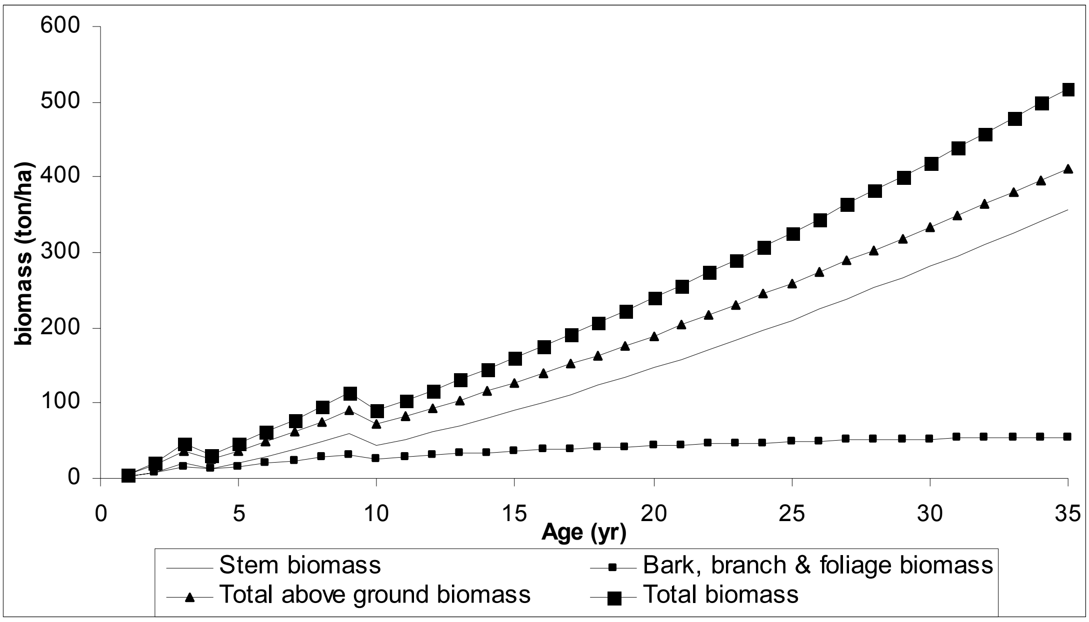


Figure 4.7 Long-term trends of biomass of the spotted gum plantation at Taabinga

The biomass of bark, foliage and branch is highly correlated with stem biomass, which in turn depends on density and volume of stem. Stem volume was determined by modelling the 15 years time series diameter at breast height (DBH) data of spotted gum trees. No trees were grown to 1.3m height (diameter at breast height, DBH, measuring point) up to four years of age, thus, there was no DBH data beyond that. Therefore, the modelling for stem volume was based on time series DBH data after four years of age. Theoretically, the model predicted some stem biomass even at age 1-3 years, but practically it should be almost zero. However, the total biomass predicted by the model during that period would be reliable, as it could be equivalent to the bark, foliage, branch and root biomass.

The biomass of bark, foliage and branches (BFB) is lower than stem biomass and is relatively constant over time. It is around 12 t in four years and would be 55 t in 35 years. The biomass of bark, foliage and branches would be more or less similar to that of stem biomass at five years. After that, the percentage of BFB biomass to that of stem biomass reduces continuously (78% at age 5, 59% at age 10, 30% at age 20 and 19% at age 30). At the harvesting age of spotted gum (34 years), the contribution of BFB is approximately 16%. These relationships have important implications because their percentages could be assumed once the stem biomass is known.

The percentage of stem biomass to the total aboveground biomass would be increasing by age. It would be 56%, 63%, 71%, 77%, 81% and 84% at age 5, 10, 15, 20, 25, 30 years respectively. At the harvesting age, 34 years, the stem biomass would be around 86% of the total aboveground biomass and 68% of the total biomass (both aboveground and belowground). This increasing trend of stem biomass to the total biomass once again validated the claim of why the assumptions of Cacho *et al.* (2003) were not followed. While simulating the Australian farm forestry system Cacho *et al*. (2003) assumed that the stem wood biomass is approximately 70% of the total aboveground biomass. Our studies invalidated this assumption, as this percent is only applicable if we harvest the tree at the age of 15 years. If we had followed Cacho *et al*. (2003) we would have assumed the same proportion (70%) of stem and non-stem aboveground biomass throughout the whole rotation ages, which would have affected our optimal rotation by manipulating carbon benefits (for a fuller explanation see the following chapters).

The total biomass covers both the aboveground and belowground biomass, which is approximately 125.9% of the above ground biomass. The total biomass of trees is estimated to be around 5 t ha^{-1} at age one and it would be around 498 t ha^{-1} at harvesting age. Around 68% (340.67 t ha^{-1}) of this would be contributed by stem, 11% by bark, foliage and branches, and 20% by roots.

There is no known research on the estimation of biomass of spotted gum in Australia. Specht and West (2003) estimated the biomass of *Eucalyptus microcorys, E grandis, E. saligna, E. nitens, Gravillea robusta and Pinus radiata* in New South Wales by destructive sampling. However, the age limit is only up to 10 years. Similarly, Polglase *et al.* (2004) predicted biomass of *Eucalyptus globulus* (350 t ha^{-1} in 10 year) and *Pinus radiata* (370 t ha^{-1} in 28 yr) for calibration of FullCAM model. Biomass depends on several factors including the nature of species and the objective of the plantation. Since *Eucalyptus globules* were planted for fibre, its biomass may not be compared with spotted gum. Pine and spotted gum are two distinct species. Comparison of biomass of pine and spotted gum does not validates our estimation. However, from the comparison it can be seen that the biomass of spotted gum in 28 years (382 t ha^{-1}) is slightly higher than the biomass of pine (370 t ha^{-1}) at the same age.

4.4 Conclusions and implications

Soil and biomass are important pools of carbon. This study has demonstrated how the timeline of land use change might be useful to predict soil carbon trends using a minimum number of land use systems. Comparison of the soil carbon trends under different land use systems suggest that the soil carbon sequestration rate in plantation and pasture are increasing but it is decreasing in cultivation. The increase in the soil carbon rate in the plantation is higher than in the pasture. This suggests the research hypothesis about soil carbon, which stated the superiority of soil carbon in plantation over the other land use systems considered in the study. Furthermore, the results clearly indicate that the current peanut-maize cultivation practices in and around the Kingaroy area are not favourable for carbon sequestration, while planting spotted gum on ex-cultivated or agricultural land has considerable potential to sequester soil carbon. This finding is currently only applicable to the Red Ferrosols of dry land farming areas having similar edaphic, topographic and climatic factors. Further research would be required to apply the model to other soil types or climatic regions.

The analysis of grass and tree biomass suggests that around 6.33 t ha^{-1} biomass could be stored in pasture permanently. In plantations, the amount of grass biomass could fluctuate from 4.48 t to 2.18 t ha^{-1} in different years and the tree biomass could reach up to 498 t ha^{-1} in 34 years. Therefore, plantations could earn significant amounts of biomass carbon benefit even if they are planted for timber. This result validates another hypothesis about biomass carbon, which has assumed the supremacy of plantation for biomass over other land use systems. However, without an in-depth analysis of other sources and sinks and tangible benefits it is difficult to say that the plantation is superior to others. Thus, the estimated soil and biomass data from this chapter have been used for the further analysis of costs and benefits in forthcoming chapters.

There are several implications of the study. The annual rate of loss of soil carbon in cultivation (2.1%) and the annual rate of gain of soil carbon in pasture (1.1%) is very high in the long-run. However, the RothC soil carbon model shows that the rate is not uniform. In earlier years (1950-1955), the soil carbon decreasing rate in cultivation was 4.4%, but during 1990-2000 it dropped to 1.48%. Similarly, in the case of pasture, in the first five years (1983-1988) the annual soil carbon increasing rate was 3.74%, but it was reduced to 0.45% during 1995-2000. In this case study, spotted gum was planted in 2001. The optimal rotation of spotted gum incorporating timber, stock and carbon values is found to be 34 years (see following chapters). Taking extrapolated soil carbon in-/decreasing rates (+1.1% yr^{-1} in pasture and -2.1% yr^{-1} in cultivation) for the years 2001-2035 may not be appropriate. Therefore, while making a comparison of cultivation, pasture and spotted gum, the RothC predicted soil carbon amounts of individual years from 2001 to 2035 be used.

As explained in chapter 3, the mature spotted gum (MSG) was studied for the proxy value of soil carbon for newly established spotted gum plantations. The newly established plantations at the research site are actually a silvipastoral system, which includes nitrogen fixing legumes along with exotic and native grass species that are planted as an intercrop along with the spotted gum. Since the accumulation of soil carbon is greater when there are nitrogen-fixing species (Paul *et al*., 2002), the prospects for soil carbon sequestration in the plantations are enhanced. However, before transferring the research benefits from mature spotted gum to plantation we have to consider four things.

Firstly, the MSG forest regrew in pastureland and nobody knows for how long the preceding pasture was dominant. Secondly, there has been selective harvesting and the crown cover of MSG is well maintained all the time. However, the plantation is scheduled to harvest every 34 years (as per the research result) and a significant amount of soil carbon could be lost after harvesting during plantation operations. Thirdly, the MSG forest is relatively dense (393 trees ha^{-1}) compared to scheduled spacing levels of plantation. The relatively dense forest would have protected soil from desiccation. Fourthly, the soil carbon under the MSG could not accurately reflect the plantations over 50 years, as the agricultural soil may be so degraded it could never return to its original condition. Therefore, for the comparison of plantations with other land uses we proposed three soil carbon scenarios, 15%, 30% and 45% lower than the actual rate. The middle scenario (30%) is close to the soil carbon value estimated by Paul *et al*. (2003) in a *Eucalyptus globules* plantation site in a similar climatic zone.

The next chapter discusses about the emissions form primary farm inputs and production.

Chapter 5

Emissions from Farm Inputs and Production

5.1 Introduction

One of the assumptions underlying efforts to convert cropping land, especially marginal cropping land, to plantations is that there will be a net reduction in greenhouse gas emissions, with a gas 'sink' replacing a high energy system in which the breakdown of biomass is routinely accelerated to prepare for new crops. Agrochemicals and petroleum products are vital for all types of human-influenced land use systems. Their production, transportation and application emits greenhouse gases into the atmosphere, as is the case for farm machinery. Some amount of nitrous oxide (N_2O) is emitted into the atmosphere from biologically fixed nitrogen in legumes and urine and cattle dung. Similarly, cattle emit some amount of methane while belching. In this chapter, the author analyses the greenhouse gas emissions of three land use systems (cultivation, pasture and spotted gum plantation) and addresses the hypothesis that the emissions of greenhouse gases from primary farm inputs and production in cultivation would be much higher than in pasture and plantations. This chapter is divided into three sections. In the first section (5.2), emission from three production inputs, fuel, farm machinery and agrochemicals (fertiliser, pesticides and herbicides), are considered. In the second section (5.3), discussion is focused on the emission from biologically fixed nitrogen, urine and dung. In the third section (5.4), methane emission from cattle in pasture and plantation is discussed. Each section is supplemented with discussion. Finally, there is the chapter conclusion (5.4).

5.2 Emission of greenhouse gases from farm inputs

This section is subdivided into three sub-sections to compare the amount of greenhouse gas emissions from agrochemicals, fuel and farm machinery.

5.2.1 Emissions from production, packing, transportation and application of agrochemicals

Agrochemicals cover all fertilisers, insecticides, fungicides and herbicides. The amount of different types of agrochemicals used in all land use systems in different years and their global warming impacts were taken from different sources. The total amount of greenhouse gas emissions from agrochemicals used in the peanut and maize rotation is approximately 1162 kgCO_2e over two years (Table 5.1 for summary and Table E-1 in Annex for detail). Over 34 years[1], the total amount of greenhouse gas emissions from cultivation (peanut-maize cropping), pasture and plantation are around 19751 kgCO_2e, 245 kgCO_2e and 933.67 kgCO_2e, respectively. The total amount of greenhouse gas emissions from cultivation in 34 years is around 81 times higher than pasture and 21 times higher than from plantations.

Table 5.1 Emissions of greenhouse gases (kgCO_2e ha^{-1}) from primary farm inputs in different land use systems in Kingaroy in 34 years, Southeast Queensland

Emissions due to	Emissions of greenhouse gases (kgCO_2eha^{-1}) in different land uses		
	Peanut-maize cropping	Pasture	Plantation
Agrochemicals	19751	245	933.67
Machinery	1940.8	151.76	1252.57
Fuel	14029.63	1215.08	6290.78
Total	35721.43	1611.84	8477.02

There are four main reasons why cultivation has the highest amount of greenhouse gas emissions from agrochemicals. As noted in chapter two, the production of nitrogen fertilisers emit greater amounts of greenhouse gases than any other fertilisers and there is a greater requirement for that form of fertiliser. Moreover, some amount of nitrous oxide is also emitted into the atmosphere after the application of nitrogen fertiliser by de-nitrification. Although peanuts fix a considerable amount of nitrogen, the net nitrogen benefit to the next crop is minimal (Peoples *et al*., 1992; Bell *et al*., 1995; Rochester *et al*., 1999). Therefore, every maize crop requires a significant amount of nitrogen fertiliser. On the other hand, in plantation and pasture, it is used only once in 34 years. There may be an argument for using some nitrogen at each stage of pasture re-establishment (every 8-10 years) but it is presumed that the pasture mix contains some legumes.

Second, a large amount of lime is used with the crops. Peanuts accelerate the soil acidity by removing cations, particularly calcium, magnesium and potassium (Bell *et al., 1995*). Moreover, calcium is absorbed directly by developing pods and low calcium leads to empty shells (DFI&F, 2004). In order to neutralise the acidity

[1] In order to make comparison more realistic, the time period of analysis of all land use systems was extended to 34 years. This is because the optimal rotation age of spotted gum incorporating timber, stock and carbon value is around 34 years (see following chapters).

problem 500 kg ha^{-1} of lime is used every year, whereas there is no need for lime in the pasture and plantation. Third, the higher amount of other fertilisers needed in cultivation is directly related to the greater frequency of peanut cropping (every second year), conventional tillage and removal of hay for sale (Bell *et al.,* 2000). While removing every tonne of peanut hay, around 40 kg of muriate of potash and 16 kg of superphosphate equivalent would be removed (DPI&F, 2004). Similarly, nuts in the shell will remove around 16 kg of muriate of potash and 30 kg of super phosphate in each ton (DPI&F, 2004). Fourth, since more greenhouse gases are emitted into the atmosphere in the production of insecticides, herbicides and fungicides on a per unit basis than any other input in the agricultures (Helsel, 1992; Government of State of Sao Paulo, 2004) a rotation such as this with susceptible crops, widely grown in the region increases the chances of disease and pest problems, leading to a commensurate increase in emissions.

5.2.2 Emissions from the use of farm machinery

As with the agrochemicals, the use of machinery in crop production results in the highest amount of consequent greenhouse gas emissions (1941 $kgCO_2e\ ha^{-1}$) in 34 years, around 13 times higher than for the pasture and 1.5 times higher than for the plantation (Table 5.1 for summary and Table E-2 in Annex for detail). In pasture, the emission of greenhouse gases due to farm machinery production and use is almost nil, just 152 $kgCO_2e$ in 34 years due to the infrequent need for cultivation and planting. On the other hand, there is much less difference between the plantation and the cropping (1253 vs. 1941 $kgCO_2e$ per ha over 34 years). Although a range of machines are used in cropping every year, the duration of each operation is relatively short. In the plantation, machines were not used every year but they were used heavily during the first, fourth (first-thinning), tenth (second-thinning) and thirty-fourth (final harvesting) years. Notably, a significant amount of greenhouse gas emissions from plantation work comes from harvesting operations which include skidding, loading, transportation and unloading. Since the processing centre for timber is farther from the site (35 km) than the collection point for peanuts, maize and beef (Kingaroy, around 15 km), machine use time for selling harvested goods in plantations is higher than the other land use products.

Usually, the second thinning is considered to be commercial (Venn, 2005), but in this case it is not commercial. Modelling shows that the average diameter at breast height (DBH) of trees at 10 years (second thinning) is around 20 cm. Wondai Sawmill, a major buyer of spotted gum in the study region, does not accept logs under 25cm diameter (for detailed discussion see following chapters). Therefore, the logs from the second thinning would not be transported to the sawmill. If they were, the emission of greenhouse gases from machines and fuel would have been higher than the estimated amount.

5.2.3 Emissions due to production and consumption of fuel

Fuel emissions include the greenhouse gas emissions in production operations. Since the emissions of greenhouse gas during the application of agrochemicals have already been considered in the agrochemical section, the fuel consumption (and greenhouse gas emissions) during the application of agrochemicals is not included in these data. As could be anticipated from the operation of machinery, the emissions of greenhouse gases in 34 years due to the use of fuel in the cropping system is highest (14030 kgCO_2e), followed by the plantation (6291 kgCO_2e) and pasture (1215 kgCO_2e) (see Table 5.1 for a summary and Table E-2 in Annex for detail). The emission of greenhouse gases due to consumption of fuel in cropping is almost 11.5 times higher than in pasture and 2.2 times higher than in the plantation. The higher the power requirement for a particular operation, the higher the fuel consumption High powered machines are used for deep ripping and digging operations in peanuts, and ripping and hilling operations in plantations. In addition, there is once again the effect of frequent machinery use with cropping.

5.3 Estimations of nitrous oxide emissions from different land use systems

Nitrous oxide would be emitted into the atmosphere in all land use activities. Emission of N_2O due to general land use, soil disturbance, application of nitrogen-fertiliser has already been discussed in chapter three and previous sections. In this section, the emission of N_2O due to biologically fixed nitrogen (BFN) and animal urine and faeces is discussed first. Then, a summary table of N_2O emissions in different land uses is presented, which includes the emissions due to general land use, soil disturbance and biologically fixed nitrogen.

5.3.1 Emissions of N_2O from biologically fixed nitrogen (BFN) of legumes

Legumes are available in all three types of land uses, that is, peanut-maize cropping land, pastureland and spotted gum plantation land. It is necessary to estimate the amount of biologically fixed nitrogen to estimate the amount of N_2O emissions from biologically fixed nitrogen. Since there has been extensive research on biologically fixed nitrogen in peanut cropping land, the most appropriate value was interpolated from Peoples *et al* (1992). See methodology sections for details of this discussion. On the basis of their research data, it is predicted that the peanuts in the research site could fix about 44.5 $kgNha^{-1}$ every two years, as they are planted in every alternate year.

The literature about BFN by pasture legume is limited to Siratro. In our research site, there were three varieties of legumes. The dominant one was Burr Medic (*Medicago polymorpha*) followed by Siratro *(Macroptilium atropurpureum*). Therefore, taking the sample of a dominant species, Vetregt and De Vries (1987) was followed to estimate the energy adjusted dry matter of legumes which was then used to estimate biologically fixed nitrogen as per the formula given by Bell *et al.* (1994) (for details see chapter three). The mass of carbon and ash per kg dry matter of dominant legumes was found to be 429 gm and 244.3 gm (average of leaf and stem) respectively. The energy adjusted dry matter of all legumes was found to be 329.18 kg ha^{-1}. It was then used to estimate biologically fixed nitrogen, which was found to be negative (-5.96 kg ha^{-1}). Since it was negative, the result was quite unrealistic. The whole process was checked thoroughly and all values were verified with the author of the article (M. Bell, 2005 pers. comm., 27 April). The overall process was found to be correct.

Later, in order to find out why the biologically fixed nitrogen value was negative, the equation given by Bell *et al*. (Fixed N=0.015 × Energy adjusted dry matter – 10.9) was analysed. It was mathematically proven that the formula is not workable; as it does not give the positive value of BFN when energy adjusted dry matter is less than 726.7 kg ha^{-1} (0.015 * 726.7=10.9). In the case of pasture, the energy adjusted dry matter was much lower than that. The energy adjusted dry matter of legumes in plantations was even lower than pasture. Therefore, this formula could not be applied for pasture and plantations.

Therefore, Armstrong *et al.* (1999) was considered instead of following Vetregt and De Vries (1987) and Bell *et al.* (1994). According to Armstrong *et al.* (1999), Siratro (the second dominant legume species) fixed 176 kg of biological nitrogen while accumulating 16160 kg of dry matter (1 kg dry matter of Siratro = 0.011 kg BFN). On the basis of this figure and dry matter of all legumes[2] in pasture (250 kg ha^{-1}) and in plantation (140 kg ha^{-1}), the biologically fixed nitrogen in pasture and plantation was found to be 2.75 kg and 1.54 kg ha^{-1} respectively. In order to estimate the amount of nitrogen emission from biologically fixed nitrogen, an emissions factors of 1.25% of was used, which was also applicable to fertiliser and animal excretion (IPCC, 1996).

The amount of CO_2e emissions from biologically fixed nitrogen in all land uses is almost negligible. In the case of a plantation, the estimated value of CO_2e could be even lower when the canopy cover increases. Since it is a very small amount, the same value has been used for further modelling in all ages of the plantation.

5.3.2 Emissions of N_2O from urine and faeces of cattle

The spotted gum plantation has been managed as a silvipastoral system. Therefore, cattle have been grazed both in pastureland and plantation. In one calendar year, 27 cattle grazed for 92 days in 12.15 ha of pastureland and the same number of cattle grazed for 94 days in 24.3 ha of the four-year plantation (Table 5.2).

All cattle stayed in the field during the grazing period. The amount of nitrogen-excretion on urine and dung in different seasons is different (Nussey, 2005). The number of cattle and their grazing days in different seasons, amount of nitrogen excreted in urine and faeces and the total amount of CO_2e[3] emitted from the cattle during the grazing period in the pasture and plantation are given in Table 5.2.

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[2] The conversion factor of siratro for total dry matter to BFN was used for all legumes.

[3] Nitrogen was converted to nitrous oxide multiplying by 1.57, which was then multiplied by 310 to estimate CO_2e mass.

Table 5.2 N excretion in urine and faeces of cattle in pastureland and plantation in Kingaroy

Seasons	No of cattle grazed	No of days	N-excreted ($g\ head^{-1}day^{-1}$) Urine	Faeces	N kg ha^{-1}
Pastureland (total area 12.15 ha)					
Summer (Dec-Feb)	0	0	82.03	34.85	0.00
Autumn (Mar-May)	27	11	42.12	28.54	1.73
Winter (Jun-Aug)	27	79	151.95	45.14	34.60
Spring (Sep-Nov)	27	2	246.12	58.43	1.35
Total amount of CO_2e ($kg\ ha^{-1}yr^{-1}$) emissions from cattle excretion in pastureland = 229.24					
Four-year spotted gum plantation (total area 24.3 ha)					
Summer (Dec-Feb)	27	34	82.03	34.85	4.42
Autumn (Mar-May)	27	50	42.12	28.54	3.93
Winter (Jun-Aug)	27	10	151.95	45.14	2.19
Spring (Sep-Nov)	0	0	246.12	58.43	0.00
Total amount of CO_2e ($kg\ ha^{-1}\ yr^{-1}$) emissions from cattle excretion in plantation =64.1					

Note: Average excretion of N from urine and faeces are 130.56 and 41.74 g $head^{-1}day^{-1}$, respectively, which, in total, emits 382.59 kg CO_2e $head^{-1}yr^{-1}$ into the atmosphere.

The total amount of CO_2e emitted from pastureland and plantation was found to be around 229.24 and 64.07 kg ha^{-1} yr^{-1} respectively. The difference in CO_2e emissions between pasture and plantation could be explained by two reasons. First, the stocking rate in pasture (0.56 head ha^{-1}) was higher than in a plantation (0.286 head ha^{-1}). Second, pasture was mainly grazed in the winter season in which the amount of faeces and urine nitrogen are higher than in the summer and autumn seasons, which were the main grazing seasons in the plantation. However, if the stocking rate was the deciding factor, the CO_2e emission in pasture could be about twice that of the plantation, but it was much more than that. Therefore, the second factor was more dominant.

5.3.3 The long-term trend of N-excretion in pastureland and plantation

In the long-run, the grazing times of pasture and plantation could be changed and that would make some differences in CO_2e emissions. As the time horizon was 34 years, the grazing would be done in all seasons over such a long period. Therefore, the average value of nitrogen excretion from urine and faeces for all seasons (172.3 $head^{-1}day^{-1}$ = emissions of 382.59 $kgCO_2e$ $head^{-1}yr^{-1}$) could be more appropriate for long-term modelling. Since the stocking rate of pasture is 0.56 ha^{-1}, the average emissions rate of 214.25 $kgCO_2e$ $ha^{-1}yr^{-1}$ has been used for long-term modelling in pastureland.

In the case of the plantation, grazing was not allowed until the tree were three years of age. Therefore, there would be no emission from excretion until the third year.

The stocking rate of cattle in the fourth year was 0.286 ha^{-1}. In that fourth year, the emissions from cattle excretion could be around 109.42 kg CO_2e $ha^{-1}yr^{-1}$ (Figure 5.1). Due to increasing canopy cover, the number of cattle grazing would be decreasing over time, which in turn would reduce the amount of CO_2e emissions. A decreasing rate of cattle is correlated with the decreasing rate of grass biomass (the rate is already discussed in chapter three). Due to a decreasing number of cattle, emissions would reduce to 94 kgCO_2e ha^{-1} at year 10. After commercial thinning (at year 10), it would return to 109.42 kgCO_2e ha^{-1} at year 11. After that, it would reduce continuously up to year 25 to 53.36 kgCO_2e $ha^{-1}yr^{-1}$. Thereafter it would remain constant until final harvesting. The summary table of nitrous oxide (CO_2e) emissions from different sources is given in Table 5.3.

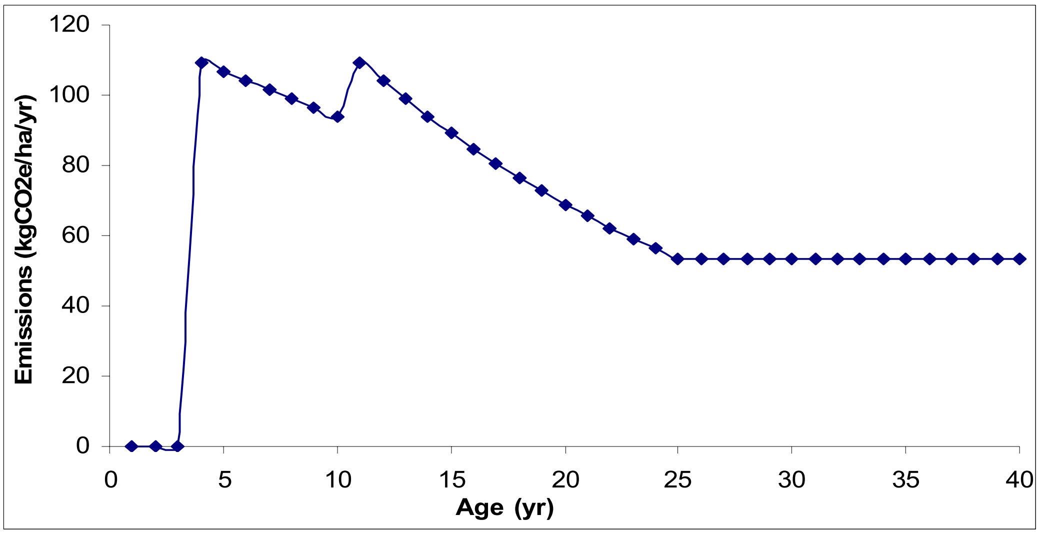

Figure 5.1 Long-term trend of emission of CO_2e from animal excretes in a spotted gum plantation in Kingaroy

Table 5.3 Summary N_20 emissions (GHGs) from various land use systems

Emissions due to	Pastureland Nitrogen	Pastureland CO_2e	Cropping land Nitrogen	Cropping land CO_2e	SG plantations Nitrogen	SG plantations CO_2e
General land use	2.5 kg$ha^{-1}yr^{-1}$	1216.7 kg$ha^{-1}yr^{-1}$	2.52 kg$ha^{-1}yr^{-1}$	1226.5 kg$ha^{-1}yr^{-1}$	2.52 kg$ha^{-1}yr^{-1}$	1226.5 kg$ha^{-1}yr^{-1}$
Biologically Fixed N	0.03 kg$ha^{-1}yr^{-1}$	14.6 kg$ha^{-1}yr^{-1}$	0.56kg ha^{-1}/2yr	136.3 kg$ha^{-1}yr^{-1}$	0.02 kg$ha^{-1}yr^{-1}$	9.7 kg$ha^{-1}yr^{-1}$
Soil disturbance	0.29 kgha^{-1}/8 yr	141.1 kgha^{-1}/8yr	0.29 kg$ha^{-1}yr^{-1}$	141.1 kg$ha^{-1}yr^{-1}$	0.29kg ha^{-1}/34yr	141.1 kg ha^{-1}/34yr
Urine & faeces	vary	214.25 kg$ha^{-1}yr^{-1}$	0	0	vary	0-109.42 kg$ha^{-1}yr^{-1}$

Emissions of nitrous oxide from nitrogen fertiliser are not included in the table. The analysis shows that around 51.1 t, 49.7 t and 44.7 t of CO_2e (ha^{-1}) are released to the atmosphere in 34 years due to nitrogenous sources in cultivation, pasture and plantations respectively. The higher amount of emission in cultivation is due to frequent soil disturbances and a higher amount of legume emissions. The higher amount of emissions in pasture than in plantation is attributed to frequent soil disturbances and higher stocking rates.

5.4 Estimation of methane emissions from cattle

The amount of methane emissions from cattle in pastureland and plantations in the calendar year (2005) was around 36 and 14 kg ha^{-1}, respectively, which are equivalent to around 750 and 301 kg CO_2 (Table 5.4). The amount of CO_2e emissions from pasture should have been twice that from the plantation, as the stocking rate in plantations (0.286 ha^{-1}) was half of that in pastureland (0.56 ha^{-1}). However, it was more than double. The reason described above in the case of nitrous oxide emissions is also applicable here. The pasture was mainly grazed in the winter season in which the amount of CH_4 emissions is higher than in the summer and autumn seasons, which were the main grazing seasons in the plantation.

Table 5.4 Emission of CH_4 from cattle in pasture and plantation in Kingaroy

Season	No of Cattle	No of days grazed	CH_4 ($kgday^{-1}$)	CH_4($kgha^{-1}$)	$C0_2e$ ($kgha^{-1}$)
Pasture (12.15ha)					
Summer	0	0	0.15	0.00	0.00
Autumn	27	11	0.12	2.93	61.60
Winter	27	79	0.18	31.60	663.60
Spring	27	2	0.26	1.16	24.27
Total				35.69	749.47
Plantation (24.30ha)					
Summer	27	34	0.15	5.67	119.00
Autumn	27	50	0.12	6.67	140.00
Winter	27	10	0.18	2.00	42.00
Spring	0	0	0.26	0.00	0.00
Total				14.33	301.00
Average of seasons (kg CH_4 $head^{-1}yr^{-1}$)=65.7= 1379.70 kg CO2e $head^{-1}yr^{-1}$					

Adopted from Nussey, 2005

Instead of taking exact values from the past calendar year, for the reasons as explained earlier in the case of NO_2 emissions, an average value of CH_4 emissions from cattle (65.7 kg $head^{-1}yr^{-1}$ = emissions of 1379.7 $kgCO_2e$ $head^{-1}yr^{-1}$) would be more appropriate for long-term modelling. Therefore, as the stocking rate (ha^{-1}) of pasture is 0.56, the average emissions rate of 773 $kgCO_2e$ $head^{-1}yr^{-1}$ has been used for the long-term modelling in the pastureland.

In the case of the plantation, there was no CH_4 emission until the third year. The stocking rate of cattle in the fourth year was 0.286. As a result, in the fourth year, the CH_4 emissions from cattle would be around 395 $kgCO_2e$ ha^{-1}. As the stocking rate was going up and down in different years at different rates, the emissions of CH_4 in each different year would be different (the rate is already discussed in the Methodology). The amount of methane emission would be down from 395 at year four to 339 $kgCO_2e$ at year 10 and would regain to 395 $kgCO_2e$ at year 11. After that, it would be down continuously to around 192 $kgCO_2e$ ha^{-1} at year 25 and remain constant thereafter (Figure 5.2).

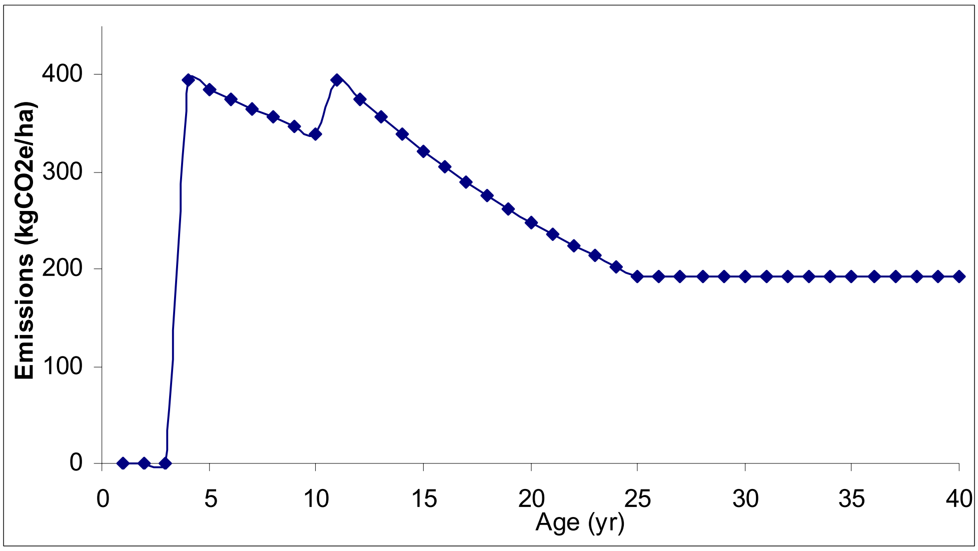

Figure 5.2 Long-term trend of emission of methane (CO_2e) from cattle in spotted gum plantations in Kingaroy

Methane emissions from cattle depends on several factors. For a given species, it depends on its genotype, level of feed intake, feed digestibility, live weight gain and feed use efficiency (Hegarty, 2001).

There are several some literature about methane emissions from livestock. The average emission rates in developed and developing countries are 55 kg $head^{-1}yr^{-1}$ and 35 kg $head^{-1}yr^{-1}$ respectively (Crutzen *et al.,* 1986 cited in Eckward *et al.,* 2000). However, even within developed countries there is a big difference in methane emissions between dairy and non-dairy cattle. For example, in New Zealand, mature dairy cows and non dairy cows emitted 80.6 and 69.5 kg $head^{-1}yr^{-1}$ respectively (Crutzen *et al.* 1986 cited in Eckward *et al.,* 2000). Looking at those figures, the estimation of 65.7 kg $head^{-1}yr^{-1}$ from beef cattle seems appropriate.

5.5 Conclusions

This study has demonstrated that there is a significant difference in greenhouse gas emissions in three land use systems due to the application of three primary farm inputs (agrochemicals, machinery and fuels) over 34 years. In total, approximately 35.7, 1.6 and 8.5 $tCO_2e\ ha^{-1}$ greenhouse gas will be emitted into the atmosphere from the crop, pasture and plantation enterprises respectively (in 34 years). This indicates that planting trees on ex-cultivated land has considerable greenhouse gas benefit but there would be a negative effect if trees were planted on current pastureland. The net difference of around 27.2 $tCO_2e\ ha^{-1}$ of greenhouse gases between plantation and cropping only from primary farm inputs has implications for achieving 'Vision 2020'.

Some caution is needed in extrapolating from these findings, given that this is a particular cropping system with relatively intensive on-ground activities. A reduced tillage system, for example, may result in a more favourable outcome for cropping, depending on the agrochemical inputs needed. Nonetheless, long-rotation pasture would still be likely to be the low emission option.

The second conclusion that there is a significant amount of greenhouse gas (CO_2e) emitted into the atmosphere from nitrogenous sources in all land use systems. The current body of literature is poorly accounting for these sources of emission. Omitting these emissions would have serious implications on the overall cost benefit analysis in all land use systems. The third conclusion that around 1.25 $t\ ha^{-1}$ (26.25 $t\ CO_2e\ ha^{-1}$) of methane from pasture and 0.41 $t\ ha^{-1}$ of methane (8.6 $t\ CO_2e\ ha^{-1}$) from plantations would be emitted into the atmosphere in 34 years, and therefore both pasture and plantation emits significant amount of methane.

The overall analyses suggest that the emissions of greenhouse gas from primary farm inputs and productions in cultivation are higher than in plantations, but pasture remained the best options. This was the main hypothesis to be tested in this chapter. However, this is a piecemeal approach. Plantation could be a net sink of greenhouse gases due to higher potential of sequestrating carbon in soil and biomass. Therefore, without a holistic analysis of total net present values from all sources and sinks and costs and benefits of all land use systems there could be no accurate conclusion. All these data have been considered for the overall cost and benefit analyses in the chapters seven and eight.

Chapter 6

Optimum Spacing for Spotted Gum Plantations

6.1 Introduction

Spotted gum is becoming synonymous with hardwood regimes in the Southeast Queensland (SEQ). The reasons for its popularity were discussed in chapter one. The Queensland Government approved a $30 million plan to increase the hardwood plantation, especially of spotted gum, in SEQ (DPI&F, 2004b). The majority of these plantations will be in the Burnett region (N. Halpin[1], 2004, pers. comm., 18 December), where this research has been focused. The success and continuity of the plantations depend on economic returns. Selecting appropriate spacing (stocking rate) is of utmost importance in maximising economic returns. Therefore, what stocking rate is optimal for maximum economic return is a major concern for all stakeholders.

Optimal spacing depends on the objectives of the plantation. If the objective is for maximising firewood and fodder biomass, trees with plenty of branches would be preferred. In such a case, a lower stocking rate would be optimal. If the objective is to produce pole size trees, a higher stocking rate would be preferred. In a dense environment, trees will have strong competition for light, which would help trees to gain height rather than diameter. A tree with large height could produce a good pole. The purpose in this study is to maximise total merchantable log volume. Therefore, what stocking rate is optimal to maximise merchantable log volume at final harvesting is the major focus of the chapter.

The Warril View hardwoods experiment site is the oldest spotted gum experimental site in the SEQ, in which trees were planted in five different spacing levels. On the basis of time series data of all spacing levels, the non-linear estimation module of STATISTICA software was run and the optimum spacing level was determined.

This chapter is divided into several sections. An analysis of the average diameter at breast height (DBH) and height of trees at different spacing levels is presented first.

[1] Hardwood Plantation Development Officer, DPI Forestry, Queensland Government

After that, growth models and thinning scenarios are discussed. Each section leads towards the determination of optimum spacing levels.

6.2 Average DBH of trees at various spacing levels

Diameter at breast height (DBH) and height are two vital attributes of a tree. Since the diameter (not height) is squared for the estimation of volume (Volume=π x Diameter^2/4 x height) of the log, the diameter plays the dominant role in volume determination. Moreover, in spotted gum, height is not generally a concern, as it has inherited the properties of good height and form. Because of these characteristics, Wilson termed the spotted gum as 'Lady of the Woods' (cited in Huth *et al.,* 2004). The DBH, therefore, is the main parameter of interest. The mean DBH of all trees and the largest 50 trees planted at five spacing levels[2] were compared (A, B, C, D and E). The graph between age and the mean DBH of the largest 50 trees is given in Figure 6.1.

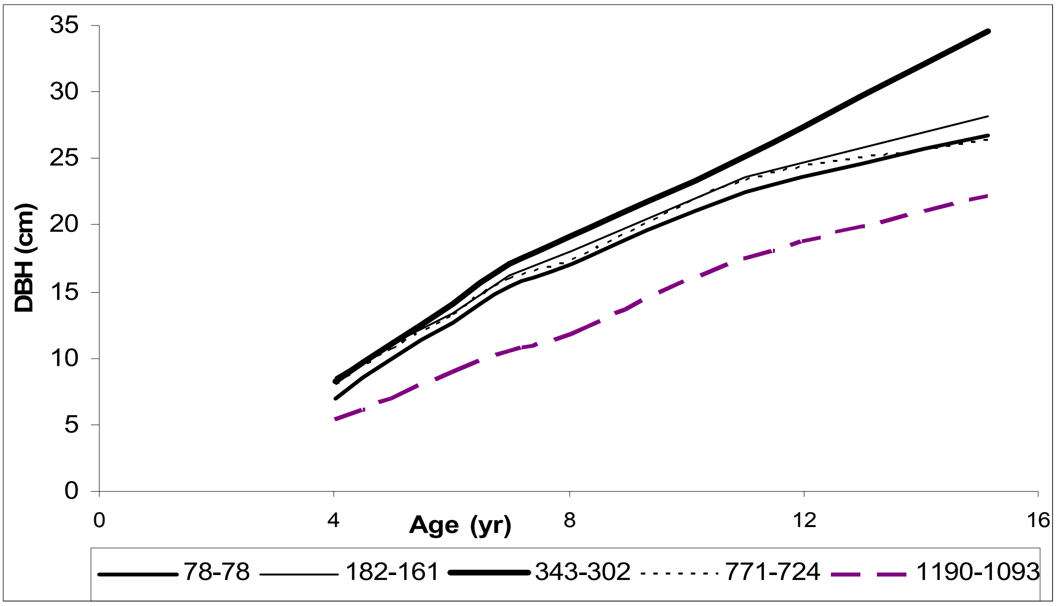

Figure 6.1 Average DBH of 50 largest spotted gum trees for each hectare, Warril View, Queensland

[2] Five spacing levels - 'A' (11.3 m x 11.3 m=78 trees ha^{-1}), 'B' (7.4 m x 7.4 m=182 trees ha^{-1}), 'C' (5.4 m x 5.4 m=343 trees ha^{-1}), 'D' (3.6 m x 3.6 m =771 trees ha^{-1}) and 'E' (2.9 m x 2.9 m=1189 trees ha^{-1}). No artificial thinning was done but natural thinning was probably occurring in all spacing levels except spacing level 'A', as there was no mortality. The number of trees at the last measurement (after 15.16 years of plantation) at spacing level 'B', 'C', 'D' and 'E' were reduced to 161 (by 21), 302 (by 41), 724 (by 47) and 1093 (by 97) trees per hectare, respectively.

The average DBH of the 50 largest trees (ha^{-1}) at year 15.16 showed that the 'C' spacing level had much higher DBH (34.62 cm) than other spacing levels. Initially, the average DBH of 'C' spacing level was lower (by 0.25 cm) than 'B' spacing level, but soon it became the highest from the fifth year. As a rule of thumb, because of the large spacing level, the average DBH of 'A' and 'B' spacing levels would have higher mean DBH than the 'C' spacing level. But selecting the 50 largest trees from the small number of trees at 'A' and 'B' spacing levels might have resulted in lower (than expected) mean DBH. Therefore, from the analysis of DBH of the 50 largest trees, it was obvious that the spacing level 'C' was better than the others. But a high amount of cost on plantation could not be compensated for from 50 trees in a hectare. This demands further analysis of the DBH of all trees.

While comparing the average DBH of all trees at five spacing levels (Figure 6.2), there was not much difference in DBHs between the spacing levels 'A', 'B' and 'C' at year 15.16 (Figure 6.2). However, the spacing level 'D' and 'E' had much lower mean DBH than the other spacing levels.

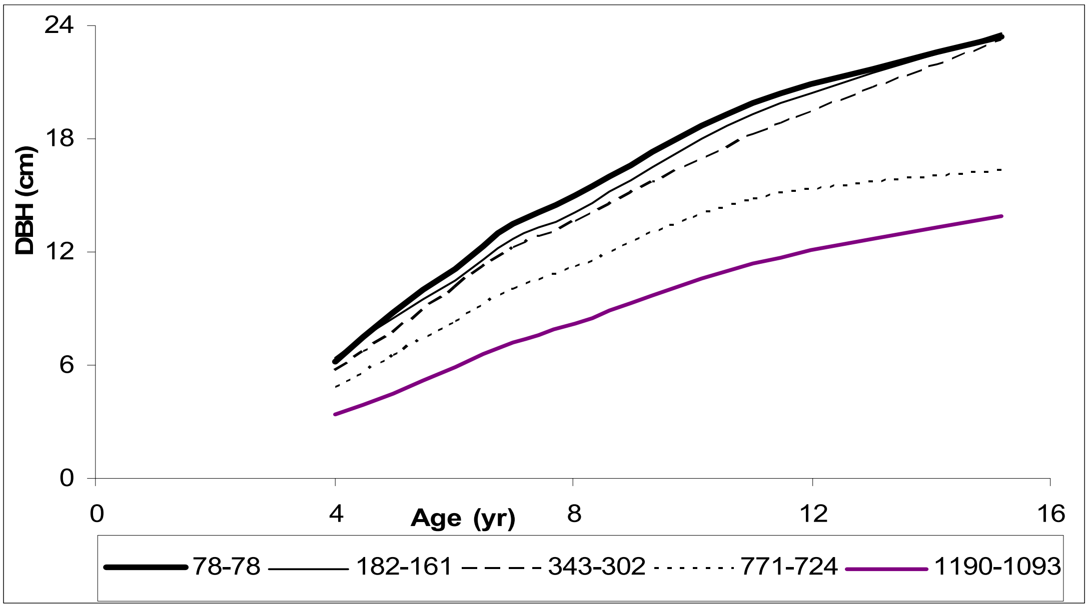

Figure 6.2 Average DBH of all spotted gum trees for each hectare, Warril View, Queensland

Since there was higher number of trees (302 trees ha^{-1}) in spacing level 'C', its similar mean DBH with 'A' (78 trees ha^{-1}) and 'B' (161 trees ha^{-1}) spacing levels confirmed its superiority over the other spacing levels. However, it is necessary to also analyse the mean height of all trees.

6.3 Average height of trees at various spacing level

The mean height of all trees at spacing level 'D' was higher than others (Figure 6.3). However, the difference in mean height between the 'C' (17.12 m) and 'D' (17.27 m) spacing levels was not so great. The mean DBH of spacing level 'A' (14.95 m) and 'B' (15.11 m) were much lower than spacing level 'C' (23.21 cm). As the number of trees per hectare in spacing levels 'A' and 'B' were lower than the other spacing levels, the lower mean height was expected at 'A' and 'B' spacing levels. This was due to the open canopy and therefore lower level of competition for light among the trees. Figure 6.3 shows that the increasing rate of mean height decreases around the age 9-12 (inflection point) at all spacing levels. This has big implications as from this age, the tree's main focus is for crown and diameter growth, rather than on height growth (Khanna, 1989). Initially trees compete for light and therefore the height is the main focus. Once they approached the inflection point, their target changes to diameter and crown cover. Therefore, this is the age at which farmers need to do the second thinning for the promotion of diameter growth.

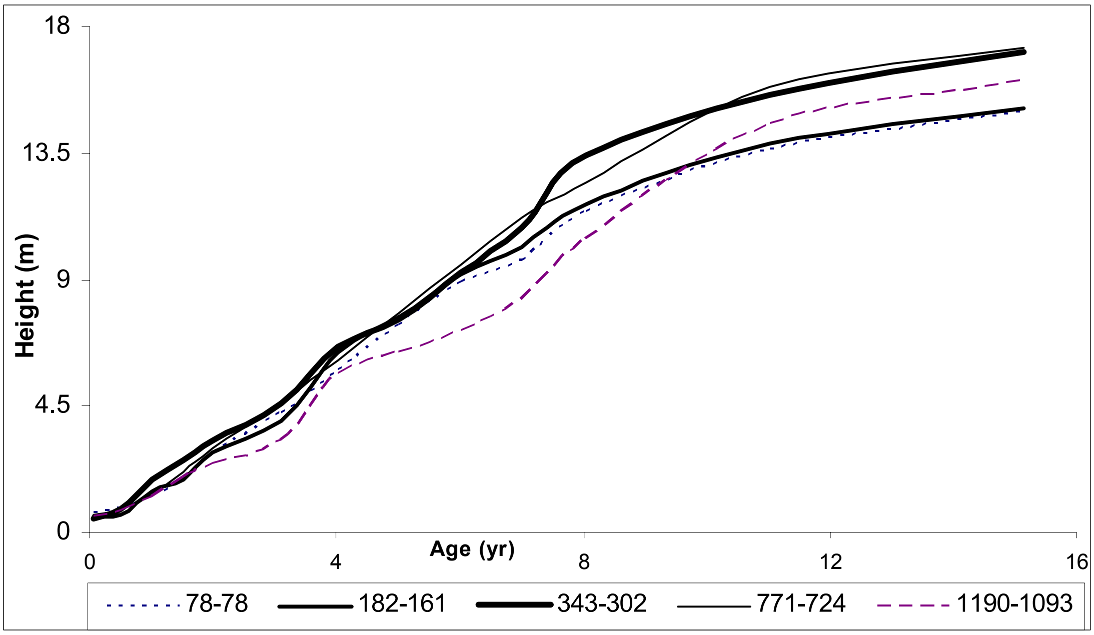

Figure 6.3 Average height of all spotted gum trees for each hectare, Warril View, Queensland

The analysis of time series data of the mean DBH of the 50 largest trees, and mean height and mean DBH of all trees suggested the superiority of 'C' spacing level over the others. However, this result is only up to the 15.16 year age and not for the long-term. There are several questions to be resolved to arrive at a final conclusion. What will be the mean DBH of all trees at different ages (say up to 60 years) in a "business as usual" scenario? What age will be the best to get the best DBH (may be 40 cm, 50 cm or 60 cm) in different spacing levels? This requires the analysis and simulation of growth models.

6.4 Analysis of growth model

The different regression parameters (b_0, b_1, b_2 and b_3), which are discussed in chapter three, of growth models of each spacing level are given in Table 6.1. The lower root mean square value and higher coefficient of determination (R^2, variance explained) value show that the models were well fitted to the actual values (Makridakis *et al*, 1998; Wilson, 2001). The potential maximum mean DBH (that is b_0) has a significant meaning. The different value of b_0 at different spacing levels shows that the potential maximum mean DBH at each spacing level would be different. For example, if the number of trees as it is at spacing level 'D' (724 tree ha^{-1} of current level) the maximum mean potential DBH of trees would be only around 55 cm. Spacing levels 'A', 'B' and 'C' have a similar value of b_0 (around 81 cm). This suggests that there would not be much difference in the maximum potential mean DBH among them.

Table 6.1 Regression parameters and accuracy measures of different growth models

Stem per ha (sph)	b_0	b_1	b_2	b_3	RMSE (cm)	Variance explained
A (78-78)	81.0492	89.3834	0.023097	-0.02226	0.867	98.47%
B (182-161)	80.9800	89.0258	0.022675	-0.02155	0.577	99.30%
C (343-302)	81.0509	88.6978	0.021561	-0.02051	0.651	99.08%
Largest 200 trees	98.4523	89.6975	0.022126	0.020296	0.712	99.16%
Largest 250 trees	90.6030	90.3706	0.022135	0.000571	0.667	99.19%
D (771-724)	54.9980	81.6793	0.022030	-0.09869	0.789	98.72%

Note: The first and second values in parentheses in column one shows the number of trees (ha^{-1}) at the time of planting and at 15.16 year respectively, and RMSE represents Root Mean Squared Error.

The maximum mean potential DBH of trees shows that keeping around 200 trees (ha^{-1}) could be the best solution among the others, but without estimating total merchantable wood volume it can nor be concluded.

6.5 Estimation of mean DBH and volume at different ages

A forest growth model is non-linear, sigmoidal in shape and has points of inflections. Therefore, the von Bertalanffy growth model, which can capture all those peculiar features of a forest growth model (Williams *et al*, 1991; Vanclay, 1994; Fekedulegn *et al.*, 1999), was used to run the non-linear estimation module of STATISTICA software. After that, using the estimated regression parameters of all spacing levels and the von Bertalanffy growth model equation on the mean DBH of trees at different ages was estimated (Table 6.1 and Table 6.2). Modelling and analysis shows that the harvesting age of trees for a given DBH could be reduced by increasing the spacing levels. For example, a 40 cm mean DBH could be achieved at 29, 30, 31 and 56 years by keeping trees at 'A' (11.3 m x 11.3 m), 'B' (7.4 m x 7.4 m), 'C' (5.4 m x 5.4 m) and 'D' (3.6 m x 3.6 m) spacing levels[3], respectively. However, there is not a big difference in age to have a 40 cm mean DBH at 'A', 'B' and 'C' spacing levels. The difference in age is increasing for a higher mean DBH. If the spacing level is fixed at 'D', there will never be a 55 cm mean DBH (maximum potential DBH is less than 55 cm, Table 6.1). Therefore, the spacing level 'D' was not considered for further analysis.

Since the number of trees were higher at spacing level 'C' (302) than spacing level 'A' (78) and 'B' (161), a greater amount of merchantable log volume would be achieved from spacing level 'C' than from 'A' and 'B'. For this, the mean DBH of trees for different ages was estimated and then the merchantable log volume (ha^{-1}, up to 25cm top diameter) was calculated. The total merchantable log volume of spacing level 'C' was found to be much higher than the merchantable log volume of 'A' and 'B' spacing levels (Table 6.2).

Table 6.2 Mean DBH (cm) and merchantable volume up to 25cm top diameter (m^3 ha^{-1}) at different ages from various spacing levels at Warril-View site

Age	Spacing level 'A'		Spacing level 'B'		Breakdown of spacing level 'C' into three different scenarios					
yr	78 trees ha^{-1}		161 tree ha^{-1}		200 trees ha^{-1}		250 trees ha^{-1}		302 trees ha^{-1}	
	DBH	Vol	DBH	Vol	DBH	Vol	DBH	Vol	DBH	Vol
25	36.2	44.8	35.7	88.1	41.1	169.6	38.5	174.5	34.4	145.4
30	41.1	66.3	40.6	131.5	47.1	245.4	43.9	255.7	39.2	222.6
35	45.5	87.7	44.9	174.8	52.4	322.1	48.8	337.6	43.5	300.3
40	49.4	108.5	48.8	217.2	57.2	398.0	53.2	418.2	47.4	376.9
45	52.9	128.5	52.3	258.0	61.5	471.6	57.1	496.2	50.8	451.0
50	55.9	147.4	55.4	296.6	65.3	542.3	60.6	570.8	53.9	521.9
55	58.7	165.2	58.1	333.0	68.8	609.2	63.8	641.4	56.7	589.0
60	61.2	181.7	60.6	366.9	71.9	672.1	66.6	707.4	59.2	652.1

[3] The discussion of spacing level 'D' data is estimated by using the regression equation discussed in methodology chapter and regression parameters given in Table 6.1.

The next section analyses the hypothetical thinning scenarios.

6.6 Thinning scenario analysis at spacing level 'C'

The overall analysis, so far, confirmed that the spacing level 'C' is a better option among the five different spacing levels. However, one question still remained. What would be the wisest decision: keeping all 302 trees for the whole rotation, or thinning some trees at some stage in time? In order to resolve this problem, two more simulations were done. Similar analyses were performed by taking the time series mean DBH data of the 200 and 250 largest trees per hectare from spacing level 'C'. The regression parameters produced from the modellings are given in Table 6.1. From modelling, it is revealed that if we keep the 200 and 250 best trees per hectare, the maximum potential mean DBH (b_0) would be increased to around 98 and 91 cm (from 81.04 cm of business as usual scenario of level 'C'), respectively (Table 6.1).

The predicted mean DBH (cm) and volume (m^3 ha^{-1}) of three different scenarios from level 'C' at different ages are given in Table 6.2. It was found that the time to get desirable DBHs can be reduced dramatically by keeping the largest 200 and 250 trees per hectare. For example, instead of waiting 44 years for a 50 cm mean DBH by using the business-as-usual scenario, farmers will be able to get the same mean DBH in 33 years by keeping the 200 best trees and in 37 years by keeping the 250 best trees per hectare. The analyses show that the merchantable volume of trees at each harvesting age would be higher than in other cases while keeping 250 trees per hectare (Table 6.2). Therefore, keeping around 250 trees per hectare would be the best possible option.

Due to the limited duration of the research plot, the extrapolation of data from the limited time series data was necessary for this study. However, the potential maximum response variable (b_0) gives an important clue about the model. Boland (1984) and Huth *et al.,* (2004) were of the view that even in dryer and poorer sites, spotted gum may reach from 70 to 120cm in DBH. Similarly, in the intensive inventory of spotted gum in similar natural sites some trees were found between 80 cm and 84 cm DBH (Margules, 1998). Since the estimated b_0s from different spacing levels were within the range of the above mentioned values, they seemed reasonable. Moreover, the root mean square error (RMSE) and coefficient of determination (R^2) of all models are 'good fit'. This evidence suggested that the models are reliable at the given limited data environment. More importantly, this study has an economics orientation, thus, sensitivity analysis is done for different spacing levels (in chapter 8). Therefore, a small deviation of spacing level would have been captured by the sensitivity analysis.

6.7 Conclusions and implications

This chapter demonstrates how the best spacing levels can be determined by using non-linear regression modelling in a limited data environment. The growth model of spotted gum was produced and the mean DBH and total merchantable log volume of different spacing levels at different harvesting ages were estimated. From the analysis, the spacing level ‘C’ (343 trees ha^{-1}) was found to be better than the others. Further analysis of mean DBH and height of the largest 200 and 250 trees from spacing level ‘C’ revealed that the merchantable volume of log could be maximised by keeping around 250 of the largest trees per hectare. This optimum spacing level is used to estimate the total merchantable volume (ha^{-1}) of trees in different ages, which is used to find the optimum rotation age and net present values of trees.

This analysis is based on the current state of knowledge and limited data. It could be applicable for broad scale financial and economic planning in similar climatic, edaphic and topographic conditions of the experimental sites. If the full rotation data are available, a more reliable model could be produced by applying the same methodology.

Chapter 7

Optimal Rotation Age for Spotted Gum Plantations

7.1 Introduction

Optimal rotation is the age at which the trees would be cut to maximise a production objective. Such a possible objective is maximum merchantable log[1] volume as discussed in the last chapter. For this thesis, there are three levels of objectives: the maximum economic return from a) timber, b) timber and grazing[2], and c) timber and grazing and carbon. In order to address these objectives, a growth model was developed, which was used to estimate the merchantable log volume at different ages. In this chapter, discussion is focused on the growth models, greenhouse gases sequestration and emissions amount, different types of cost and benefit data and then estimates of different types of optimal rotations and their respective net present values (NPVs). After that, different NPVs determining variables, which are most sensitive to the NPVs, are discussed. Finally, the possibility of in-/decreasing NPVs are discussed and the chapter conclusions are presented.

7.2 Optimal rotation for maximum sustainable yield (MSY)

Current annual increment (CAI or marginal product in economic terms) and mean annual increment (MAI or average product in economic terms) are two important concepts for determining maximum sustainable yield rotation. There were two ways to estimate the maximum sustained yield rotation age: first, based on the merchantable log volume[3] increment rate, or second, based on the total biomass increment rate. Since farmers in the research site were concerned with merchantable log volume, the discussion is based on the first option. The growth model shows that there would be no merchantable logs up to age 13. This is because the diameter at breast height (DBH) of trees until then would be less than 25 cm. Therefore, CAI and MAI curves below age 13 are not shown in the graph (Figure 7.1). Hence, the effects of the first and second thinning at the age of 4 and 10, which would reduce wood

[1] Throughout the thesis, the price of logs (not timber) is considered. In general, log volume is directly related to timber volume. Therefore, in some cases, timber and logs are used interchangeably, even though they have different technical meanings. Timber is used in the literature as a symbolic meaning, just to separate it from non-timber benefits, such as the benefit from grazing and greenhouse gases. Throughout the thesis, 'timber value' represents 'merchantable log value'.

[2] For simplicity, grazing value is described as stock value in many places.

[3] In this study, merchantable log volume represents the log volume only up to 25 cm top diameter.

volume, are not shown. In order to find maximum sustainable yield rotation based on total biomass, these thinning effects would to be seen.

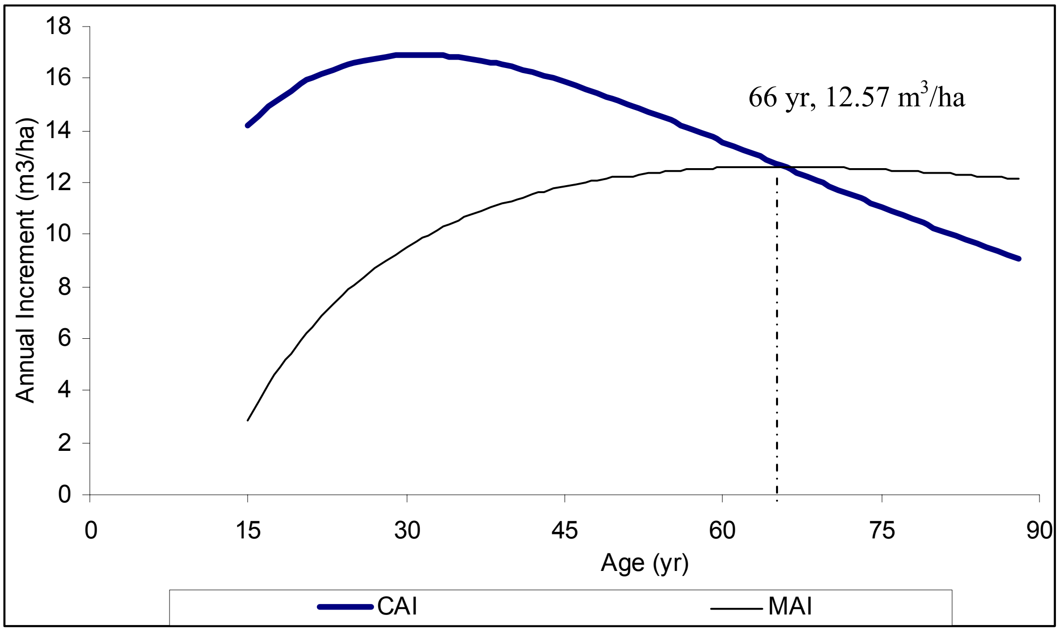

Figure 7.1 Maximum sustainable yield rotation age of spotted gum plantation in Kingaroy, Queensland

The CAI increased slowly at first[4], and then increased rapidly to the maximum of 16.91 m^3 ha^{-1} at age 31, after which it begins to decline (Figure 7.1). Theoretically, the CAI could be zero when the total volume approaches the maximum. As we have produced graphs only up to age 88, those points are not shown in the graph. Since MAI is the average volume of all previous years, it increased slowly and even after the culmination of CAI, MAI still continued to rise. At the CAI culmination point (year 31), MAI was around 9.73 m^3ha^{-1}. The MAI increased continuously and approached the maximum (12.57 m^3ha^{-1}) at age 66. This is the age at which CAI=MAI or MAI culminated. After this age, MAI started to decline. Therefore, age 66 is the optimal rotation age, if the objective is to maximise the maximum sustainable yield in terms of log volume. This rotation is used to maximise timber volume. The MSY rotation has no relation to costs and benefits and greenhouse gases, they represent CAI and MAI in physical term not in economic term. Therefore, it is not affected by depreciation rates and the demand and the supply situation of the market.

[4] In figure, slowing increasing part is not seen, as the graph start from age 15

7.3 Optimal rotation age for maximum economic yield from timber

There are two principles to estimate the maximum economic yield (MEY) rotation: the static efficiency principle and the dynamic efficiency principle (refer to chapter two). The static efficiency principle suggests that the maximum economic yield rotation is the age at which marginal benefit equals marginal cost. The dynamic efficiency principle suggests harvesting trees when there is maximum net present value. Fortunately, both principles give the same result (Campbell, 1999). Should there be no cost data, a third approach of the percentage growth rate of timber value could be applied. However, this approach can only be used to estimate the optimal rotation age, not the net present value. Unlike the maximum sustainable yield rotation, maximum economic yield rotation considers cost and benefit data. In this section, cost and benefit data are discussed first. After that, the optimal rotation age of plantations based on the percentage growth rate and the dynamic efficiency approach are discussed.

7.3.1 Cost and benefit of plantations

In plantations, costs are heavily incurred during the establishment period. The details of cost data (ha^{-1}) are given in the Annex (Table G-1). During the first four years of the establishment period, around \$2077 (ha^{-1}) was spent[5]. The major spending was for hilling and ripping (\$150 ha^{-1}), seedlings production (\$750 ha^{-1}) and transportation (\$250 ha^{-1}), labour for the plantation operation (\$170 ha^{-1}) and fertilisers (\$137 ha^{-1}) in the first year, and thinning and form pruning (\$355 ha^{-1}) in the fourth year. Initially, around 1000 trees ha^{-1} were planted. There was around 20% mortality until the third year of plantation. By the fourth year, around 800 trees were left. In the first thinning, the total number of plants was reduced from 800 to 400 ha^{-1}. The higher cost for thinning and pruning was due to this being a labour intensive activity. The modelling shows that the optimal spacing of plantations after the second thinning is a final outcome of 250 trees ha^{-1}. The second thinning and tidying-up operation costs around \$390 ha^{-1}.

[5] All cost and benefit data in this chapter are for one hectare, except where it is described explicitly more.

In Australia, trees are usually harvested by contractors or sawmillers. They offer a stumpage price to the farmers based on log volume and grade. Therefore, the farmers may not often know the harvesting cost. With a small scale farm plantation it may not be feasible, or they may not want to harvest themselves. However, in 25-30 years time, the farm forestry may be on a commercial scale. Therefore, two different scenarios are developed for cost and benefit data: a) current or business-as-usual scenario and b) optimistic scenario.

The business-as-usual scenario is based on the current practice of harvesting by sawmillers or contractors. Only the after-harvest tidying-up cost of \$170 ha^{-1} would be borne by farmers. All the other costs of harvesting, loading, unloading and transportation would be borne by the harvester. This approach assumes current equipment and practices will remain constant over time and the farmers would receive a stumpage price based on grades and volume of logs on their farm.

The optimistic scenario assumes that farm forestry will advance towards a commercial scale in the next 30 years and advanced harvesting equipment similar to that used in current commercial forestry will become available, which will significantly reduce the harvesting costs. Furthermore, it is assumed that farmers will harvest themselves and have marketing institutions. They will search for more competitive prices in different market places, and instead of taking a stumpage price they will sell logs directly at the processors. Therefore, the harvesting, and loading and transportation costs will be borne by farmers (Annex Table G-1). The harvesting costs vary with the sizes of trees, which in turn vary with the age of plantations (Annex Table G-1). For example, the final harvesting operation in the 34th year (except loading, transportation and unloading) would cost around \$1925 (ha^{-1}). The loading at Kingaroy, transporting from Kingaroy to Wondai Sawmill and unloading at Wondai Sawmill[6] would cost around \$9.4 (m^{-3}).

Wood can be classified by different uses. Poles are the most valuable, followed by piles and girders, veneer logs, saw logs and pulp logs. No poles are produced from spotted gum in Wondai Sawmill, and most of the harvested logs were used for saw logs. The Wondai Sawmill, as per Queensland government regulations, categorises

[6] The Wondai Sawmill is the major sawmill in the region, where more than 90% of sawing is of spotted gum.

three different types of logs for valuation: compulsory logs, optional logs and landscape logs. Compulsory logs are good quality logs that the purchaser must accept as part of their volume allocation. The price of compulsory logs is around \$100 m^{-3} at stumpage and \$170 m^{-3} at factory (Table 7.1). The optional logs are lower quality logs than compulsory logs and their acceptance depends on customer choice and the sawmill's specification. The price (m^{-3}) for optional logs is around \$140 at factory and \$70 at stumpage. The landscape logs are usually less than the acceptable diameter and so the price is very low (\$20 m^{-3} at stumpage and \$90 m^{-3} at factory).

Table 7.1 Percentage of compulsory, optional and salvage logs of spotted gum at different ages and price of different types of log at Kingaroy[7]

Types of log	Various types of log at different ages (%)				Price of log (\$/m3)	
	26 yr	30 yr	35 yr	40 yr	Stumpage	Factory
Compulsory	76	76.6	77.3	78	100	170
Optional	15	15.6	16.3	17	70	140
Landscape	9	7.8	6.4	5	20	90
DBH cm (UB)	41.46	45.74	50.59	54.59		
Total Volume/ha	217.4	284.81	369.17	452.17		

Source: Wondai Sawmill Staff

The predicted volume and average diameter at breast height (DBH) of logs under bark (UB) and percentage of different types of log at different ages are given in Table 7.1. At age 26, the average DBH of trees will be around 41 cm and this will increase to around 55 cm by year 40. The percentage of compulsory logs and optional logs are directly related to DBH, whereas the percentage of landscape logs is inversely related to DBH. At the 26th year, the percentage of compulsory logs would be around 76 and it would increase to 78% at 40 years. The percentage of landscape logs at age 26 years will be 9% and would decrease to 5% at the 40th year, which may seem quite low. This is because the Wondai Sawmill is buying logs only up to 25 cm diameter. If they had bought the logs up to 10 cm top diameter, the percentage would be much higher than this.

In Australia, the central parts of the heartwood are not preferred as much as they in countries such as Nepal and India. They are assumed to be weak parts of the log. The discussion with the Wondai Sawmill staff and experts revealed that this was due to

[7] The average DBH of trees (250 trees ha^{-1}) in this Table does not match with the average DBH of the same age trees in the earlier optimal spacing chapter, as this model is for the Kingaroy area whereas the earlier model was for Warril-View site.

soil moisture deficit and dry conditions. Moreover, after 60 cm DBH the percentage of acceptable compulsory logs will drop significantly, as most of the logs would have pipes (defects) by then as shown in Figure 7.2. Therefore, spotted gum logs above 60 cm diameter are not preferred. The implication of this for the study is that there is no financial benefit of keeping trees un-harvested after getting to 60 cm DBH.

Figure 7.2 Landscape log (small) and compulsory log (large) with pipe (defect). Photo taken at Wondai Sawmill, Wondai

7.3.2 Percentage growth rate of log value

The percentage growth rate of log value could be used to estimate the optimal rotation age of a plantation. The percentage of the difference of log values of two consecutive years divided by the base year log value gives the percentage growth rate of log value for that year {% growth rate of log = $(TV_t - TV_{t-1})*100/(TV_{t-1})$}. This is the gross growth rate of logs value in that particular year. The optimal rotation age is the age at which the gross growth rate of log equals the desired discount rate. Keeping trees un-harvested after this age would be less attractive than harvesting trees and spending money on best alternative businesses, which gives higher interest rates than the selected discounted rate.

The percentage growth rate of timber value would decrease exponentially (Figure 7.3). It would be around 50% in year 15 and 2.5% in year 50. At possible harvesting ages of 28, 31 and 35 years, the predicted growth rates would be seven percent, six percent and five percent, respectively. Therefore, the given ages would be optimal for harvesting trees for the given discount rates. The higher the discount rates, the earlier it encourages harvesting. If farmers chose the discount rate of seven percent, they would harvest earlier (year 28), and if the discount rate is 2.51%, they would harvest in year 50. Since the study is using a six percent discount rate for the comparison of all land use systems, the optimal rotation age for this discount rate would be around 31 years. However, it is the optimal rotation age only for maximising merchantable log benefits. If additional costs and benefits for stocking and carbon are included the optimal rotation would change.

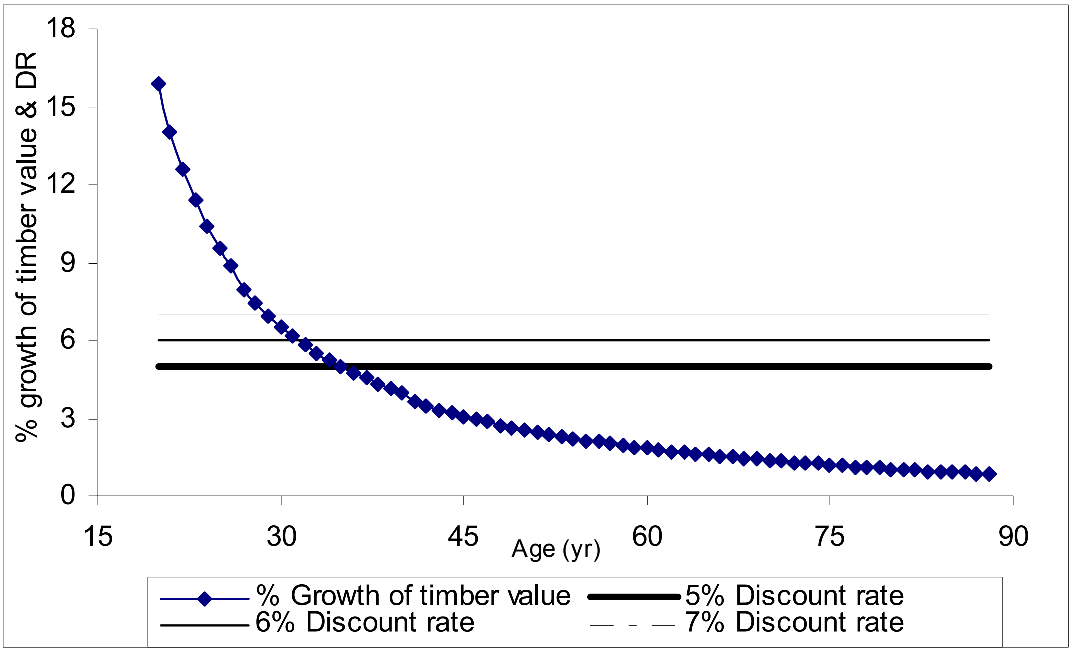

Figure7.3 Percentage growth rate of timber value in different ages in different discount rates

7.3.3 Optimal rotation age based on the dynamic efficiency

Dynamic efficiency suggests cutting trees at the age when net present value (NPV) for a given objective is maximised. A summary of NPV for timber over typical ages is shown in Table 7.2 and Figure 7.4, and detailed calculations and estimations are shown in the Annex (Table G-2, Table G-3, Table G-5 and Table G-6). As discussed elsewhere there are two scenarios, a) business-as-usual and b) optimistic. There is a great deal of difference between the NPVs from timber in the two scenarios, but the NPVs from stock and carbon values are same. Therefore, the optimal rotation age and NPVs from timbers of both scenarios are compared here. Since stocking and carbon NPVs of both scenarios are the same, they are not discussed individually. But due to differences in timber NPV, the combined NPV from timber, stock and carbon values would be different. They are discussed in later section. However, throughout the thesis the major focus is on a business-as-usual scenario.

Until age 13, the average DBH of trees would be less than 25 cm. This size is not acceptable for the sawmill, as they need logs of more than 25 cm at the small end diameter. When the average DBH of trees approaches around 28 cm at age 14, then there would be a possibility of getting some cash by selling logs. In a business-as-usual scenario, since the cost would be higher than the benefit, the NPV from timber would be negative up to age 17 (Figure 7.4). Age 18 would be the break-even age when net present value of costs and net present value of benefits would be equal. After that the NPV from timber would start rising and approach the maximum (around \$2100 ha^{-1}) at year 31. Therefore, this is the age at which trees need to be cut for maximising timber benefit. After this age, the NPV would start to decline and approach zero at age 58 and therefore would be negative after that age. Both ages, year 18 and year 58, therefore would be the break-even ages.

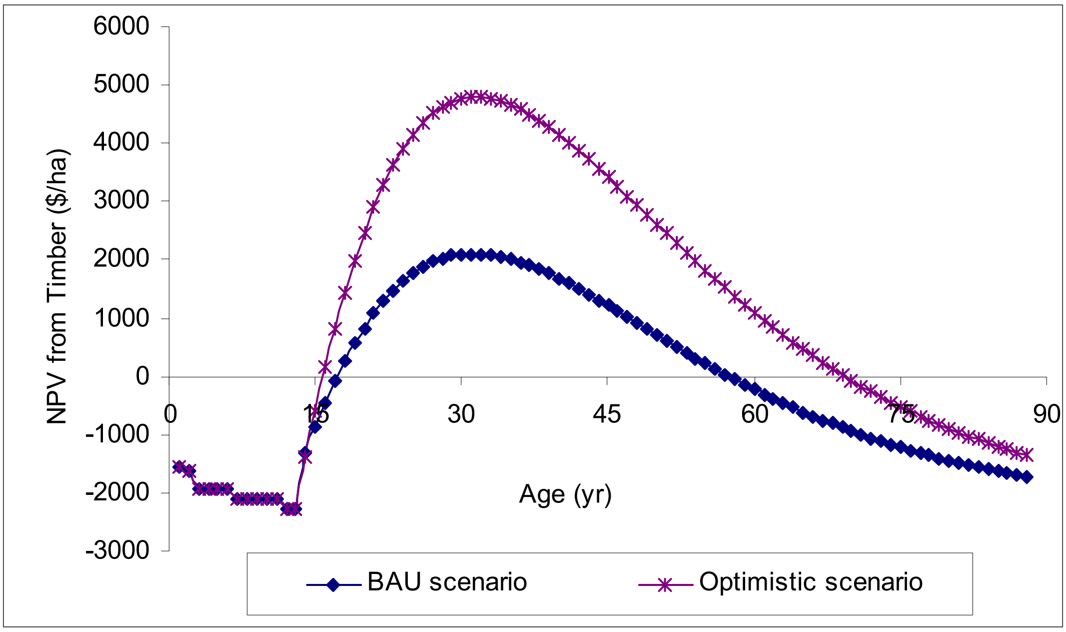

Figure 7.4 Net present values from timber (business-as-usual and optimistic scenarios) in Kingaroy, Queensland

The estimated optimal rotation for maximum sustained yield was around the 66th year, at which the estimated NPV from timber would be negative (around -\$684). Since the maximum economic yield rotation (Faustmann rotation) accounts for the time value of money (discounting), this rotation is much shorter than the maximum sustained yield rotation. The closeness of these two rotation ages depends on the price of logs, harvesting and regeneration costs during that time, and largely on the discount rate. A lower discount rate increases the rotation age, thus the lower the discount rate, the closer are the two rotations.

Table 7.2 Net present value ($ ha^{-1}) from timber, stock and greenhouse gases in Kingaroy, Queensland

Age	Timber	Timber & Stock	Timber, Stock & Carbon1	Timber, Stock & Carbon2	NPV from Stock	NPV from C1	NPV from C2	Total gain from C1&C2
Business-as-usual scenario								
30	2091.4	2865.0	3593.7	4102.5	773.6	728.7	508.8	1237.5
31	2099.6	2878.8	3641.5	4144.9	779.2	762.7	503.4	1266.1
32	2093.8	2878.2	3674.4	4171.6	784.4	796.3	497.2	1293.5
33	2075.1	2864.5	3693.8	4184.1	789.3	829.3	490.3	1319.6
34	2045.0	2839.0	3700.8	4184.7	794.0	861.8	483.8	1345.6
35	2004.6	2803.0	3696.7	4171.5	798.4	893.7	474.8	1368.5
Optimistic scenario (commercial scale, good-institution, self-harvest & factory gate price)								
31	4785.5	5564.6	6327.3	6830.7	779.1	762.7	503.4	1266.1
32	4786.3	5570.7	6366.9	6864.2	784.4	796.3	497.2	1293.5
33	4764.8	5554.2	6383.5	6873.8	789.3	829.3	490.3	1319.6

What would be the result in the optimistic scenario (see Figure 7.4, and Table 7.2, for a typical part and Annex Table G-3 and Table G-6 for a full calculation)? In this scenario, the optimal rotation would increase marginally, from 31 to 32 years, but NPV would increase significantly (to around $4786) compared to the NPV of a business-as-usual scenario. The lower break-even age would be more or less similar in both cases but the higher break-even point in this scenario would be around age 70, i.e. 12 years later than the business-as-usual scenario, mainly due to the big difference in profit margins.

In the business-as-usual scenario, the actual harvesting cost, and loading, transportation and unloading costs are implicit. From the difference between stumpage price and factory gate price it was indirectly revealed that this cost would be around $70 m^{-3}. The optimistic scenario shows that the explicit costs for the plantation owner could be much lower than that. The $70 cost would be reasonable for the current fragmented farm forestry practices, especially at some distance from a sawmill. Travelling from one forest patch to another would take much time, sometimes for a harvesting operation of a few hours. Commercial scale harvesting would save a significant amount of transportation time. With saving on harvesting costs, the optimistic scenario has a much higher NPV than the business-as-usual scenario.

7.4 Optimal rotation age for maximum economic return from timber and stock

It is discussed elsewhere that the plantation is managed as a silvipastoral system, with grazing permitted after three years. In this section, cost and benefit data of stocking are discussed first and then the optimal rotation age of plantation incorporating both timber and pasture values is discussed.

Most of the costs and benefit data of a silvipastoral system were discussed in the above section under the cost of plantation. The focus in this section is on the additional costs and benefits in the plantation due to the addition of pasture. During the first year of the establishment period, around \$72 (ha^{-1} or per 0.286 head) was spent on seeds, planting operations and the arrangement of a water system (Annex Table G-4). Since then, there is no cost until the start of grazing. In the fourth year, the first grazing year, the stocking rate per ha was around 0.286. In 12 months, the gross gain of cattle weight was around 250 kg per head. At a rate of \$2 kg^{-1} live weight, the gross gain in price in the 4^{th} year would be around \$143 ha^{-1} (\$500 * 0.286). After deducting the selling costs of \$3.86 (\$13.49/head), annual health costs \$1.68 (\$5.87/head), annual ear tag cost of 0.57 (\$2/head), annual electricity cost of \$0.85 (\$1.66/0.56 head) and annual maintenance cost of \$30 ha^{-1}, the total annual benefit for the 4^{th} year was around \$100 ha^{-1}. The stocking rates of cattle in different ages of plantations have already been discussed. The total annual benefit for each grazing year was estimated with the help of stocking rates and the above mentioned principles.

Since there was no grazing in the first three years, the net benefit from stocking was negative and it was positive only after the 4^{th} year (Figure 7.5). There would be no major costs after three years. Therefore, the NPV of stocking would continue to increase despite the decreasing rate of stock. However, the rate of increase of NPV started to decline after 15 years. This is due to two reasons: decreasing the stocking rate as a result of increasing the crown cover and decreasing the grass biomass; and the lower discounted value of later income.

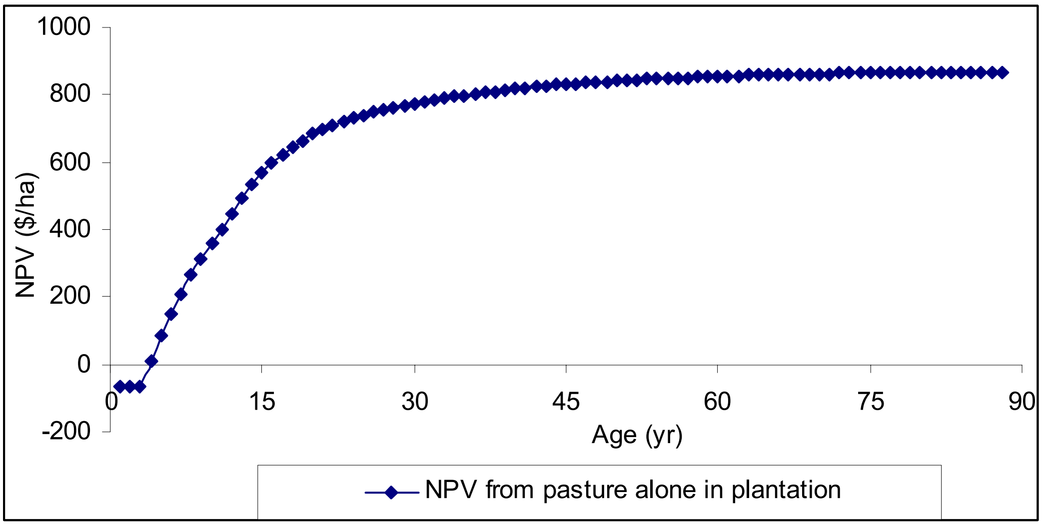

Figure 7.5 Net present value ($ha^{-1}) from pasture alone in plantation, Kingaroy

The combined NPV of plantation from timber and stock values in a business-as-usual scenario is shown in Figure 7.6 while the optimistic scenario is shown in Figure 7.8. The critical parts of both scenarios are given in Table 7.2. However, the focus in this discussion is on the business-as-usual scenario and the optimistic scenario is further considered later in the chapter.

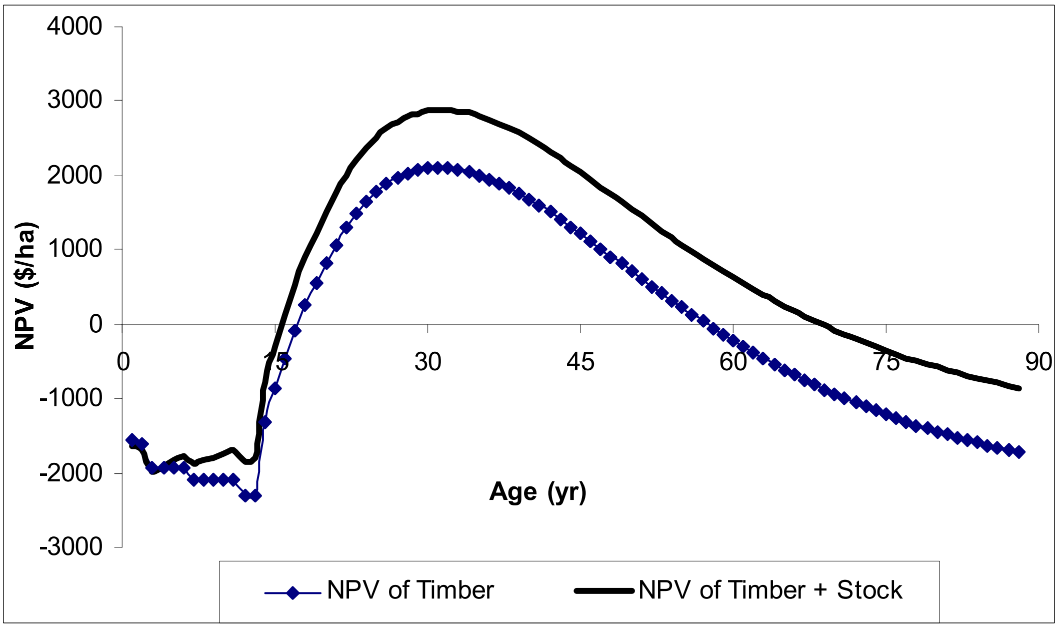

Figure 7.6 Net present values in a business-as-usual scenario ($ha^{-1}) from timber and stock in plantations, Kingaroy

Because of the high initial costs of plantations, the combined NPV of plantation and stock would remain negative until the 15th year. After this, the combined NPV would be positive and would peak in the 31st year. It would approach zero at year 68 and then remain negative in all years. The range of positive values of NPV from timber and stock would be 16 to 68 years, compared with 18 to 52 years in timber (only). The high NPV from pasture plays a significant role in increasing the range of positive values.

The combined NPV would approach a maximum (\$2878.8 ha^{-1}) at age 31 (Figure 7.6 and Table 7.2). The net NPV gain from stock at this age would be around \$780 ha^{-1}. This is lower than the net NPV gain from stock (784) at age 32 (Table 7.2). In fact, the combined NPV falls down due to a reduction in the NPV increasing rate in plantations. Since the combined NPV was maximised at age 31, this is the harvesting age of the plantation, if we consider both timber and stock values. This shows that there is a considerable chance of increasing NPV by practicing a silvipastoral system without reducing the rotation age of a plantation. The increase in \$780 ha^{-1} NPV in 31 years due to the inclusion of a pasture system would be the same in both the business-as-usual and an optimistic scenarios.

7.5 Optimal rotation age for maximum economic return from timber, stock and greenhouse gases

This study hypothesised that the plantation could be a competitive land use system, if the carbon benefit is included. In the previous chapters, carbon sequestration by trees and grass biomass and in soil of different ages, and the annual emissions of greenhouse gases from the use of machines, fuels and fertilisers were discussed. Similarly, the annual emissions of methane and nitrogen from cattle have also been discussed. In this section, the net gain of net present value from greenhouse gas from two different carbon scenarios are discussed first, followed by discussions of an optimal rotation age of a plantation incorporating timber, pasture and greenhouse gases values. All greenhouse gases are converted into carbon dioxide equivalents, so the words ‘greenhouse gas value’ and ‘carbon value’ are used interchangeably.

7.5.1 Present value from carbon

Two different carbon scenarios discussed in this section are C1 and C2. The C1 scenario assumes that the entire harvested products emit carbon in the atmosphere immediately after harvesting. In fact, carbon lock up amount and duration may vary according to the product. In the Wondai Sawmill, the average recovery rate of logs is around 43%, which is mostly used for flooring and decking products. The life span of these products is around 90 years (Jaakko Poyry, 2000). Moreover, due to an environmental policy for Southeast Queensland, the residues are not allowed to be burnt. Therefore, the residues can also store carbon for a long period. Similarly, the soil carbon gain due to plantations may not drop to the same level of zero age plantations after harvesting the trees, as significant amounts of residues will be left on the ground after harvesting. Therefore, the C2 scenario assumes that at least 40% of the gained soil carbon and harvested product carbon would be locked for another 46 years. The reasons for choosing 46 years are discussed in chapters two and three.

The calculation of present value (PV) from two different scenarios is shown in the Annex (Table G-2, Table G-3, Table G-5 and Table G-6). The combined and individual PV from the two scenarios are given in Figure 7.7 and in Table 7.2. The value of greenhouse gas emissions from cattle and primary farm inputs (machine, fuel and agrochemicals) outweighs the value of carbon sequestration in grasses and trees in the first five years. Consequently, the PV from greenhouse gas was negative during that period. Since then the PV of greenhouse gas would increase and would always be positive in scenario C1. The increasing rate has developed the sigmoidal curve similar to the growth curve of a plantation. The sigmoid shape of PV in the C1 scenario was expected, as there was a dominating effect of plant biomass on greenhouse gas PV. The greenhouse gas PV would increase at a slow rate in the first few years and then it would be faster. After that, it would be increasing at a slower rate.

Up to age 14, trees are below harvesting size. Therefore, the graph for the C2 scenario is shown only from 15 years. In the beginning, the PV from scenario C2 was a bit higher than the PV from scenario C1 and equal at 23 years. In scenario C2, PV was at a maximum ($521) at year 26, and thereafter declined. The shape of the C2 curve may be counter-intuitive, but the shape is explained in the following discussions.

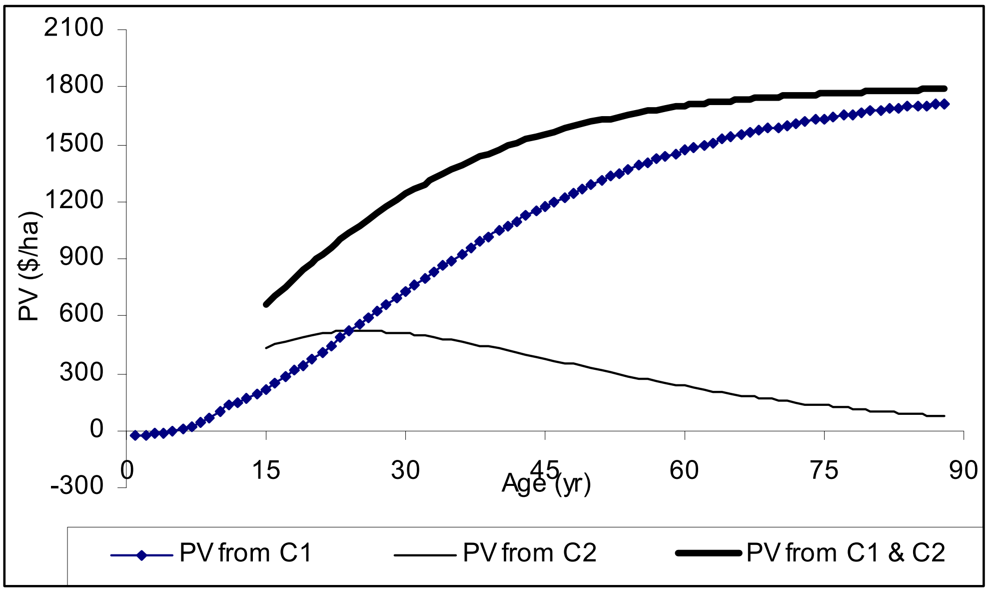

Figure 7.7 Present values of GHGs alone in a silvipastoral system in Kingaroy

The C2 curve is the net present value of 40% of the carbon benefit from the harvested products and 40% from the increased soil carbon. As it was assumed that the 40% carbon is locked at least for 46 years, its value was equal to the carbon credit of the energy sector, as that of permanent sequestration. This means it was not divided by 46. However, as the increasing rate of carbon benefit from the soil and harvested product is lower than the discount rate (6%), it would start to decline from age 23. Since then it would decrease continuously and would approach to $70 at age 90. This shows that the PV benefit from the C2 scenario would be less significant with the age of the plantation.

The combined PV of greenhouse gas (C1+C2) is highly influenced by the C1 scenario. The nature of the combined PV curve is almost sigmoid (Figure 7.7). However, unlike a sigmoid curve, there is no clear distinction between the three different stages (inception, growth and maturity). The greenhouse gas VP of the forest investment varies depending on harvesting age but it is almost asymptotic at age 80.

7.5.2 Optimal rotation of plantation incorporating stock and carbon values

So far the discussion was focused on the NPV gain from two different carbon scenarios. In this section the discussion is focused on the optimal rotation age incorporating timber, stock and carbon values. The combined NPVs from timber, stock and carbon in a business-as-usual scenario is shown in Figure 7.8. The critical part of the scenario is given in Table 7.2.

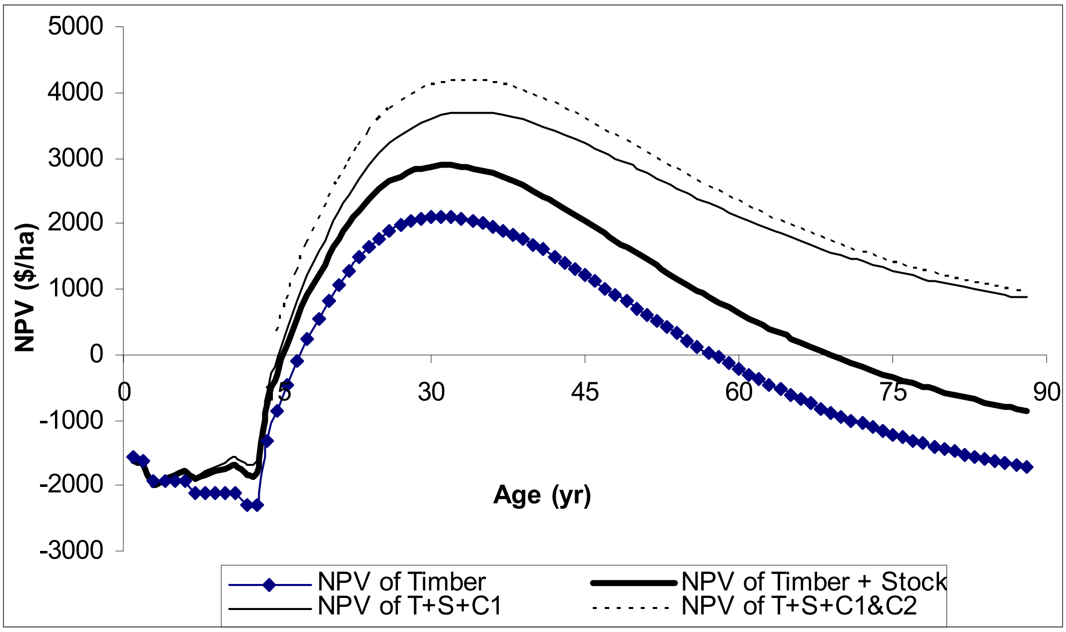

Figure 7.8 Net present values from timber, stock and greenhouse gases in a business-as-usual scenario in Kingaroy

As in the combined NPV of plantation and stock, the combined NPV of plantation, stock and carbon would remain negative until the 15th year. However, the amount of NPV would be slightly higher (by \$219 ha^{-1}) than that of the silvipastoral case at that age. The negative NPV until the 15th year was due to the higher initial cost of plantation, and higher emissions from machines, fuels and fertilisers and the accumulation of lower amounts of soil and biomass carbon. After the 15th year, the combined NPV would continue to be positive and never return to zero even at 100 years. The range of positive NPV values was around 34 years (18 to 52) in timber. It was increased to 52 years (16 to 68) in the timber plus stock case and more than 100 years in the timber plus stock plus carbon case (C1 scenario). The range would be even higher when the C1+C2 scenario is considered.

The combined NPV would approach a maximum at age 34 in both scenarios. It would be around \$3700 ha^{-1} in the C1 scenario and around \$4184 ha^{-1} in the C1+C2 scenario (Figure 7.8 and Table 7.2). The net NPV gain from carbon at this age would be around \$862 in the C1 scenario and \$484 in the C2 scenario. The NPV gain from the C1 scenario would still be increasing after 34 years. However, due to a lower rate of increase in NPV from the timber value, the combined NPV would be pulled down

(Table 7.2). Therefore, age 34 would be the optimal harvesting age of plantations, if timber, stock and carbon benefits are considered.

This shows that there is considerable potential for increasing NPV by considering carbon values in plantations. For this to happen, there would need to be an increase in the rotation age from 31 to 34 years. The increase in NPV (ha^{-1}) of $862 in the C1 scenario and $484 in the C2 scenario in 34 years would be the same in the business-as-usual and optimistic scenarios. This is because commercialisation in farm forestry would have decreased the tangible costs, but would have little effect on carbon sequestration and greenhouse emissions.

7.6 Comparison of rotation ages

In the business-as-usual scenario, the optimal rotation age for maximising timber NPV and timber and stock NPV would be the same (31 years). The corresponding NPV values would be around \$2100 ha^{-1} and \$2879 ha^{-1}. Incorporating a pasture system in a plantation would increase the net NPV by \$780 ha^{-1}. In the business-as-usual scenario, the optimal rotation age of a plantation incorporating stock and carbon value of the C1 and C1+C2 carbon scenarios would be the same (34 years). The combined NPV for the C1 and C1+C2 scenarios would be \$3700 ha^{-1} and \$4184 ha^{-1}, respectively. Utilising carbon benefits in plantation systems would increase the net NPV of \$862 ha^{-1} from the C1 scenario and \$1345 ha^{-1} from the C1+C2 scenario.

The optimal rotation of plantation for timber (only) in the optimistic scenario would be 32 years and NPV would be around \$4786 ha^{-1} at that age. The inclusion of stock in a plantation would not change the optimal rotation, but the combined NPV would increase to \$5571 ha^{-1} (Table 7.2 and Figure 7.9). The optimal rotation of plantation for timber, stock and carbon values would be the 33rd year and the consequent NPVs would be around \$6383 ha^{-1} and \$6873 ha^{-1} in the C1 and C1+C2 scenarios, respectively. The decrease in the optimal rotation by one year in the optimistic scenario compared to business-as-usual scenario could be due to the greater effect of timber benefits compared to carbon benefits. The net increase in NPV due to stock (\$789 ha^{-1}) and carbon values of \$829 ha^{-1} from C1 and \$490 ha^{-1} from C2 conditions in both the business-as-usual and optimistic scenarios are the same.

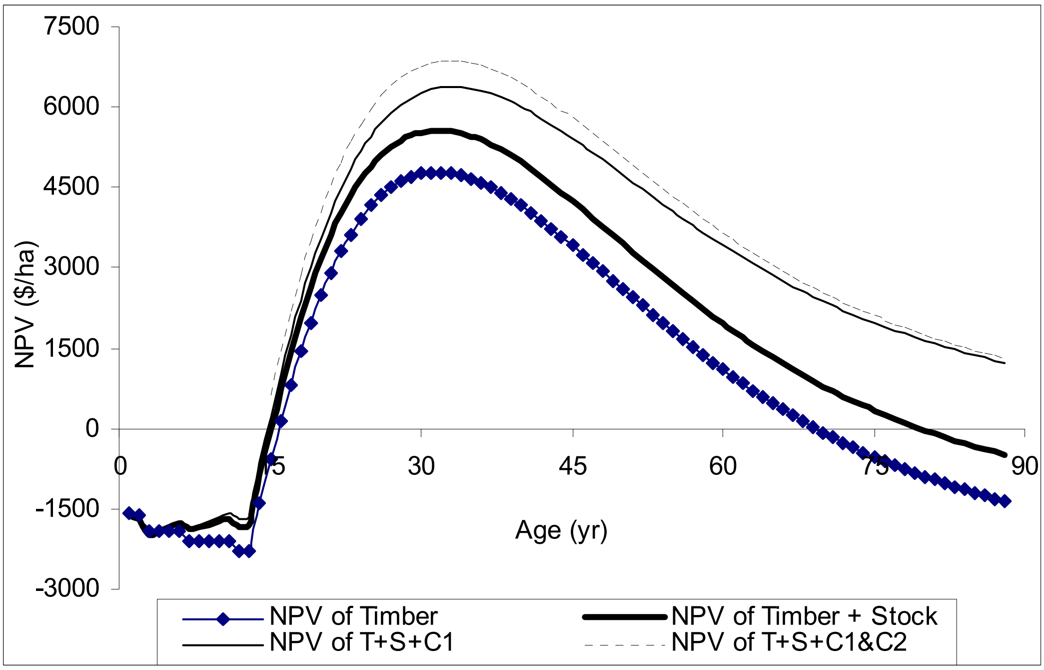

Figure 7.9 Net present values from timber, stock and greenhouse gases in Kingaroy, Queensland (estimation based on the optimistic scenario)

To understand this reasoning it would be worthwhile to revisit the assumptions. In an optimistic scenario, the owner would sell logs to the factory and would get a factory gate price. Therefore, all greenhouse gas emissions from harvesting, loading, transportation and unloading operations would be borne by farmers. In the business-as-usual case, the contractor would harvest and farmers would receive a stumpage price for trees. Even in this case, we assume that the emission during the harvesting, loading, transportation and unloading of logs would be borne by the farmer. The reason behind this assumption is that if there is a carbon market, the equivalent price of emission from all activities up to the factory gate would be deducted from the stumpage price.

It has been discussed elsewhere that there is no research on the financial returns of spotted gum. There is one piece of research based on expert views on the financial performance of hardwood plantations (Venn, 2005). It is general research for all hardwood species and has covered the whole Southeast Queensland Regional Forest Agreement Area. According to Venn (2005), the panel of experts assumed that the mean annual increment of hardwood plantation in the study area would be in between 7.5 and 12.5 $m^{-3}ha^{-1}yr^{-1}$. Since the estimated mean annual increment of spotted gum at the 31st year in this study is around 9.7 $m^3ha^{-1}yr^{-1}$ (301 m^3ha^{-1}/31 year), this seems quite reasonable.

From the overall analyses, it is obvious that the maximum possible NPV from plantation in the business-as-usual and optimistic scenarios would be around \$4185 ha^{-1} and \$6873 (ha^{-1}), respectively. However, considering the current plantation practice and Australia's position in the carbon market, the business-as-usual scenario with C1 carbon conditions would be more realistic. In such a situation, the maximum NPV would be around \$3700 (ha^{-1}), with net gain of \$794 from carbon value. On the basis of the experts' view, Venn (2005) assumed that the carbon sequestration value of plantations would be around \$630 (ha^{-1}) in 30 years (\$21 yr^{-1}) in the area of 10 $m^3ha^{-1}yr^{-1}$ productivity. Since he has not considered many sources and sinks including soil carbon, our value of \$794 in 34 years in the area of 9.7 $m^3ha^{-1}yr^{-1}$ seems more realistic. The current estimation does not cover the overhead and land costs. The prevailing land price in the study area is around \$1500 to 3000 ha^{-1} (M. Bell, 2006, pers. comm., 26 June) and if this was included, plantation could never be profitable as noted by Venn (2005). This, however, would also be the case for cropping and beef production as farmers rarely consider a return on current capital value.

7.7 Factors affecting optimal rotation age and NPV

In the interface of timber, stock and carbon markets there are several exogenous factors that may affect the estimated rotation age. In particular, the factors affecting the costs and benefits of given farming activities could be influential. An increase in harvesting costs and any additional cost during the harvesting period would suggest a need for a longer rotation. If the timber, cattle and carbon prices increase, there will be an incentive for early harvesting and therefore the rotation age will shorten. For example, ratification of the Kyoto Protocol by USA and Australia will create more demand for carbon, and increase the carbon price, which will encourage early harvesting.

The discount rate is another important determinant of optimal rotation age. So far, the discussion was based on a six percent discount rate. If the discount rate increases to seven percent, the optimal rotation age of plantations including timber, stock and carbon (C1 scenario) values in the business-as-usual scenario would reduce to 31 years (from 34 years) and the total NPV of plantations in 31 years would be only around \$2315 ha^{-1} (Table 7.3). If the discount rate further increases to eight percent, the optimal rotation of plantations would be down further to 29 years and the combined NPV would be down to around \$1343 ha^{-1}. In plantations, most of the costs incurred in the early ages and benefits from timber come only in the harvesting age. Therefore, benefits are more heavily discounted than costs. As a result, timber NPVs and optimal rotation ages decrease drastically with increasing discount rates. At six, seven and eight percent discount rates the timber NPV would be around \$2045 (in 34 yrs), \$990 (in 31yrs) and \$242 (in 29 yrs) respectively.

Table 7.3 Effect of discount rates on optimal rotation and NPVs (\$ ha^{-1}) of plantation

Discount rate (%)	Timber NPV	GHG NPV	Stock NPV	Total NPV*	Rotation age
6	2045	862	794	3701	34
7	990	634	692	2315	31
8	242.3	490	610	1343	29

All NPVs (from timber, GHG, stock and total) are based on respective optimal rotational ages

Since the carbon and stock benefits of plantations start early, the discount rates do not affect stock and carbon NPVs so heavily. Therefore, the decreasing rates of stock and carbon NPVs in plantations are lower than the rates for timber NPV. At six, seven and eight percent discount rates the stock NPV would be \$794 (in 34 yrs), \$692 (in 31yrs) and \$610 (in 29 yrs), respectively. Similarly, at six, seven and eight percent discount rates the carbon (C1 scenario) NPVs would be around \$862 (in 34 yrs), \$634 (in 31yrs) and \$490 (in 29 yrs), respectively.

The higher the discount rates the lower would be the competitive position of plantations. Not only this, at nine percent discount rate timber NPV would be always negative, but the total NPV would still be positive for some years because of the positive NPVs from stock and carbon values. However, at an 11% discount rate, the total NPV (timber plus stock plus carbon) of plantations would be never positive. At that rate, the positive NPVs of stock and carbon values are not enough to offset the negative NPV from timber.

7.8 Optimal rotation age for multiple harvests

The discussion so far has been based on the assumption of a single rotation. Optimal rotation for multiple harvests is based on the case of a perpetual cycle of cutting-plantation-cutting for many generations. Several assumptions are necessary for estimating the optimal rotation age of perpetual multiple harvests: for example, stumpage value at each rotation is the same, productivity is unimpaired by continuous cropping, climatic factors remain the same, and all types of prices, costs and benefits associated with different activities remain constant over time (Campbell, 1999). In fact, none of these assumptions are likely to be true. Logging and re-plantation activities can cause erosion, and cultivation for re-planting can emit significant amounts of soil carbon into the atmosphere. Temperature and rainfall patterns may change overtime. These phenomena can affect the site's productivity. The price of timber could rise due to shortages, or fall due to substitute development and technological changes could reduce the costs of developing plantation and greenhouse gas emissions.

In the face of uncertainty, it could be argued that the overall effect of all those factors would be neutral. However, it is worthwhile to recall that this research is based on limited data. There was no full rotation data of spotted gum plantations. The optimal spacing was determined and the growth model was developed only from the 15 years of time series data. Soil carbon for spotted gum plantations was taken as a proxy value of mature spotted gum. Further assumptions cannot be made for multiple harvest optimal rotations in these limited data environments. More importantly, confining the analysis to a single rotation is acceptable, because the rotation of spotted gum is long and discounting will mean that cash flows from all land uses after long-time (first harvest of plantation) will have very small present values.

There are several uncertainties in the context of global warming and carbon sequestration. The increasing temperatures under current climatic conditions reduce the soil moisture in dry places (like these sites), which may help to increase soil carbon by reducing the decomposition rate of litters (Smith *et al*., 2006). The increasing temperature, CO_2 and N_2 increase the growth rate of trees in cold places and therefore the carbon storage in the stands (Makipaa, 1995; Pussinen *et al*., 1997; IPCC, 2000; Smith *et al*., 2006). This may alter the soil carbon for all rotation ages. Even if the growth rate of trees increases in cold areas due to increased temperatures, the question comes up to what temperature, as the optimal temperature for photosynthesis is only around 25°C. It is uncertain what would be the likely net effect of the increased temperature, CO_2 and N_2 in dry areas such as this study site.

Moreover, most of the soil carbon modelling studies show that the soil carbon level goes down immediately after harvesting and then increases again (Paul *et al*., 2002; Paul *et al.*, 2003; Horvath and Somoyogyi, 2006). In the case of multiple harvests and perpetual plantations, soil carbon could approach equilibrium levels after a certain time (Coleman and Jenkinson, 1999). After that there may not be any further soil carbon benefit. Because of this limited data and climatic uncertainty there was no attempt at estimating a multiple harvest optimal rotation age. However, considering the microclimatic condition of the research sites and the long-term trend of decreasing rainfall and increasing temperature there is a limited chance of increasing growth rates of trees at the current level of knowledge and technology. Having these facts and the limitation of soil carbon levels after certain ages, it may be said that there is limited chance in further improving the NPV from the carbon value of multiple harvests. However, there is some chance of increasing NPV by genetic improvement programs, which will be discussed in the next chapter.

7.9 Sensitivity analysis on business as usual scenario

Plantations are a long-term industry and therefore are likely to have a large number of risks and uncertainty. It demands critical analysis of several key factors that may affect the NPV from plantations in the long run. The optimistic scenario with C1 carbon conditions is found to be more realistic in the present context of Australia. This is mainly due to three reasons. First, there is still uncertainty as to whether or not the current level of farm forestry will advance towards commercial forestry. If not, using sophisticated equipment is not possible. Therefore, the optimistic scenario may not be realistic. Second, the current market for carbon in Australia is not as well advanced because Australia has not ratified the Kyoto Protocol. Third, institutions play a significant role in market development. Since farm forestry in Queensland is in the infant stage, there is a lack of mature farm forestry institutions. The second and third reasons preclude the possibility of getting the full carbon benefit from the C2 scenario in the short-term.

The sensitivity of the results from the realistic scenario is tested by changing several key parameters. Considering current Queensland circumstances (knowledge, technology, marketing and the institutional setting), many experts (see names in the acknowledgement section) assume that there is less likely to be a scaling-up to the different parameters of the realistic scenario. However, there are several possibilities of increasing combined NPVs, other than the factors considered for their estimation. Therefore, these are discussed separately in the discussion section. The sensitivity of different parameters of a business-as-usual scenario is tested in different scales and the resultant NPVs are given in Table 7.4

The main factors affecting combined NPVs are spacing levels (stocking rates) and timber price. Changing stocking rate affect the total volume of timber and biomass of trees and therefore, the NPVs from timber and carbon values[8] (Table 7.4). By decreasing the stocking rates from 250 to 200 trees ha^{-1}, the total NPV from timber would decrease from \$2100 to \$1215 (by 42%) in 31 years. However, the optimal rotation age remains the same (31 yrs).

The reduction of timber NPV is due to two main reasons. First, the reduction of tree numbers does not change the establishment cost (early years' costs) that does not discount heavily. It slightly increases the harvesting costs (the final year's cost), but it discounts heavily. Second, due to the decreasing stocking rate from 250 trees ha^{-1} to 200 trees ha^{-1}, the timber benefit would decrease by a fifth at the harvesting age. As a result, the overall effect on timber NPV was significant. Again, the rotation age incorporating timber, stock and carbon values (C1 scenario) remained the same (34th year). However, the combined NPV in 34 years reduced by \$1050 (\$3700 to \$2650 ha^{-1}). The majority of the reduction was due to a reduction in timber value of \$872. If the timber price reduces by 20% the timber NPV in 31 years will reduce by \$885 or 42% (\$2100 to 1215). This effect is equivalent to the effect of a scaling down of stocking rate of trees from 250 to 200 ha^{-1}.

[8]We could argue that decrease in tree density may increase the size of trees. Therefore, it may produce the large size logs, which would be sold at a higher price. Similarly, we can argue that the decrease in tree density would increase grass biomass thereby the stocking rate and present value from stock . Similarly, a decrease in tree density may decrease litter fall, thereby, the soil carbon. Since this is not an ecosystem based model these effects are not considered. This analysis is moving around the optimal tree density. If the extreme range is considered (for example 250 trees to 100 trees ha^{-1}) that argument would work. Therefore, although there is some effect theoretically, it would be insignificant. A similar principle is applied in many cases in this section.

Table 7.4 Sensitivity analysis of NPVs by changing different parameters

Age	Timber	Timber & Stock	Timber, Stock & Carbon1	Timber, Stock & C1&C2	NPV from Stock	NPV from C1	NPV from C2	Tot. NPV gain from C1&C2
Original case (Estimation based on business-as-usual condition (stumpage price))								
31	2099.6	2878.8	3641.5	4144.9	779.2	762.7	503.4	1266.1
32	2093.8	2878.2	3674.4	4171.6	784.4	796.3	497.2	1293.5
33	2075.1	2864.5	3693.8	4184.1	789.3	829.3	490.3	1319.6
34	2045.0	2839.0	3700.8	4184.7	794.0	861.8	483.8	1345.6
Stocking rate down to 200trees from 250 trees ha^{-1}								
31	1215.3	1994.5	2596.6	2999.3	779.2	602.1	402.7	1004.9
32	1210.9	1995.3	2625.0	3022.8	784.4	629.7	397.8	1027.5
33	1196.3	1985.6	2642.6	3034.8	789.3	656.9	392.2	1049.2
34	1172.5	1966.5	2650.1	3036.4	794.0	683.7	386.3	1069.9
Price of timber down by 20%								
31	1215.3	1994.4	2757.1	3260.5	779.2	762.7	503.4	1266.1
-	-	-	-	-	-	-	-	-
34	1172.5	1966.4	2828.3	3311.1	794.0	861.8	482.8	1344.6
35	1140.4	1938.8	2832.5	3307.3	798.4	893.7	474.8	1368.5
MAI of trees decrease by 10%								
31	1656.7	2435.9	3118.3	3571.4	779.2	682.4	453.1	1135.5
32	1652.9	2437.2	3150.2	3597.7	784.4	713.0	447.5	1160.5
33	1636.3	2425.6	3168.7	3610.0	789.3	743.1	441.3	1184.4
34	1608.4	2402.4	3175.2	3609.7	794.0	772.8	434.5	1207.3
Soil carbon decrease by 10%								
31	2099.6	2878.8	3623.2	4114.0	779.2	744.4	490.8	1235.2
32	2093.8	2878.2	3655.5	4140.3	784.4	777.4	484.8	1262.1
33	2075.1	2864.5	3674.4	4152.4	789.3	809.9	478.1	1287.9
34	2045.0	2839.0	3680.9	4151.6	794.0	841.9	470.7	1312.6
Carbon price down by around 50% (\$5.5 $t^{-1}CO_2e$ from \$10.5 $t^{-1}CO_2e$)								
31	2099.6	2878.8	3270.7	3534.4	779.2	392.0	263.7	655.6
32	2093.8	2878.2	3287.7	3548.1	784.4	409.5	260.4	670.0
33	2075.1	2864.5	3291.3	3548.1	789.3	426.8	256.8	683.7
34	2045.0	2839.0	3282.9	3535.8	794.0	443.9	252.9	696.8
Gross gain of cattle weight decrease to 220 $kghd^{-1}$ from 250$kgha^{-1}$								
31	2099.6	2630.5	3393.2	3896.6	530.9	762.7	503.4	1266.1
32	2093.8	2627.7	3424.0	3921.2	533.9	796.3	497.2	1293.5
33	2075.1	2612.0	3441.3	3931.6	536.9	829.3	490.3	1319.6
34	2045.0	2584.6	3446.4	3929.2	539.6	861.8	482.8	1344.6
Beef price drop by 10%								
31	2099.6	2793.9	3556.6	4060.0	694.3	762.7	503.4	1266.1
32	2093.8	2792.7	3589.0	4086.2	698.9	796.3	497.2	1293.5
33	2075.1	2778.6	3607.9	4098.2	703.5	829.3	490.3	1319.6
34	2045.0	2752.6	3614.4	4097.3	707.6	861.8	482.8	1344.6
Stocking rate drop by 10%								
31	2099.6	2794.1	3556.8	4060.2	694.5	762.7	503.4	1266.1
32	2093.8	2792.9	3589.2	4086.4	699.1	796.3	497.2	1293.5
33	2075.1	2778.7	3608.0	4098.3	703.6	829.3	490.3	1319.6
34	2045.0	2752.8	3614.6	4097.4	707.8	861.8	482.8	1344.6
If all cases happen at the same time (worst case)								
31	224.8	658.1	914.6	1104.5	433.3	256.5	189.9	446.4
-	-	-	-	-	-	-	-	-
34	195.2	635.7	929.4	1111.6	440.5	293.8	182.1	475.9

Mean annual increment (MAI) not only affects the NPV of timber but also affects the NPV from carbon by reducing the tree biomass (Table 7.4). The decrease in MAI does not affect most of the costs, except a small fraction of harvesting and transportation costs, but significantly affects the overall benefit. As a result, the NPV from timber reduced significantly, from \$2100 to \$1657 ha^{-1} in 31 years. However, again the optimal rotation age remains the same (31 yrs), as the decreasing rate of MAI was the same in all years. However, the combined NPV from timber, stock and carbon (C1 scenario) reduced to \$3175 from \$3700 ha^{-1} in 34 years. Of the total decreased amount, \$437 was from plantations and only around \$89 was from greenhouse gases.

Soil carbon is another variable, even though it has no significant influences on overall NPVs. The optimal rotation age incorporating timber, stock and carbon (C1) would remain the same (34 yrs) even after reducing soil carbon levels in all years by 10%. However, the combined NPV decreased by \$20 ha^{-1} (\$3700 to \$3680 or 0.5%). This result shows that the combined NPV is less sensitive on the soil carbon amount and suggests not going for different soil carbon scenarios, as discussed in the end of chapter four. Carbon price is another vital variable. The reduction in carbon price from \$10.5 to \$5.5 $5t^{-1}CO_2e$ would reduce the combined NPV from \$3693 to \$3291 ha^{-1} in 34 years.

Gross gain of cattle weight, beef price and stocking rates are other important variables in a silvipastoral system. It affects the combined NPV from timber and stock value in general, and net gain in NPV from stock in particular. If the gross gain of cattle weight in 12 months decreases from 250 kg to 200 kg, the NPV from stock would reduce from \$779 to \$531 ha^{-1} in 31 years. This reduces the timber and stock NPV by the same amount (from \$2879 to \$2631 ha^{-1}), as it has no effect on timber value. The reason is obvious; it reduces the benefit but does not reduce any types of cost, except the commission cost of four percent. Therefore, the stock NPV is highly sensitive with gross weight gain of cattle. Reducing beef price by 10% reduces the net gain of NPV from stock by \$85 ha^{-1} (\$779 to \$694) in 31 years. As it has no effect on the timber NPV, the combined NPV of timber and stock would decrease by the same amount. Similarly, if the stocking rate decreases by 10%, the NPV from stock would reduce by \$85 ha^{-1} in 31 years (\$779 to \$794), which is identical to that of the decreasing beef price by 10% (Table 7.4).

7.10 Sensitivity index of NPVs and ranking of different parameters

The sensitivity of the NPV can be measured in the form of a sensitivity index. This concept is similar to the concept of price elasticity of demand or supply (see chapter 3, for a detailed explanation). While drawing the possible NPV curve (time series) from possible returns of plantation in various harvesting ages, the slope of the NPV curve changes frequently. Therefore, the elasticity of NPV is dynamic in nature. The value may be different in different parts of the curve. This means it is different in different years. It seems constant in the Table (7.5), as only a small part (the critical part) of the whole NPV sensitivity curve is reproduced. This sensitivity index (or elasticity of NPV) would work nicely within a small range (fluctuation) from the original condition. If the range is too large (a large fluctuation) the sensitivity index value may change slightly. Since our analysis is based on a small fluctuation from the original condition, it would be precise for that range.

In the case of timber NPV, the most sensitive parameters are tree density, timber price and mean annual increment. A one percent decrease in tree density would reduce the NPV from timber at harvesting age by 2.4% (Table 7.5). The result with the timber price is similar. A decrease in the price of timber would have no effect on stock NPV and carbon NPV. Therefore, stock and carbon NPV, due to the change of these parameters, is perfectly inelastic (zero). However, a one percent decrease in tree density would reduce carbon NPV by around one percent, thus, timber price elasticity of carbon NPV is one (unitary elastic). A decrease in mean annual increment has a similar effect on timber and carbon NPV.

A decrease in soil carbon and carbon price has no effect on timber and stock NPV (perfectly inelastic)[9]. These parameters affect only carbon and combined NPV. A one percent decrease in soil carbon would reduce combined NPV by around 0.1% and carbon NPV by around 0.2%. This indicates that changing soil carbon has little impact on combined NPV. Reducing carbon prices by one percent reduces the carbon NPV by one percent (unitary elastic) and combined NPV by only 0.2%. Since the

[9] One can argue that the decrease in soil carbon may reduce pasture biomass, which in turn may reduce stock benefit. In fact, it is insignificant within the small range of soil carbon. As discussed in the previous section, an ecosystem or process based model is not used in this thesis. Therefore, these effects are not captured and are not considered in this study.

contribution of carbon NPV to the combined NPV is relatively smaller, the overall effect of the reduced carbon price on combined NPV is minimal.

Table 7.5 Sensitivity of NPV in terms of 1% change in NPVs caused by 1% change in given parameters

Age	Timber	Timber + Stock	T + S + Carbon	Stock only	Carbon only
Tree density decrease from 250 to 200trees/ha					
31	2.4	1.6	1.5	0.0	1.1
32	2.4	1.6	1.5	0.0	1.1
33	2.4	1.6	1.5	0.0	1.0
34	2.4	1.6	1.5	0.0	1.0
Price of timber down by 20%					
31	2.4	1.6	1.2	0.0	0.0
32	2.4	1.6	1.2	0.0	0.0
33	2.4	1.6	1.2	0.0	0.0
34	2.4	1.6	1.2	0.0	0.0
MAI down by 10%					
31	2.2	1.6	1.5	0.0	1.1
32	2.2	1.6	1.5	0.0	1.0
33	2.2	1.6	1.5	0.0	1.0
34	2.3	1.6	1.5	0.0	1.0
Soil carbon down by 10%					
31	0.0	0.0	0.0	0.0	0.2
32	0.0	0.0	0.0	0.0	0.2
33	0.0	0.0	0.1	0.0	0.2
34	0.0	0.0	0.1	0.0	0.2
Carbon price down from \$10.5 to \$5.5/tonCO_2e					
31	0.0	0.0	0.2	0.0	1.0
32	0.0	0.0	0.2	0.0	1.0
33	0.0	0.0	0.2	0.0	1.0
34	0.0	0.0	0.2	0.0	1.0
Gross gain of cattle weight decrease to 220kg/hd from 250kg/hd					
31	0.0	0.7	0.6	3.0	0.0
32	0.0	0.7	0.6	3.0	0.0
33	0.0	0.7	0.6	3.0	0.0
34	0.0	0.7	0.6	3.0	0.0
Beef price drop to \$1.8 from \$2					
31	0.0	0.3	0.2	1.1	0.0
32	0.0	0.3	0.2	1.1	0.0
33	0.0	0.3	0.2	1.1	0.0
34	0.0	0.3	0.2	1.1	0.0
Stocking rate drop by 10%					
31	0.0	0.3	0.2	1.1	0.0
32	0.0	0.3	0.2	1.1	0.0
33	0.0	0.3	0.2	1.1	0.0
34	0.0	0.3	0.2	1.1	0.0

The gross gain in the weight of beef is the most sensitive parameter for stock NPV, but it has little effect on timber and carbon NPVs. Approximately three percent of NPV from stock would be reduced by reducing a one percent gross gain in live weight of cattle. Because of this large effect, the elasticity of combined NPV from timber and stock is pulled to 0.7% from zero percent of the timber only case. The beef price and stocking rate is almost unitary elastic, as a one percent decrease in price would reduce the stock NPV by the same percent. However, the combined NPV from timber and stock would decrease by 0.3% and timber, stock and carbon NPV would decrease by 0.2% by reducing one percent of those parameters (Table 7.5).

The ranking of the sensitivity of the parameters depends on the objective of plantation. If the objective is to maximise the timber NPV, tree density and the price of timber are equally highly sensitive parameters followed by the timber price. If the objective is to maximise timber plus stock NPV, then all these three parameters are equally sensitive. However, if the objective is to maximise the combined NPV from all three sources of timber, stock and carbon; then tree density and MAI are equally sensitive to the total NPV followed by the price of timber. Other parameters would be sensitive for NPV from carbon or from stock individually, but they have very little role on total sensitivity of the combined NPV. Among these insignificant parameters, gross weight gain of cattle is relatively more sensitive. Therefore, while considering the objective of maximising combined NPV from timber, stock and carbon values, we should be thoughtful about the tree density, MAI, price of timber and gross weight gain of cattle.

7.11 Discussions

In the previous sections, different types of optimal rotations, their corresponding NPVs and their sensitivity indices were discussed. At the same time, some discussions were made, where necessary, to explain the results. In this section, the reasons why there was not much difference between just timber, and timber plus stocking plus carbon optimal rotation ages is discussed first and then, whether it is possible or not to increase combined NPV is considered.

At one time, for the determination of optimal rotation age for the production sets of timber and carbon, the production possibility frontier (PPF) would have been used (Vincent and Binkley, 1993; Boscolo and Vincent, 2003). Applying the principle of comparative advantage and the non-convex nature of a PPF curve, an argument had been made in favour of specialised use instead of multiple use for a single stand forest (Vincent and Binkley, 1993). In the context of non-marketed or public good nature of carbon, total protection would have been justified by the carbon benefit. This argument is also supported by this study, as the biomass of trees at the maximum sustained yield rotation age (1164 t ha^{-1} in 66 years) is one-third of the biomass of mature trees (3383 t ha^{-1} in 200 years). Now, the carbon is being sold and it has some value attached to it. It is not mutually exclusive with the timber value. The NPV can be maximised by including timber and carbon value together rather then taking them individually. But the question is then why the difference between the timber, and the timber plus stock plus carbon optimal rotation age was lower than expected.

This lower difference in optimal rotation age could be due to three main reasons. First, the lower price of carbon dioxide of \$10.5 t^{-1} does not makes little difference to NPV for with-and-without a carbon scenario. Second, this study followed a risk free, tonne-year approach, in which payment is made annually and only the fraction ($1/46^{th}$) of carbon stocked in soil and biomass in that year is paid. This approach significantly reduces the NPV and encourages early harvesting. If it was an ex-ante payment, the carbon benefit would not have been discounted to such a great extent. This would have lengthened the rotation age and would increase the NPV difference between the with-and-without (timber only) carbon rotation ages. Third, although there was a big difference in NPV between the two cases, the growth rate of NPV in carbon was almost similar to the growth rate of NPV in plantations, as they were highly positively correlated. Therefore, in both cases the NPV approached a peak more or less at the same time.

Another important question is whether there is a possibility of increasing combined NPVs. Two current pieces of research (Jackson *et al*., 2005; Keppler *et al.,* 2006) show the possibility of decreasing NPV of plantations. Keppler *et al*. (2006) report that the living plants and fallen leaves emit methane. Jackson *et al.* (2005) reveal that the plantations in a dry land area can increase soil acidity and salinity problems. These findings need comparative analyses of all land use systems. Therefore these issues are discussed in the next chapter.

In the earlier sections, sensitivity of different parameters, which were directly used in the optimisation models were discussed. Citing the current knowledge and technology, and the marketing and institutional setting in Queensland, all parameters were scaled-down and tested. There are several possibilities of increasing combined NPVs, but they are not related to the model parameters. Therefore, these possibilities were not discussed in the previous sections and are discussed in this section. There are four main reasons for the possibilities of increasing combined NPV.

First, NPV could be increased by changing current practices of log size utilisation. Currently, logs only up to 25 cm small end diameter are acceptable at the sawmill. According to the Wondai Sawmill staff[10], the processing of logs below that size is not profitable due to the large handling cost. However, in many parts of the world logs up to 10 cm top diameter are used. The analysis shows that the tapering of spotted gum logs from 10 cm to 25 cm diameter is around 0.97 cm per metre (Annex Table C-1). It means around 0.37 cubic meters of log between 10 to 25cm diameters would be lost from each tree of harvestable age. This is equivalent to around 90 cubic metres log ha^{-1}, with as optimal tree density of 250 ha^{-1} (Annex Table G-8). There is a very good chance of increasing timber NPV by developing some efficient technology and using these sizes of logs. This can be achieved even with the use of a current portable sawmill on the spot. As timber is the main contributor, this would assist with increasing the combined NPV.

Second, the combined NPV could be increased by managing the residue in a proper way. The current recovery rate of compulsory and optional logs is around 38% and landscape logs is around 48%. On average, around 43% of the logs would transform into timber and 67% would be lost as residues. The modelling shows that the average density of spotted gum trees at harvesting age (34th year) would be around 760 kg m^{-3}, and total volume (ha^{-1}) at that age would be around 350 m^3. Using the simple mathematical relationship of volume and density, it is found that around 178 t (760 × 350 × 0.67/1000=178 t) of residues would be lost from each hectare. If including the 90 m^3 of logs between 25 cm and 10 cm diameter, another 68 t of biomass would be lost. Locking this whole biomass at least for 46 years, around \$4739[11] of extra benefit would be there at the 34th year. With the 6% discount rate, this would add around \$650 ha^{-1} to the combined NPV.

[10] As per face-to-face discussions with Mr Ron Bergman (Site Manager) and Jason Worling (Training Officer) on the 1st June 2006.
[11] 246 t of biomass, 246*0.5=123tC, 123t*3.67=451.41 tCO2e and price of carbon =\$10.5$t^{-1}CO_2e$. Total benefit at 34 year = 451.41 tCO_2e * \$10.5/ tCO_2e = \$4739 (ha^{-1})

Substitution efficiency is another important factor to be considered. If forest products containing a 100 tC can be used to offset the utilisation of fossil fuels that would have released 50 tC, the efficiency will be defined as 50%. In Australia, coal is the most important source of fossil fuel. Coal releases about twice as much as CO_2 per unit of energy as natural gas (Kirschbaum, 2003). Therefore, there is a good chance of getting carbon benefits by replacing coal with these residues. This is more practicable in the context of Australian's electricity policy, in which it is mandatory for electricity retailers to obtain an additional 9.5 TWh of energy from renewable sources by 2010 (Fung *et al*., 2002). In Southeast Queensland, people are not allowed to burn residues because of environmental concern. There is an extra cost to manage these residues, which would have caused the log prices to come down to some extent. Therefore, if these residues were used for coal replacement and biomass energy production, the benefits would be twofold.

Furthermore, if the recovered timber can be used for longer lifespan products, its carbon benefit would be increased. However, this chance is rare, as it is currently used for the longest lifespan product of 90 years. However, there is still some chance of replacing energy intensive products such as steel and cement by these harvested products (including residue and recovered). This can increase the carbon benefit, which in turn would help to increase the combined NPV.

Third, there is a chance of improving the growth rate of trees by launching a genetic improvement program. In Australia, hardwood plantations have just started and they have a very short history. Its increasing demand from local environment and housing markets is recently being realised. As explained elsewhere, the soil moisture is the most important limiting factor for plant growth and density. By viewing the fast pace of genetic engineering, it is possible to produce drought bearing spotted gum species with a fast growth rate. This process has already been initiated (Lee *et al*., 2001; Huth *et al*, 2004; Lee, 2005). Preliminary results of a genetic improvement program are promising, as the vegetative propagative capacity, and frost and ramularia shoot blight resistance capacity of spotted gum are enhanced (Lee, 2005). If the genetic improvement program can produce more water efficient spotted gum hybrids with fast growth rates, the timber NPV and combined NPV for timber and carbon could be increased.

Fourth, some value adding could be possible to the plantation from different ecosystem services. Biodiversity could be the main domain for value adding among the others. In this context, pure plantation is not so admirable in comparison to native forest. However, plantations changes microclimates and make the area more suitable for many micro-fauna and flora. Thousands of known and unknown chemical compounds may occur in their tissues. Many invaluable uses could be made from them in the future. Therefore, it has some attached option value.

Aborigines have traditionally used the leaves of the spotted gum species. With current knowledge, it is used for food additives and perfume, curing food poisoning, acne and athlete's foot caused by microbial activities (Takahashi *et al.*, 2004), controlling leaf cutting ants (Marsaro *et al.,* 2004) and leaf oil (Asante *et al*., 2000). There could be some recreational and aesthetic value too. In this regard, Costanza *et al*. (1997) came up with a residual value of around US\$100 ha^{-1} yr^{-1} for the average temperate forest in the world (cited in Venn, 2005). In Australia, Bueren and Bennett (2000) estimated the average willingness to pay \$0.000007 ha^{-1} for protected bush-land or farmland, which is equivalent to around \$52 ha^{-1} (assuming 7.5 million households). If these values could be added to the total value of plantations, the attraction on plantations could be higher. The next section presents some conclusions.

7.12 Conclusions

This chapter has explored different types of optimal rotation ages and their respective NPVs. Many key parameters for sensitivity analysis are investigated, and the reasons why the differences between the different rotation ages are low are discussed. Finally, the ways of increasing combined NPV are evaluated.

The optimal rotation age of spotted gum for maximising timber and stock NPVs is the same (31 yrs). The optimal rotation would increase by three years, if carbon benefit was added. The business-as-usual scenario, based on current practices and technologies, shows that the NPVs from timber, stock and carbon are around \$2045, \$794 ha^{-1} and \$862 ha^{-1} respectively in 34 years (combined NPV = \$3700 ha^{-1}). Pasture (~21%) and carbon (~23%) alone accounted for over 44% of the total NPV. This implies that there is potential to increase combined NPV by incorporating pasture and carbon benefits.

Tree density, mean annual increment and the price of timber are found to be the most sensitive parameters for combined NPVs. However, plantation is still profitable even if decreasing these parameters by 20-25%. There is a good chance of increasing NPV by going towards commercialisation, utilising the logs between 10-25 cm diameter and producing renewable energy from residues. However, if land and overhead costs are considered, plantations do not survive easily. Without comparing other land use systems in a similar way, it is difficult to say whether plantation can compete with pasture and cultivation. The next chapter will compare these results with the results from other land use systems.

Chapter 8

Re-evaluating Land Use Choices Incorporating Carbon Value

8.1 Introduction

In the previous chapter, the optimal rotation age of plantations was determined by incorporating traditional tangible benefits and greenhouse gas values into the estimations. Other land use systems also need to include greenhouse gases for full comparison. In this chapter, the costs and benefits of a peanut-maize rotation crop (cultivation) and pasture are assessed by incorporating greenhouse gases and traditional tangible benefits. The optimal rotation of plantations was found to be 34 years (chapter 7), and thus the cost-benefit analysis of cropping and pasture has been extended to 34 years for meaningful comparison with plantations. The greenhouse gas data for these analyses are assessed from previous chapters.

This chapter is divided into six sections. In the first section (8.2), the net present values (NPVs) from traditional tangible products and greenhouse gases are estimated. After that, the NPV over 34 years from all those sources and their sensitivity with different key-parameters are analysed. In the second section (8.3), similar analyses are done for the pasture system. In the third section (8.4), the cultivation and pasture NPVs are compared. In the fourth section (8.5), the NPV from plantations (from previous chapter) is compared with the NPVs from cultivation and pasture. In the final two sections discussions and conclusions are given.

8.2 Cost benefit analysis for peanut-maize cropping system

It has been already discussed that peanuts remove large quantities of nutrients from soils. Therefore, a balanced rotation of legume and cereals is needed to sustain fertility, as cereals help to break soil borne disease, return some organic matter to the soil and help to protect soil from erosion (DPI&F, 2004). In the research site, for this reason, peanuts are alternatively grown with a maize crop. As both are summer crops, the land will usually remain fallow for around seven months every year. In this section, the costs and benefits data, gross margin, and breakeven yields and prices of each crop are discussed first. After that, the NPV of net benefit from both crops and greenhouse gas are examined. Finally, sensitivity analysis is done for different parameters, and those parameters are ranked based on their sensitivity index.

8.2.1 Cost and income from peanuts cropping

The detailed cost-benefit and gross margin data for peanuts is given in Annex Table H-1. Peanuts need relatively intensive cultivation, and multiple operations associated with plantings and harvesting. The total cost of peanuts production from cultivation to final selling is around \$865 ha^{-1}. The major cost (31%) is for harvesting, drying and marketing operations. A significant part of that cost (9.3% out of 31%) is incurred for the threshing/cleaning operation, which is followed by digging (5.7% out of 31%). The purchase of seed is the second largest source of cost (around 20% of the total cost).

Planting and spraying, and fertiliser costs are the third largest sources of costs, each account for around 13% of the total cost. The planting and spraying includes slashing, sprayings four times and six different types of cultivation, with deep ripping incurring a major cost (2.3% out of 13%). Fertiliser includes lime, CK1 and muriate of potash (KCl). Lime is a source of calcium which is vital for neutralisation of acidity problem and peanut kernels. The CK1 is the main source of phosphorus (14.4%), potassium (14.2%) and calcium (10.7%). Among the fertilisers, CK1 incurs a major cost (6.4% out of 13%). The fertilisers' cost depends on the fertiliser type, the amount used in the previous crop and the residues management practices. Since a large amount of nitrogen fertiliser is used in maize crops (see next section), it is not used in the subsequent peanut crop. Some nutrients are also exported through the sale of peanut hay made from post harvest residue. This practice might have resulted in the higher fertiliser cost in peanut-maize cropping.

Herbicides, insecticides and fungicides are the fourth largest sources of cost, which incur around 12.6% of the total cost. The majority of that cost goes for fungicides (7.93%) and herbicides (4.64%). Finally, weed chipping is responsible for around 9.2% (\$80 ha^{-1}) of the total cost.

There are only two sources of income, peanut hay and peanuts. It is assumed that on average, approximately 0.5 tonnes (effective weight) of peanut hay is sold in every year. With the selling price of \$150 t^{-1}, around \$75 ha^{-1} is earned every year from hay. The average of long-term peanut production is 2 t and selling price is \$600 t^{-1}. Therefore, of the total income of \$1275 (ha^{-1}), more than 94% is accounted for by peanuts and around 6% from peanut hay.

8.2.2 Gross margin and breakeven points of peanut

As discussed before, the total cost of peanut cropping is around \$865 (ha^{-1}) and the total income is \$1275 (ha^{-1}). Therefore, the gross margin of a single peanut crop is around \$410 (ha^{-1}). This gross margin is on the basis of given costs and benefits, site conditions and cultivation practices. Even within this boundary, there are two major variables (yield and price) that could fluctuate to some extent every year. The effect of changing yield and price of peanut on gross margin is shown in Table 8.1.

Table 8.1 Effect of yield and price of peanut on gross margin per hectare

Yield	Price (\$ t^{-1})						
t ha^{-1}	\$570 t^{-1}	\$580 t^{-1}	\$590 t^{-1}	\$600 t^{-1}	\$610 t^{-1}	\$620 t^{-1}	\$630 t^{-1}
1.00	-\$116	-\$106	-\$96	-\$86	-\$76	-\$66	-\$56
1.50	\$117	\$132	\$147	\$162	\$177	\$192	\$207
2.00	\$350	\$370	\$390	\$410	\$430	\$450	\$470
2.50	\$583	\$608	\$633	\$658	\$683	\$708	\$733
3.00	\$819	\$849	\$879	\$909	\$939	\$969	\$999

Change in peanut yield does not change most of the costs, as many activities are not related to yield. It will only affect the threshing, drying and freighting costs. Therefore, the gross margin is not proportionate to yield. If the yield is one tonne (ha^{-1}), the gross margin will be positive only when the price exceeds \$686 t^{-1}. However, 1.5 t yields generate positive gross margin even at the price level of \$500 t^{-1}. If the price is \$630 t^{-1}, the gross margin will be around \$470 ha^{-1} even at the same yield of 2 t. Higher price and higher yield are most favourable conditions for higher gross margin. In the study areas, two tonnes yield and \$600 t^{-1} price are long-term averages. The landholders say the price and yield reached \$630 t^{-1} and 2.2 t ha^{-1} only once or twice in more than 20 years. Higher production usually increases the supply of peanuts, which in turn will reduce the demand and the price level.

In general, the breakeven point (BEP) of yield is the yield at which gross margin becomes zero in a given price. In this case, it was estimated by dividing the difference of total variable cost and bale income by the peanut price {($865-$75)/$600 t^{-1} = 1.31 t}. The calculation shows that the yield of 1.31 t (ha^{-1}) would generate zero gross margins for a given price of $600 t^{-1}. The BEP of price is the price at which the gross margin equals zero in a given yield. It was calculated by dividing the difference of total variable cost and bale income by peanut yield {($865-75)/$2 t^{-1} = $395 t^{-1}}. This means, for a given yield of two tonnes, even if farmers get a low price of $395 t^{-1}, they will not be in loss. Any prices after this price would be profitable.

8.2.3 Cost and income from maize cropping

All sources and their respective costs and benefits of maize cropping are given in Annex Table H-2. The total cost of maize cropping is around $472 ha^{-1}, which is almost 46% lower than for peanut cropping. Unlike peanuts, maize does not need intensive cultivation. There are only four cultivation operations, with no need for deep ripping. The cultivation for planting and spraying activities costs $73 ha^{-1} compared to $113 ha^{-1} for peanuts.

The highest cost in maize cropping comes from fertilisers. As discussed in earlier chapters a large amount of nutrients are removed with peanuts and hay. These removals are partly compensated for by fertilisers in maize cropping. Four different types of fertiliser have been used, which incurred around 35% of the total cost. Among them diammonium phosphate (DAP) accounts for around 12.7%, muriate of potash accounts for 8.7%, lime accounts for 6.9% and urea accounts for 6.4%. The DAP is the most popular source of phosphorus, as it contains around 46% of phosphorus (around 18% of nitrogen). Similarly, urea is mainly used for nitrogen, which contains more than 46% of the nitrogen.

Herbicides are another major cost. They account for around 15.4% of the total cost. Among them, *Kamba 500* alone is responsible for around 7% of costs, which is followed by *Roundup CT* (3.4%), *Express* (2.5%), *Amicide* 500 (1.5%) and *Surpass* (1%). The total herbicides cost for maize ($73 ha^{-1}) is much higher than the total herbicides cost in peanuts ($40 ha^{-1}). In maize cropping, there is no chipping. In peanuts, part of the herbicide cost is a trade-off by chipping. Seed is the third largest source of cost, which accounts for 13.8% of the total costs. Harvesting and freighting operations cost around 13.2% and 7.4% of the total cost, respectively.

In the study areas, the long-term average of maize production is around 3.5 t ha^{-1}. With the market price of \$160 t^{-1}, the average total income from maize would be around \$560 ha^{-1}.

8.2.4 Gross margin and breakeven points of maize

The estimation shows that the total cost of maize cropping is around \$472 (ha^{-1}) and total income is \$560 (ha^{-1}). Hence, the average gross margin of maize cropping is around \$88 (ha^{-1}). This gross margin of maize is estimated on the basis of long-term average yield of 3.5 t ha^{-1} and price of \$160 t^{-1}. The effect of changing yield and price on gross margin is shown in Table 8.2.

As with peanuts, fluctuations in maize yield do not reduce most of the costs and will only affect the freighting costs. If the yield is 2.5 t (ha^{-1}), gross margin will be negative, even at the price of \$185 t^{-1}. After that price level, gross margin will always be positive. About 3.75 t ha^{-1} yields generate positive gross margin even at the price of \$125 t^{-1}. If the price reduces to \$130 t^{-1}, the current production level of 3.5 t ha^{-1} will no longer be profitable. However, if the price increases to \$185 t^{-1}, the current gross margin will be doubled.

Table 8.2 Effect of yield and price of maize on gross margin per hectare

Yield	Price (\$ t^{-1})						
t ha^{-1}	\$130 t^{-1}	\$140 t^{-1}	\$150 t^{-1}	\$160 t^{-1}	\$170 t^{-1}	\$180 t^{-1}	\$190 t^{-1}
2.50	-\$137	-\$112	-\$87	-\$62	-\$37	-\$12	\$13
3.00	-\$77	-\$47	-\$17	\$13	\$43	\$73	\$103
3.50	-\$17	\$18	\$53	\$88	\$123	\$158	\$193
4.00	\$43	\$83	\$123	\$163	\$203	\$243	\$283
4.50	\$103	\$148	\$193	\$238	\$283	\$328	\$373

The breakeven point (BEP) of maize yield is around 2.95 t ha^{-1}. Similarly, the BEP of price is around \$135 t^{-1}. For the given maize yield of 3.5 t ha^{-1}, any prices above \$113 t^{-1} would be profitable.

8.2.5 Net present value of peanut-maize cropping incorporating carbon value

The major goal of this research was to compare peanut-maize cropping, pasture and spotted gum plantation incorporating both traditional tangible benefits and carbon value. Analysis from the previous chapter shows that the optimal rotation age of spotted gum is 34 years. Therefore, in order to estimate the NPV from maize and peanuts, all marginal benefits of 34 years need to be discounted to the present year with the discount rate of 6%, the same as that of plantation and pasture.

Earlier sections of this chapter show that there is a big difference in gross margin between maize and peanuts cropping (\$88 ha^{-1} vs \$410 ha^{-1}). If we take peanuts-maize-peanuts and so on as a sequence of crops, the higher gross margin of peanuts will be discounted less being counted in year one and so on. The opposite bias would occur, if we sequence in an alternative way. Only from the first two years, the NPV from the first sequence and the second sequence would be around \$465 and \$448, respectively. This difference of \$17 NPV over two years is quite significant. The discounted amount of gross margin would be lower and lower over time and the difference would be diluted. However, only because of this mathematical bias, the difference in NPV from the first and the second cropping sequences in 34 years would be around \$135 ha^{-1} (\$3646 ha^{-1} Vs \$3511 ha^{-1}). Therefore, the average value of gross margin of both crops is used, which is around \$249 ha^{-1} (Annex Table H-3). With the discount rate of 6%, the NPV of the peanuts-maize cropping is around \$3579 ha^{-1} in 34 years. This is equal to the average value of two different sequences {(\$3646 + \$3511)/2}. This process is also justified because some fertilisers are overused in maize for the benefit of the subsequent peanut crop.

The emissions of greenhouse gases from different sources have been modelled in chapter 4 & 5. Their amount in each year has been given in Annex Table H-3. Since the plantation started in 2001, the reference year for the cropping is assumed to be 2001. The RothC model (chapter 4) shows that the soil carbon amount in 2000 was around 75.46 t ha^{-1}. This amount would have reduced by 1.23 t in 2001. The model shows that the decreasing trend will continue but the rate will decrease over time. By 2035, the soil carbon level would reduce to around 48.5 t ha^{-1}. The amount of soil carbon loss, in terms of CO_2e, in an individual year is given in the Annex Table H-3. The annual average of greenhouse gas emissions from primary farm inputs is 1.05 tCO_2e. Similarly, annual greenhouse gas emission amounts from general land use, soil disturbances and biologically fixed nitrogen is around 1.5 tCO_2e. The discount rate, carbon price and carbon payment method used in plantation are also used here. From the analysis, the cultivation was found to be a net source of greenhouse gases, with a discounted value of net emissions of \$922 (ha^{-1}) in 34 years with a carbon price of \$10.5 $t^{-1}CO_2e$.

The high and negative value of NPV from greenhouse gases is mainly due to four reasons. First, in plantation and pasture, the soil carbon amount has been increasing, but from the literature (discussed in earlier chapters) we assumed that this is non-permanent. As a result, that amount was divided by 46 to make it equivalent to a carbon mitigation project. In the case of cultivation, soil carbon has been decreasing over time and the decreased amount is permanently emitted into the atmosphere. Therefore, there was no division of these amounts. Second, unlike plantation and pasture, there was no sink of greenhouse gases with cultivation and all activities were net sources.

Third, the emissions effect is exacerbated by the removal of hay, which has multiple impacts. There is the additional costs of fertilisers; the direct and indirect reduction in soil carbon levels; and the consequent damage to soil structure decreases the infiltration capacity of soil, which in turn reduces carbon levels (Bell *et al.,* 2000). Fourth, the collection and transportation of hay generates further greenhouse gas emissions. If we consider all these costs associated with hay removals, the current income from hay may not be profitable in the long-run.

The final contributing factor to the carbon emissions is associated with the frequency of peanut cropping and the use of a conventional tillage system. The impact of the conventional tillage system could be reduced by zero tillage, but this may also cause waterlogging and may exacerbate soil salinity in the low lying areas (Bell *et al.,* 2001). Moreover, zero tillage may increase the soil carbon, improve the soil structure and reduce the cost of production, but it may also reduce yield, considering water logging and disease from residues. Therefore, without holistic analysis of all sources of costs and benefits at a landscape level, discussions in favour of any particular cultivation system would be speculative and outside the scope of this research.

8.2.6 Sensitivity analysis and ranking of parameters

Given the long period (34 years), variables could considerably differ from the selected values with changes in technology, policy and markets. The variation in different parameters in different scales and consequent NPVs are given in Table 8.3.

Table 8.3 also shows a sensitivity index (or elasticity of sensitivity). As discussed in the analysis of plantations, the rates of elasticity of NPVs change over time, since the NPV curve is not linear. Hence, the elasticity of NPVs resulting from a downward change of the parameter is not the same as the-same percentage increase. For example, the elasticity of sensitivity by changing peanut yield from 2 to 1.8 t ha^{-1} is 1.9. It is different to that of changing yield from 2 to 2.2 t ha^{-1}, which is 2.1, even though the percentages of the fluctuation are the same (10%). If we need the sensitivity of the range of values, the average value for that range is used.

In this section, the effect of fluctuation of different parameters to the overall NPV is discussed first and then the sensitivities of those parameters are ranked.

The long-term average yield of peanuts, used in this study, is two tonnes. At the time of writing, the research area appeared to be getting drier and the frequency of dry years had increased, though it was not clear whether this was due to global warming or not. Nonetheless, for the given practices of cultivation and technology, there is the possibility of decreasing yields. On the other hand, with a shift to wetter periods and if higher yielding peanuts varieties are developed, there is some chance of increasing yield. In these circumstances, it could be assumed that the yield could fluctuate between 1.8 to 2.2 t ha^{-1} in the long run. If the yield increases from 2 to 2.2 t ha^{-1}, the NPV from crops in 34 years will increase by \$710 ha^{-1} and if it is reduced to 1.8 t ha^{-1}, the NPV would decrease by \$712 ha^{-1}. Since yield has nothing to do with greenhouse gas NPV, the total NPV would fluctuate by the same amount (Table 8.3).

The maize yield could fluctuate between three and four tonnes per hectare for similar reasons outlined above. If the yield increases from 3.5 t to 4 t ha^{-1}, the total NPV and crop NPV will increase by \$538 ha^{-1} in 34 years, and if it reduces to 3 t ha^{-1} the crop NPV will decrease by \$540 ha^{-1}. Fluctuating maize yield has no effect on greenhouse gases NPV. Therefore, the total NPV will fluctuate by the same amount (Table 8.3).

Table 8.3 Sensitivity of NPVs (\$ ha^{-1} in 34 yr) from peanut-maize cultivation in Kingaroy and ranking of most important parameters

Change in parameter	NPV (\$ ha^{-1}) in cultivation			Elasticity of NPV		
	Crops	GHGs	Total	Crops	GHGs	Total
Original conditions	3578.89	-921.71	2657.18	0.00	0.00	0.00
Peanut yield (2 to 2.2 t ha^{-1})	4288.89	-921.71	3367.18	1.90	0.00	2.47
Peanut yield (2 to 1.8 t ha^{-1})	2866.44	-921.71	1944.74	-2.10	0.00	-2.94
Peanut price (600 to \$620 t^{-1})	3865.03	-921.71	2943.32	2.34	0.00	3.12
Peanut price (600 to \$580 t^{-1})	3290.30	-921.71	2368.60	-2.48	0.00	-3.39
Maize yield (3.5 to 4 t ha^{-1})	4116.47	-921.71	3194.77	1.05	0.00	1.38
Maize yield (3.5 to 3 t ha^{-1})	3038.86	-921.71	2117.16	-1.06	0.00	-1.47
Maize price (\$160 to \$180 t^{-1})	4080.55	-921.71	3158.85	1.11	0.00	1.47
Maize price (\$160 to \$140 t^{-1})	3074.78	-921.71	2153.08	-1.14	0.00	-1.57
Soil C decreasing rate increase by 10%	3578.89	-868.02	2710.87	0.00	-0.57	-0.19
C price down to \$5.5 t^{-1}CO2e	3578.89	-482.80	3096.09	0.00	1.00	-0.24

Although Australia produces only 0.2% of the world's peanuts, the majority of its product goes to the world market (PCA, 2004). Therefore, the exchange rates of the Australian dollar and the demand and supply situation of peanuts determines the price of peanuts. In some markets, per capita consumption may be decreasing, as one to two percent of the Australian population is allergic (from a rash to anaphylaxsis) to peanuts (PCA, 2005). However, decreasing level of aflatoxin (lowest recorded in 2003), growing overall consumption in USA and China, and the signing of Free Trade Agreement between Australia and USA may have a positive effect on peanut prices (PCA, 2004). Hence, the peanut price is assumed to fluctuate between \$580 t^{-1} and \$620 t^{-1}. If the price increases from \$600 to \$620 t^{-1}, the NPV from crops in 34 years will increase by \$286 ha^{-1}, and if it reduces to \$580 t^{-1} the NPV will decrease by \$288 ha^{-1}. As the peanuts price does not affect greenhouse gas NPV, the total NPV will fluctuate by the same amount (Table 8.3).

The price of maize solely depends on domestic supply and demand. The supply side could increase, since maize is a substitute in production for cotton and sorghum in low rainfall irrigated areas due to its greater water use efficiency (Birch *et al*., 2003). On the other side, demand of maize is also increasing due to the expansion of the feedlot beef industry in the region (Robertson *et al.,* 2003). Moreover, a new market for maize may emerge with ethanol production (Birch *et al.,* 2003). Therefore, the maize price could fluctuate in the range of \$140 to \$180 t^{-1}. If the price increases from \$160 t^{-1} to \$180 t^{-1}, the NPV from crops in 34 years will increase by \$502 ha^{-1}, and if it reduces to \$140 t^{-1}, the crops' NPV will decrease by \$504 ha^{-1}. The maize price does not affect the greenhouse gas NPV. Therefore, the total NPV will fluctuate by the same amount.

In plantation, cropped areas and pasture, the soil carbon is assumed to have fluctuated by 10%. If soil carbon loss rates decrease by 10% in all 34 years, then the NPV from greenhouse gases will increase by \$54 ha^{-1}, and if it increases by the same percent, NPV will reduce by \$49 ha^{-1}. Variation is soil carbon will have no effect on the crops' NPV, thus the total NPV will fluctuate by the same amount. The elasticity results show that the total NPV is less sensitive with soil carbon than prices and yields of maize and peanuts. Because of this, the different scenarios of soil carbon were not analysed. It could be argued that the fluctuation of soil carbon could affect the yield and therefore the crop NPV; but within the small range of given soil carbon values, this effect would be insignificant and therefore is not identified in this study.

This study has used the carbon (or greenhouse gas) price of \$10.5 $t^{-1}CO_2e$. In the near future, there is a rare chance of increasing the carbon price, especially in Australia. The reasons are already explained in the literature review (chapter 2) and optimal rotation of plantation (chapter 7) chapters. As in plantation and pasture, it is assumed that the carbon price could decrease from \$10.5 to \$5.5 $t^{-1}CO_2e$. Changes in carbon price do not affect the NPV from crops. It only affects the NPV from greenhouse gases. If the carbon price decreases to \$5.5 $t^{-1}CO_2e$ from 10.5 $t^{-1}CO_2e$, the NPV of greenhouse gases will increase by \$439 ha^{-1} and overall NPV will increase from \$2657 to \$3096 ha^{-1}. This result shows that the carbon price is sensitive to greenhouse gas NPV, but is not very sensitive to the overall NPV. However, this could be due to a large fluctuation in prices. This study will now analyse the sensitivity index and rank the different NPV determining parameters.

The sensitivity index (elasticity of sensitivity) of crops, greenhouse gas and total NPVs due to fluctuating different key parameters are given in the last three columns of Table 8.3. These values are applicable only for the fluctuation of the given scale. For example, if the yield of peanuts increases or decreases by more than 10%, this value may not be applicable. The nature of the sensitivity index values and the conditions of their applicability are discussed in chapter seven.

The most sensitive parameter for the NPV is the peanut price. A one percent decrease in the peanut price will reduce the total NPV by 3.39% (Table 8.3) in 34 years, and a one percent increase in peanut price will increase total NPV by 3.12%. Therefore, an average value of the elasticity of peanut price to the total NPV is around 3.25. However, a one percent fluctuation in the peanut price will change the crop-only NPV by 2.41% (Table 8.3).

The second most sensitive parameter is the peanut yield. If the peanut yield is altered by one percent, the overall NPV (in an average) would fluctuate by 2.7%. However, the average sensitivity to the crop NPV is only around two percent. The third most sensitive parameter is the maize price. If the maize price varies by one percent, the overall NPV from cultivation will vary by 1.52% in 34 years. The fourth sensitive parameter is maize yield. If the maize yield is changed by one percent, the total NPV will change by 1.42%. From the analyses, it is obvious that the prices and yields of peanut and maize are elastic, as the percentage change in outcomes are greater than the percentage change in causes. However, soil carbon and carbon prices are inelastic to the total NPV. A one percent decrease in soil carbon decreasing rates in all years will increase the total NPV by 0.19% in 34 years. Similarly, a one percent decrease in carbon price will increase the total NPV by 0.24%.

8.3 Financial analysis for the pasture system

In order to compare pasture with other land use systems, the costs and benefits of pasture need to be assessed by incorporating greenhouse gases and tangible values. This section is divided into four sub-sections. The first sub-section analyses the costs and benefits data; the second estimates and analyses the grazing or stock NPV and the total NPV incorporating both stock and carbon values. In the last two sub-sections, some discussions are given and a sensitivity analysis is done and key NPV determining parameters are ranked.

8.3.1 Cost and benefit data of pasture

The stocking rate of pasture was estimated to be 0.56 head ha^{-1} yr^{-1}. The details of costs and benefits data for pasture are given in the Annex (Table H-4). During the first year of the establishment period, around \$158 ha^{-1} was spent, with the majority of that spent on the watering system (45%), followed by cultivation (23%), which includes slashing, ripping and seeding operations. Fertilisers and seeds are other sources of costs; each accounted for about 16% of the total establishment cost. In the past, cultivation was carried out every 10 years, but due to increasing dryness, more frequent cultivation of pasture is needed for revitalising the pasture system, with every eight years being the practice at the study site. Approximately \$61 ha^{-1} will be incurred for revitalising activities in 34 years. Out of that, around 59% will be spent on cultivation operations and 41% for seeds.

Total annual costs for 0.56 cattle (ha^{-1}) are around \$36, which includes annual health costs (9%) and annual other costs. In 12 months, the gross weight gain of cattle would be 250 kg hd^{-1}. At a rate of \$2 kg^{-1} live weight and a 0.56 head (ha^{-1}) stocking rate, the gross gain in price will be \$280 (ha^{-1}) every year.

8.3.2 Net present value of pasture incorporating carbon value

The NPV of pasture from stock and carbon is given in Annex Table H-5. Since there is a huge cost in the first year, the net benefit was lowest (\$153 ha^{-1}) in that year. After that it would be \$225 (yr^{-1}) in every year, except in the 8th, 16th, 24th, 32nd, 33rd and 34th years. There are some revitalising costs (cultivations costs, as discussed above) in those years, which reduce the net benefit. With the common discount rate of 6%, the NPV from stock would be around \$3079 (ha^{-1}) in 34 years, which is greater than the NPV from plantations (timber only) but lower than the NPV from cultivation (crops and hays only).

The emissions of greenhouse gas from different sources have been modelled in earlier chapters. Unlike cultivation, pasture has both sources and sinks of greenhouse gases. The soil and grass and legume biomass are carbon sinks. Similarly, cattle excretion, cattle burping, primary farm inputs, legumes and soil disturbances are the sources of carbon. The annualised amount of greenhouse gases from all sinks and sources is given in Annex Table H-5. The reference year, pasture establishment year, is assumed as 2001, the year of plantation.

The RothC model shows that the soil carbon amount in pasture in 2000 would be around 144.45 t ha^{-1}. The RothC model predicted amount is 145.23 t ha^{-1} (increased by 0.78 t) in 2001. The model shows that that the yearly increase in carbon would become smaller over time. For example, the predicted increase rate in 2000-2001 was around 0.53%, and it would be only 0.27% in 2034-2035. In total, the soil carbon level will increase from around 145 t ha^{-1} to 164 t ha^{-1} in 34 years. Since the soil carbon is increasing every year, the cumulative soil carbon was estimated for each year for the estimation of gross carbon benefit in that year. This was necessary, as a tonne-year carbon accounting system was used in all land use systems. The pasture contains around 6.33 t of grass and legume biomass (or 3.17 t C mass). There may be some fluctuations in biomass but it was assumed to be constant over time for modelling purposes. The estimated NPV gain from these two sinks in 34 years is around $133.

The greenhouse gas emissions from primary farm inputs also vary and range from 0.44 tCO_2e in the first year to around 0.02 tCO_2e in the 34th year. The higher amount of greenhouse gas emissions in the first year was due to the higher intensity of cultivation activities. Similarly, the greenhouse gas emissions from general land uses, soil disturbances and biologically fixed nitrogen is 1.37 tCO_2e in the first year and 1.23 tCO_2e in other years, except the pasture revitalising years. However, as the stocking rate is constant in all years, the methane emissions from cattle burping (0.77 $tCO_2e\ yr^{-1}$) and nitrogen excretion from urine and faeces excretion (0.21 $tCO_2e\ yr^{-1}$) is constant in all years. The analyses show that $347 ($ha^{-1}$) of NPV will be lost from these sources of greenhouse gases in 34 years.

If both sources and sinks are considered, pasture is a net source of greenhouse gas and the total NPV from greenhouse gases in 34 years would be around -$214 ha^{-1} ($133 ha^{-1} - $347 ha^{-1} = - $214 ha^{-1}).

The lower value of NPV from soil and biomass carbon is mainly due to the use of a tonne-year carbon accounting method. The total carbon from soil and biomass has been increasing over time, but it is non-permanent in nature. Therefore, the total carbon amount was divided by 46 to make it equivalent to a mitigation project, a permanent emissions reduction project. Similarly, the higher value of negative NPV from sources is due to the inclusion of emissions from cattle burping and excretion, which were absent in cultivation. Higher frequency of revitalizing activities, every eight year instead of every ten years, is also responsible for increasing negative NPV from sources.

8.3.3 Reviewing beef production

The total NPV of pasture incorporating both stock and carbon values is around $2865 in 34 years. The overall NPV depends on growth factors, marketing factors and greenhouse gas emission factors. The growth rate of cattle is related to genetic factors (breeds) and pasture quality. The research area is characterised by relatively high temperatures and low rainfall. So farmers have adopted a crossbreed of *Bos indicus* and *Bos taurus* cattle. The former tropical breed *B. indices* was chosen for heat and tick resistant behaviours and the British breed was chosen for good marbling content, which has significant meaning in Japan, a major buyer of Australian beef (C. Marshall, 2005, pers.com., 7 April)[51].

Most of the markets demand the cattle growth rates of at least 100 kg live weight in two months and 325 kg in 12 months (MLA, 2006), though this should not be a trade-off with many other market specifications relating to the quality of the meat (MLA, 2006). Each pasture has different grass composition, amount and quality. Selling time is not only guided by growth rates, but also by beef price. If farmers can find the growth rates of their cattle in that particular pasture environment and model this with different market prices, they can estimate the optimum selling time. This would help them to increase their total NPV.

Australia is the largest beef exporter in the world, which contributes 25% of the total beef trade (ABS, 2005). Being the largest exporter, it can influence the world market to some extent. Because production is a small proportion (4%) of the world production, beef prices in Australia are largely determined by the world market (ABS, 2005). It exports beef in several countries, but Japan is the major one (Alexander and Groth, 2005), where it mainly competes with the USA. Therefore, the US cattle production cycle is one of the major influencers on the export prices of Australian beef. Peaks in this cycle have occurred in every 10-12 years, usually triggered by a high level of grain production in the USA (ABS, 2005).

In the past, the Australian beef industry was influenced by many other factors and is susceptible to production events. Increased exchange rates for the Australian dollar, implementation of the US quota system and drought in the eastern part of Australia

[51] Collin Marshal, property owner, Taabinga, Kingaroy

are some examples (Cattle Council of Australia Yearbook, 2002). Until 2003, the Japanese beef market was divided 50% - 50% between Australia and the USA (MLA, 2006). When the US announced its first case of BSE (bovine spongiform encephalopathy) in December 2003, Japan (and also South Korea) banned US beef (Condon, 2006) and Australia monopolised the Japanese beef market (MLA, 2006). Japan conditionally reopened doors to US in July 2006, so it can be argued that the demand for Australian may again decrease.

At the time of writing it was predicted that demand for beef will remain steady at 390,000 t for the year as the lifting conditions will not have big influx of US beef (Condon, 2006); especially, as alternative markets open up in Korea, Taiwan, Middle East and Russia. Moreover, the opening of the Japanese market for US beef means the fear of disease is over and this will help to increase the beef consumption rates in Japan (Condon, 2006). Considering the new markets, new consumption rates in Japan and the lifting of ban conditions of US beef, the price of beef may remain the same. Moreover, a long-term average market price is used for this study, therefore, the ups and down of a few years may not affect the long-term average.

The total NPV from pasture could increase through increasing cattle stocking rates, cattle quality and increased demands, and also by reducing the costs of production and greenhouse gas emissions. Production costs would be reduced by producing cattle on a large scale. For example, the per head cost of water management in the first year and the annual electricity costs would be reduced. Similarly, the loss in NPV from greenhouse gas emissions could be reduced by decreasing the methane emissions and the frequency of pasture re-establishment activities. Reducing the amount of methane emissions without compromising the stocking rates, size and growth performance is a challenging task for researchers.

Genetically improved cattle may provide opportunities to reduce feed consumption and then methane emissions without compromising size and growth performance (Hegarti, 2003). Finding the acetate producing bacteria in kangaroo and replacing them in the rumen of cattle would help to keep out methanogenic bacteria from rumen, which will dramatically reduce methane emission (Black, 2002). The repeated treatment of beef cattle with hormonal growth promotants could lead up to a 16% reduction in lifetime methane production and also lead to a 7-11% reduction in slaughter age (McCrabb and Bob Hunter, 2003). If these researches are translated into general practice, the net loss of greenhouse gas NPV would decrease and the total NPV would increase.

Soil carbon could be increased by planting some trees around the pasture area, as plantation of hardwood species was found to be better than pasture for soil carbon sequestration. Trees also provide shades to the cattle during the hot season and also sequester carbon to their biomasses. If the trees have fodder value, the benefits would be twofold.

8.3.4 Sensitivity analysis and ranking of most important parameters

After obtaining the results, the value of different NPV determining parameters were discussed with experts. The possible fluctuation of different parameters and their reasons are already discussed in the previous chapter (chapter seven) along with discussion about the optimal rotation age of spotted gum plantation. As the plantation is managed as a silvipastoral system, the logic of the pasture in plantations is also applicable to the pasture system. The fluctuation of different parameters in different scales and the likely NPVs due to those fluctuations are given in the first three columns of Table 8.4. Similarly, the elasticity of NPVs by fluctuating the given parameters are given in the last three columns of Table 8.4.

Table 8.4 Sensitivity of NPVs (\$ ha^{-1} in 34 yr) from pasture in Kingaroy and ranking of NPVs determining parameters

Change in parameter	NPV (\$ ha^{-1}) in cultivation			Sensitivity of NPV		
	Stock	GHGs	Total	Stock	GHGs	Total
Original conditions	3079.08	-213.99	2865.08	0	0	0
Gross wt down to 220kg hd^{-1}	2615.71	-213.99	2401.71	-1.27	0.00	-1.38
Beef price (from \$2 to \$1.8 kg^{-1})	2692.86	-213.99	2478.87	-1.27	0.00	-1.37
Stocking rate down by 10%	2712.41	-196.99	2515.42	-0.60	0.79	-1.23
Soil C decrease by 10%	3079.08	-223.48	2855.60	0.00	-0.41	-0.03
Biomass down by 10%	3079.08	-217.80	2861.28	0.00	-0.17	-0.01
C price down to \$5.5t^{-1}CO_2e	3079.08	-112.09	2966.99	0.00	1.00	0.06

The original stock NPV, greenhouse gases NPV and total NPV (both from stock and greenhouse gas) in 34 years are \$3079, -\$214 and \$2865 ha^{-1}, respectively. Similarly, the long-term average gross weight gain of cattle assumed in this study is \$250 kg yr^{-1} and the long-term average live weight price is \$2 kg^{-1}. Moreover, the assumed long-term average stocking rate is 0.56 ha^{-1}. If the average gross weight gain of cattle in

12 months decreases from \$250 kg to \$220 kg hd^{-1}, the livestock NPV (or stock NPV) will decrease by \$463 ha^{-1} in 34 years. Since it has no effect on the greenhouse gas NPV, the same amount will decrease from the total NPV (Table 8.4).

If the long-term average price of beef drops from \$2 kg^{-1} to \$1.8 kg^{-1}, the stock NPV will decrease by \$386 in 34 years. There will be no effect on greenhouse gas NPV. Thus, the same amount of NPV will decrease from the total NPV. If the stocking rates drop by 10% in all 34 years, the stock NPV will reduce from \$3079 to \$2712 ha^{-1}. Decreased stocking rates also reduce greenhouse gas emissions (especially methane and nitrous oxide). Therefore, the greenhouse gas NPV will increase by \$16 ha^{-1}. Considering the overall effect, a reduction in stocking rates by 10% in all 34 years, will reduce the total NPV by \$349.66 ha^{-1}.

If the estimated soil carbon rates are reduced by 10% in all 34 years, the NPV lost from greenhouse gas will increase from \$214 to \$223 ha^{-1} (by \$9 ha^{-1}) and the total NPV will also decrease by the same amount. While changing the same percentage of the soil carbon in cultivation, the total fluctuation of NPV was around \$50 ha^{-1}. The small amount of total NPV fluctuation in pasture compared to cultivation was due to the nature of emissions and/or sequestration. In cultivation, the emission of soil carbon was permanent whereas in the case of pasture, the increasing soil carbon rate is non-permanent in nature. Therefore, the total sequestered amount was divided by 46 to make it equivalent to a permanent mitigation project (for detail see chapter 2 and 3), whereas this was not the case for cultivation.

The pasture biomass plays a very small role in greenhouse gas NPV and total NPV, as the amount is small and it is also considered non-permanent. A 10% decrease in the biomass of pasture in all 34 years will result in a decrease in the total NPV of \$4 ha^{-1}. Changing the carbon price has a significant impact on greenhouse gas NPV, but has little impact on total NPV. If the carbon price decreases from \$10.5 $t^{-1}CO2e$ to \$5.5 $t^{-1}CO2e$, the loss of greenhouse gas NPV in 34 years will decrease from \$214 to \$112 ha^{-1}. Since it has no relation with stock NPV, total NPV will increase by the same amount.

Elasticity of sensitivity of stock, greenhouse gas and total NPVs due to fluctuation of key parameters are given in the last three columns of Table 8.4. The most sensitive parameter for the stock and total NPVs is the gross weight gain of cattle. In totality, a one percent decrease in gross weight gain will reduce the total NPV by 1.38% (Table 8.4). It can be argued that the fluctuation of gross weight gain could occur due to fluctuation of feeding amount or digestibility. These factors could affect the CH_4 and N_2O emissions as well. However, it is assumed that within the small range of fluctuation this would be insignificant.

The second, third and fourth most sensitive parameters are beef price, stocking rate and carbon price respectively. The soil carbon and biomass are inelastic to both greenhouse gas and total NPV, as the elasticity values are less than one. Therefore, the soil and biomass carbon fluctuation in pasture is less significant for overall NPV (Table 8.4).

8.4 A comprising of crops and pasture

The above sections analysed the costs and benefits data and estimated the total NPV of cultivation and pasture in 34 years incorporating both traditional tangible benefits (crops and hay in cultivation and beef in pasture) and greenhouse gas values. The analyses showed that the NPV from crops was satisfactory (\$3579 ha^{-1}). However, due to intensive and traditional cultivation systems, NPV loss from greenhouse gas was very high. If we consider the greenhouse gas values, the total NPV will decrease by \$922 ha^{-1} in 34 years. This shows that the net benefits of cultivation would reduce significantly, if the greenhouse gas emissions values are considered. The contribution of peanuts to the total NPV was the highest, thus, the peanuts price was found to be the most sensitive factor to the total NPV. It was followed by peanut yield, maize price and maize yield. On the other hand, soil carbon was found to be the least sensitive to the total NPV and was followed by carbon price.

In the case of pasture, the NPV from stock was satisfactory (\$3079 ha^{-1}). However, the emission of greenhouse gases from sources were always (every year) higher than sequestrations from sinks. Therefore, the NPV gain from the sequestrations of greenhouse gases (\$133 ha^{-1} in 34 years) is lower than the NPV loss from greenhouse gas emissions (\$347 ha^{-1} in 34 years). As a result, the total NPV from stock and greenhouse gas is reduced from \$3079 to \$2865 ha^{-1} in 34 years. The effect of stock variables on the total NPV was much higher than the effect of greenhouse gases. The gross gain in stock weight and beef price were found to be the most sensitive to the total NPV. They were followed by stocking rate, carbon price and soil carbon. The biomass of pasture was found to be the least sensitive to the total NPV.

From the overall analysis, cultivation seems a favourable option, if we do not consider the carbon value. However, after the inclusion of carbon value, pasture would be favourable than cultivation. These results will be compared with the NPV of plantation system to ascertain the most preferable option among the three highly competitive land uses in the study area.

8.5 Comparison of NPVs from different land use systems

The aim of the study was to compare different land use systems incorporating both greenhouse gas and traditional tangible benefits. So far, stock NPV from pasture, crops NPV from cultivation, timber and stock NPVs from plantations and greenhouse gas NPVs from all three land use systems have been estimated and discussed. On the basis of these results, this section first compares the traditional tangible values of all land use systems and then evaluates the total NPV incorporating both traditional tangible benefits and greenhouse gas values. After that, it presents some discussions linking with the introduction and hypotheses of the study.

8.5.1 Comparison of NPVs from traditional tangible products

The comparative figures of NPVs of all land use systems are given in Table 8.5. The traditional tangible benefit is the net benefit from traditional tangible products. This is what farmers are actually receiving. These estimations include the benefits from peanut and maize cropping in cultivation, stock in pasture and timber in plantations. Analysis shows that the cultivation, pasture and plantations return \$3578 ha^{-1}, \$3079 ha^{-1} and \$2045 ha^{-1} of NPVs from traditional tangible products in 34 years (Table 8.5). Therefore, the cultivation is around 1.75 times more profitable than plantations and around 1.16 times more profitable than pasture.

Table 8.5 NPVs (\$ ha^{-1}) from different land use systems in Kingaroy in 34 years

Land uses	Crop	Timber	GHGs	Stock	Total
Cultivation	3578.89	0	-921.71	0.00	2657.18
Pasture	0	0	-213.99	3079.08	2865.08
Plantation	0	2045	861.8	794	3700.8

It is stated elsewhere in this study that the plantation is silvipastoral (chapter 3 & 7). It includes both timber and pasture components. The livestock NPV of a plantation is around \$794 ha^{-1} in 34 years. If this value is added to the timber value, the total NPV from plantation would be around \$2839 ha^{-1} in 34 years. Even after the inclusion of stock value, the plantation would be less preferable than pasture. Cultivation would still be the best option, as the cropping NPV is higher than plantation by \$740 ha^{-1}.

8.5.2 Comparison of NPVs from traditional tangible products and GHGs

The cultivation and pasture are net sources of greenhouse gases, whereas plantation is a net sink. Cultivation results in the highest emissions of greenhouse gas into the atmosphere than pasture. The total NPV lost from greenhouse gases in cultivation (\$922 ha^{-1}) is 4.3 times that in pasture (\$214 ha^{-1}) in 34 years (Table 9.5). In contrast, total NPV gain from greenhouse gases in plantations is around \$862 ha^{-1} in 34 years. When we adjust the greenhouse gas NPV to the NPV from other sources, the total NPV in plantations would increase from \$2839 to \$3701 ha^{-1} in 34 years. However, in cultivation it would decrease from \$3579 to \$2657 ha^{-1}, and in pasture it would decrease from \$3079 to \$2865 ha^{-1}. Without including the greenhouse gas NPV, cultivation was the best option followed by pasture and plantation. However, after inclusion of greenhouse gas values, plantations become the best option and cultivation has the worst position. Pasture still remains in the second best position. Plantations could be the most attractive land use option, if we consider the greenhouse gas values in all land use systems. Therefore, this result supported the main research hypothesis.

8.6 Discussion

It was hypothesised that plantations would be more profitable than pasture and cultivation, if stock and carbon benefits are included in the timber benefit.

The NPV of plantation will be greater than the NPV of pasture, and the NPV of pasture will be greater than the NPV of cultivation, if carbon and stock values of plantation are considered.

This main hypothesis was fully supported by results and analyses on the basis of business-as-usual scenario. In order to support this main hypothesis, several specific hypotheses were set out. All of the hypotheses are verified in business-as-usual scenario and carbon price of \$10 $t^{-1}CO_2e$.. The first hypothesis stated that the total NPV of plantations from timber would be lower than the NPV from other land use options (traditional tangible benefit). This was verified.

The second hypothesis stated that the NPV from plantation would increase by including the livestock component. As the pasture contributes an additional \$794 ha^{-1} in 34 years, this hypothesis is also validated. The third hypothesis was that if three main greenhouse gases from all sources and sinks of all land uses were considered, the NPV from cultivation and pasture would reduce and the NPV from plantation would increase significantly. This specific hypothesis was further supported by several sub-hypotheses. These include the soil carbon, biomass carbon, and emissions from primary farm inputs, cattle burping and excretions and biologically fixed nitrogen. These hypotheses are all verified. As all specific hypotheses and their complementary hypotheses are independently verified, the main hypothesis is proved to be a logical extensions of these.

Farmers may not switch to another land use option unless they believe that the new land use is financially more attractive and less risky (Cockfield, 2005). In this regards, further analyses of several factors such as productivity, domestic and international markets and risk factors, are necessary. All these factors, of all land use systems, are already discussed. Here, the discussion will focus on the comparative advantage of one land use system over the others.

Productivity: Production is mainly concerned with crop yields in cultivation; beef yields in pasture and mean annual increment (MAI) or growth rates in plantation. Even if the long-term gross weight gain of live cattle increases from 250 kg hd^{-1} to 275 kg hd^{-1}, pasture cannot compete with plantation. Similarly, even if the long-term peanut yield increases from 2 t ha^{-1} to 2.2 t ha^{-1} or maize yield increases from 3.5 t ha^{-1} to 4 t ha^{-1}, cultivation will not compete with plantations. However, if the peanut and maize yield increases at the same time and all other variables remain constant, cultivation (NPV \$3900 ha^{-1} in 34 years) will be more attractive than plantations (\$3701 ha^{-1} in 34 years). This is unlikely because as supply increases, prices may decrease, which will reduce the total NPV from cultivation.

In the context of global warming and uncertainty in rainfall and temperatures, it may be argued that the optimal spacing level and mean annual increment (MAI) may vary. If the optimum spacing level (or MAI) predicted by this model is decreased by 10%, the total NPV from plantations would be only around $3146 in 34 years. Even with that condition, plantations would be a superior land use options to others. Moreover, global warming will not only affect spotted gum plantations, but will also affect other land use systems because of the geographical proximity (Kikic *et al.,* 2005). If the MAI decreases in plantation due to climate change, the pasture and cultivation biomass and crops and beef yields will also decrease. This suggests that the plantation will still be in a better position.

It has already been discussed that there is less chance of increase in gross gain in weight of beef. The research and development in plantations, especially on the hardwood species, is in the infant stage. There is a good chance of increasing the NPVs of plantations. In the past, it was thought that the forest products from plantations could be of inferior quality than the product from natural forests and may not get equal market opportunities (Yang and Waugh, 1996). Later research on eucalyptus plantations in different parts of Queensland invalidated this (Leggate *et al.,* 2000). Recently, three case studies in Southeast Queensland found that the well managed forest stand could produce a superior product worth 20% more standing value than an average natural stand (Ryan and Taylor, 2001). Therefore, there is a chance of increasing the current NPV in plantations.

Moreover, in this study, the MAI of the spotted gum plantations was modelled from the time series data of the trees planted in 1990. Since then, genetic improvement programs have gained significant achievement (Lee *et al.,* 2001; Huth *et al*., 2004; Lee, 2005). This program alone could increase productivity of plantations by 30-50% (Lewty *et al.,* 2001). Because of this comparative advantage of plantations, NPV from plantation could be further increased in the long run.

Price of crops, beef and timber: Even if the long-term average price of peanuts increases from $600 t^{-1} to $620 t^{-1} and maize price increases from $160 t^{-1} to $180 t^{-1} at the same time, the cultivation will not be as a profitable as a plantation. However, if price increases to $630 t^{-1} in peanuts and $190 t^{-1} in maize at the same time, the cultivation (NPV $3850 ha^{-1} in 34 years) will be more profitable than for plantations.

Similarly, if the peanut yield increases to 2.2 t ha^{-1} and the price increases to \$620 t^{-1} at the same time (or if the maize yield increases to 4 t ha^{-1} and price increases to \$180 t^{-1} at the same time), cultivation will be more profitable (NPV around \$3800 ha^{-1} in both cases) than plantations (NPV \$3701 ha^{-1}). However, the law of demand and supply proves that these mutually inclusive events are unlikely.

Similarly, pasture will not able to compete with plantations even if the live weight beef price increases from \$2 kg^{-1} to 2.2 kg^{-1}. Moreover, even if the gross weight gain of beef in 12 month increases from 250kg to 260kg (hd^{-1}) and live weight beef price increases from \$2 kg^{-1} \$2.2 kg^{-1} at the same time and all other things remain the same, the pasture (NPV around \$3340 ha^{-1}) will be less profitable than plantations (\$3951 ha^{-1}). Therefore, although pasture is in the second position by NPV, it never can compete with plantations. This is because an increase in beef price and gross beef weight not only increases the pasture NPV, but it also increases the plantations NPV to some extent, as plantation has a stock component as well.

The price of timber is the third most sensitive factor (sensitivity 1.2) for total NPV from plantations. It means that if the timber price decreases by 10%, the total NPV from plantation will decrease by 12% (from \$3701 ha^{-1} to \$3257 ha^{-1}). Even in that condition, plantations will be more profitable than pasture and cultivation.

NPVs from different scenarios in plantation: In the case of plantations, two scenarios were analysed in the previous chapter. The first one is the business-as-usual scenario, a continuation of current practices. The typical attributes of the business-as-usual scenario are small and fragmented forest areas, selling logs from farms, getting a stumpage price, harvesting by contractors and no special farmers institution. All of the analyses, so far, in this chapter were based on a business-as-usual scenario. The optimistic scenario assumes commercial scale of plantation, good institutions, sophisticated machines, highly competitive markets and a factory gate price. If these conditions are achieved, the optimal rotation of plantations would be 33 years and total NPV in 33 years would increase to \$6383 ha^{-1} from \$3701 ha^{-1}in 34 years in the business-as-usual case. This finding is partially supported by three recent case studies in Southeast Queensland (Ryan and Taylor, 2001). They found that the landowner could get a net extra benefit of \$28 m^{-3} by employing a miller to saw the logs and then sell the sawn product himself. If the landowner mills and sells his timber using a portable sawmill the net return will increase by \$142 m^{-3} (Ryan and Taylor, 2001).

Moreover, Wondai Sawmill staff said that logs below 25 cm diameter were not acceptable, as they are not cost effective for processing. Our analysis in a previous chapter showed that around 90 m^3 of logs (ha^{-1}) between 25 cm to 10 cm diameter are lost for this reason. If the owner can process these logs by using a portable (mobile) sawmill, a significant amount of NPV could be increased. However, for this to happen, either they should go for commercial scale or adopt co-operative processing and marketing systems. If all these conditions prevail, a plantation will be much more profitable than other land use systems.

Export of spotted gum timbers in the international markets: The Southeast Queensland Regional Forest Agreement program has provision to cease all natural forests logging on state owned land by 2024 (Venn, 2005). The supply of hardwood species diminished from natural forest but their demand is increasing by two-to-three percent every year (DPI&F and DNR, 1999). Therefore, most of the hardwood production in this region would be consumed in the domestic markets. In the whole of Australia, only around \$782 million worth of hardwood was exported in 1999 (Love, *et al.*, 2000). By 'Vision 2020', Australia is planning to treble the national plantation state, with a major focus on hardwood species, to about three million hectares by the year 2020 (Kirschbaum, 2000). As a result, the proportion of hardwood plantations in Australia has been increasing (15% in 1994 to 74% in 2003) (National Forest Inventory, 2004). If this policy becomes effective and get continuity in the long run, huge amounts of hardwood will be produced in the country. All of that production will not be consumed in the domestic markets. In those conditions, international markets would have a dominant effect. Therefore, it would be worthwhile to analyse international hardwood markets.

Since 1997 the export value of forest products from China increased from \$4 billion to \$17 billion, a period in which imports of Chinese wood products rose nearly by 1000% in the United States and 800% in the European Union (UNECE/FAO, 2006). As the tropical hardwood supplies from Malaysia and Indonesia is increasingly limited, both China and India are looking for large volumes of hardwood. Provided Australian products are internationally competitive, they may easily penetrate the

Chinese and Indian markets (ANU, 2004). Among the competitor suppliers, Australia generally face lower energy costs and have an overall capital cost advantage because of lower sawmill construction costs and cost of capital (Love *et al*., 2000).

Around 50% of the United Nations Economic Commission for Europe (UNECE) region's flooring is based on oak trees. The price of the white oak is increasing by three to five percent annually (UNECE/FAO, 2006). Therefore, in the international level, spotted gum would need to compete with white oak. The current market price of white oak in the USA is around US$355 m^{-3}. The hardness, density, load bearing capacity, grain and colour of spotted gum is superior to white oak (from comparison of American Hardwood Export Council, 2002; James Piers & Associates, 2005; Outdoor Structure Australia, 2006; FastFloor.com literature). The only problem with spotted gum for producing quality products was due to joint movement, which results from seasonal changes in moisture content and is a particular problem during transport overseas. However, this problem has been resolved (DPI&F, 2005). If Australia can supply spotted gum for a lower price than white oak, it could have comparative advantage over the export countries. Moreover, spotted gum is not only good for flooring, it is much better than many other species for structures and decking because of its hardness, colour and durability (Wondai Sawmill staff, 2006, pers. comm., 1 June). These facts and figures show that the spotted gum plantation could have a good export value and therefore has more comparative advantages over other land use systems.

Carbon benefit: Carbon price is another important factor that affects NPVs of all land use systems. The market price of carbon is not stabilised yet (Lecocq and Capoor, 2005). The global demand and supply situation of carbon credits under the Kyoto market and current and prospective Kyoto and non-Kyoto policy, legal and regulatory issues would have a huge impact on carbon price. These factors are already discussed in chapters two and three (for details see UNFCCC, 1997; Point Carbon, 2003; UNEP, 2003; Kooten, 2004).

Although this study has considered all those fear factors while fixing carbon price in the Australian context, the comparative figures of NPVs in different carbon prices have also been tested (Table 8.6). Carbon price would have a diverse effect on different land use systems. Since cultivation and pasture are net sources of carbon (greenhouse gas), the decrease in carbon price will increase their NPVs and vice versa. The lower the carbon price, the higher will be their total NPV. However, plantation is a net sink of greenhouse gases. Therefore, carbon price and total NPV are directly proportional. The higher the carbon prices, the greater will be the total NPV of plantations.

If a plantation is not managed as a silvipastoral system, plantations would be less profitable even at the given carbon price of \$10 $t^{-1}CO_2e$. However, if stock value is considered, plantation would be profitable even if the carbon price falls up to \$4.5 $t^{-1}CO_2e$. Nonetheless, if it decreased to \$4.4 $t^{-1}CO_2e$, cultivation would be more profitable than plantations. In the range of \$2.6 to \$4.4 $t^{-1}CO_2e$ carbon price, plantation would be in the second position. However, if the carbon price gets further down, plantation would be the least preferred option. Therefore, the carbon price should be higher than \$4.4 $t^{-1}CO_2e$ for the better position of plantations. The higher the carbon price from \$4.4 t^{-1}CO2e, the more profitable would be the plantation than the cultivation and pasture land use systems.

Table 8.6 NPVs (\$ ha^{-1}) from different land uses with respect to different carbon prices

Land uses	Carbon prices			
	\$2.5 $t^{-1}CO_2e$	\$4.4 $t^{-1}CO_2e$	\$5 $t^{-1}CO_2e$	\$10.5 $t^{-1}CO_2e$
Cultivation	3359	3191	3140	2657
Pasture	3028	2990	2977	2865
Plantation	3024	3192	3241	3701

While comparing the NPV of plantations with other land use systems, it was assumed that the harvested forest products would emit carbon immediately in the atmosphere after harvesting (C1 scenario in chapter 7). In fact, carbon may lock up in ranges of products for a long time (Jaakko Poyry, 2000; Haripriya, 2001). At Wondai Sawmill, the average recovery rate of logs is around 43%. After using and reusing, finally, these wood products ended up in landfills. The chemical analysis of buried wood in Australian landfills showed that only up to 3.5% of the carbon in wood products was lost through decomposition in 46 years (Ximenes, 2006 cited in Gardner *et al.,* 2002). Similarly, the soil carbon may not fall to the level of zero age plantations (at the starting of the first rotation plantation) after harvesting. Therefore, if 40% of the gained soil carbon and the harvested product carbon would be locked for another 46 years (C2 Scenario), the net additional NPV gain would be around

\$484 in 34 years. This shows that there is a considerable potential of increasing NPV by considering carbon values of harvested products and soils. If these benefits are considered, plantations will be in a much better position than other land use systems.

The amount of forest residues at the harvested sites and at sawmill, and the potential benefit of utilising those residues are already discussed in previous chapters. If these residues can be locked up at least for 46 years, an additional amount of \$650 ha^{-1} will be added to the total NPV in 34 years. There is further benefit of using these residues for the replacement of fossil fuels or production of bio-fuels (renewable energy). Recent estimates from South-eastern Australia show that the use of firewood collected from thinning, slash and other residue in plantation grown for sawlog production leads to carbon sequestration equivalent of -0.17 kg CO_2kWh^{-1} compared to the emissions from non-renewable sources (Paul *et al.,* 2006). These discussions show that there is further chance of increasing carbon benefit in plantations and therefore the comparative advantage of plantations over other land use systems.

Effect of discount rate on optimal rotation age of plantation and NPVs of all land use systems: So far, all discussions were based on a six percent discount rate, in which optimal rotation of plantation was found to be 34 years, and that plantations were found to be the most profitable option among the three land use systems in a 34-year time period. This section discusses the effect of different discount rates on optimal rotation age and total NPVs. If the discount rate increases from the current rate of six to seven percent, the optimal rotation of plantation would reduce to 31 years (Table 8.7).

The total NPVs of plantation, pasture and cultivation in 31 years would be around \$2315 ha^{-1}, \$2492 ha^{-1} and \$2305 ha^{-1}, respectively. Therefore, the plantation and cultivation would be highly competitive to each other for the second position, and the pasture would be marginally better than the others. If the discount rate further increases to eight percent, the optimal rotation of plantation would reduce to 29 years. With that discount rate, the total NPV of pasture would be around 1.64 times that of plantation and 1.08 times that of cultivation in 29 years. Increasing discount rates above six percent is not favourable for plantation compared to other land use systems.

Table 8.7 Effect of discount rates on optimal rotation age of plantation and the NPVs ($ ha^{-1}) of different land use systems in the given optimal rotation ages

Land use	Crop	Timber	GHGs	Stock	Total
Discount rate 6%, optimal rotation 34 yrs (NPVs in 34 yrs)					
Cultivation	3578.89	0	-921.71	0	2657.18
Pasture	0	0	-213.99	3079.08	2865.08
Plantation	0	2045	861.8	794	3700.8
Discount rate 7%, optimal rotation 31 yrs (NPVs in 31 yrs)					
Cultivation	3121.49	0	-816.20	0	2305.29
Pasture	0	0	-194.40	2686.81	2492.41
Plantation	0	990	633.6	691.8	2315.4
Discount rate 8%, optimal rotation 29 yrs (NPVs in 29 yrs)					
Cultivation	2779.39	0	-734.98	0	2044.42
Pasture	0	0	-178.69	2385.88	2207.19
Plantation	0	242.3	490.3	610.1	1342.7

The total NPVs of plantation, pasture and cultivation in 31 years would be around \$2315 ha^{-1}, \$2492 ha^{-1} and \$2305 ha^{-1}, respectively. Therefore, the plantation and cultivation would be highly competitive to each other for the second position, and the pasture would be marginally better than the others. If the discount rate further increases to eight percent, the optimal rotation of plantation would reduce to 29 years. With that discount rate, the total NPV of pasture would be around 1.64 times that of plantation and 1.08 times that of cultivation in 29 years. Increasing discount rates above six percent is not favourable for plantation compared to other land use systems.

In plantations, most of the costs are incurred in the early ages while the benefits from timber come only in the harvesting age. Therefore, benefits are more heavily discounted than costs. Since timber benefit contributes the most to the total plantation benefit, the total NPVs and optimal rotation decreases drastically with increasing discount rates. In the case of pasture and cultivation, all costs and benefits stream since the beginning years. As a result, the effects of discount rates are not that pronounced. This is the main reason why increasing discount rates is not favourable for plantation compared to other land use systems.

The higher the discount rates, the lesser will be the competitive power of a plantation. A plantation would be more beneficial than other land use systems only if the discount rate equal to or less than six percent. The lower the discount rate from six percent the higher the benefit from a plantation compared to other land use systems. Therefore, a six percent discount rate is the threshold for a plantation decision. If the recent trend of increasing interest rates and inflation rates is continued in Australia, a plantation may not be an easy choice for farmers.

Higher discount rates from six percent are more favourable for pasture. It would be the first choice for farmers. However, higher discount rates will narrow down the NPV gap between the pasture and cultivation, as the increase in greenhouse gas NPV from cultivation is proportionately higher than in pasture at higher discount rates (Table 8.7). However, pasture will still be more profitable than cultivation even at a 50% discount rate, and it will be tied (total NPV $293 in 29 yr) with cultivation only at a 60% discount rate.

Implication of recent findings to this research: Two recent findings from Keppler *et al.* (2006) and Jackson *et al.* (2005) have some implications in this study. Keppler *et al.* (2006) reported that living plants and fallen leaves emit methane, which could reduce the carbon sequestration benefit of the plantation by four percent. This finding does not indicate any clear differences in CH_4 emissions among the crops, grasses, shrubs and trees. Therefore, this finding may equally reduce the currently estimated benefits from all land use systems, and it will have no effect on the final conclusion. However, further investigations on this finding are continuing (Duke University, 2006). Duke University organised round table discussions of renowned experts. They unanimously concluded that the effect of this finding would be only around 0.4% reduction of carbon sequestration benefit in plantations (Duke University, 2006). It can be argued that the plantation has more fallen and live biomass than pasture and crops. Therefore, plantations may emit a higher amount of CH_4 than other land use systems. However, even if the carbon sequestration benefit in plantations is reduced by four percent (as claimed by Keppler *et al.,* 2006) and remains constant in pasture and cultivation, the total NPV from plantation would still be higher than other land use systems.

Another finding is about the salinity problem with plantations. In Australia, 2.5 million hactares (5% of cultivated land) are affected by dryland salinity, and it costs around $3.5 billion every year (ANU, 2001). So far, it was believed that plantations would reduce dry land salinity by sucking underground water and through transpiration into the atmosphere. With this in mind, Australian federal and state governments are advocating for the replacement of crops and pastures by deep rooted plantations (ANU, 2001; Insight, 2001). Like carbon credit, Salinity Control Credit[52] has been offered to the farmers. In South Australia, salinity control reward rates in 2000 were $250 and $125 for each ha of farm forest block and each linear km for the farm forestry belt, respectively. In Queensland, the present benefit of salinity amelioration of single rotation plantation is assumed as $400, even though the range in many studies was from $400 to $1300 (Venn, 2005).

On the other hand, the finding from Jackson *et al.* (2005) reveals that the plantations, especially in dry land area, can increase soil acidity and salinity and decrease fertility. This effect is most probable when plantations are established on ex-pasture and shrub lands, but plantation may still be beneficial when it replaces the intensive croplands. In the study site, salinity problems were minimal. However, based on Jackson *et al.* (2005), it may be argued that salinity could result from a plantation in the long run. The extent of the problem may be site-and-species-specific. The validity of this finding to the given site is still debatable among the experts in Queensland, as the soil quality in terms of organic matter is much better in plantations than in pasture and cultivation in many sites (Paul *et al*., 2002; Paul *et al*., 2003; Saffigna *et al.* 2004; Maraseni *et al.,* 2006). Therefore, this research is neutral, neither considers salinity to be a benefit like Venn (2005), nor consider it to be a cost like Jackson *et al* (2005).

Risk: Risk can be defined as the probability of a disaster occurring. Forestry is a long-term business. It has 34 years interval between the formation and harvesting, whereas agriculture and pasture are harvesting every year. Waiting a long time for a return makes plantation less attractive (more risky) than other land use systems. The matter becomes serious if a land use decision is strongly linked with daily livelihood. The cumulative risk-year for all land use systems is 34, but any types of risk will affect crops and pasture benefit for a single year. In the case of a plantation, it will affect the whole benefit, as both increment (interest) and capital are not separable and could be destroyed as a whole. Although there are some risks in all land use

[52] Transpiration of 1 million litters of water equivalent to 1 Salinity Control Credit

systems, plantations are more vulnerable than others, due to the length of time needed to preserve the asset, and the susceptibility of that asset to adverse events.

The major risks factors associated with plantations are disease, insects, herbivores, frost, dryness, fire and wind throw. For example, there was a ramularia shoot blight problem in some plantations, but due to a genetic development program it is now under control (Lee, 2005). Because of its typical chemical property, spotted gum is resistant to many insects (Asante *et al.,* 2000; Marsaro *et al.,* 2004; Takahashi *et al.,* 2004). However, the grasshopper outbreak and herbivores (such as hares and rabbit) can damage trees in their first year (Noble, 2000). Similarly, plantations are also susceptible to frost. It damages growing tips and double shoots can result. This is the main reason why form pruning is necessary in the spotted gum plantation (discussed in plantation costs).

Being a dry continent, fire is the greatest risk factor in Australia, especially in the south-eastern corner from Sydney to Adelaide. This is identified as the top three fire prone area in the world along with southern California and Southern France (Australian Government, 2006). Each year, disaster-level bush fires (events with total insurance cost more than $10,000) cost Australia an average of $77 million, a figure that does not necessarily cover forestry losses (Australian Government, 2004). Thousands of small bushfires are not included in this figure. There were 2,618 fires only in Queensland from July 2002 to July 2003 covering over one million ha (ABS, 2004). However, spotted gum is a fire resistant species because of its low flammable smooth bark. Even if there is a fire, spotted gum can regenerate rapidly due to the presence of lignotubers (Noble, 2000).

Drought is another important risk factor. Its frequency in Australia has increased in recent years. Drought may have some effect on all land use systems, but its major impact will be on cultivation. Wind throw is another serious risk factor in plantations. For instance, over 60 million m^3 of timber was damaged by a storm in Sweden in early 2005 (United Nations, 2006). Its overall impact would be higher on mid- and old-age plantations. Unlike fire it does not destroy all parts. However, its effect on mid age trees (16-17) would be more catastrophic than fire, wind thrown products cannot be used (size problem) and there us extra cost to clean-up the mess. However, wind is not a big problem for our species in the research area.

From overall analyses, it can be said that the risk factors affect all land use systems but major effects will be on plantations. However, in the context of spotted gum in the research site, many risks are minimal. These risks may not be enough to make plantation less attractive than other land use systems, if they are not catastrophic.

8.7 Conclusions

This chapter compared NPVs from the traditional tangible benefits and carbon in cultivation, pasture and plantation. If the comparison of NPVs is limited to the traditional tangible benefits (crops and hay in cultivation, beef in pasture and timber in plantation), the cultivation would be the most preferred option followed by pasture and plantation. Even after inclusion of the stock value, plantations could not compete with other land use systems. Plantation is a net sink of greenhouse gases, whereas both pasture and cultivation are net sources of greenhouse gases. Cultivation lost greater amounts of NPV from greenhouse gases than pasture in 34 years. Therefore, after inclusion of greenhouse gas value, plantations are found to be the most preferred option followed by pasture and cultivation. However, if the carbon price is less than \$4.4 $t^{-1}CO_2e$, cultivation would be more profitable than plantation.

Although pasture is in the second position by NPV, it can never compete with plantation. Since plantation is evaluated as a silvipastoral system, it also has a stock component. Therefore, an increase in beef price and gross weight gain of cattle not only increases the pasture NPV but also increases the plantation NPV to some extent. Therefore, although the cultivation is in the third position by NPV, it would be the main competitor of plantation. Any favourable condition of cultivation and *Ceteris paribus* in plantation and pasture systems would be favourable for cultivation.

The discount rate has implications on optimal rotation and total NPVs. This study used a six percent discount rate. If the discount rate increases from six to seven percent, the optimal rotation of plantation would reduce from 34 to 31 years, and if the discount rate increases to eight percent, the optimal rotation would further reduce to 29 years. At seven percent discount rate, the plantation would be less profitable than pasture, but still be more profitable than cultivation. However, if the discount rate is eight percent, plantation would be the least profitable option. Moreover, if the discount rate is 11%, the total NPV of plantation would be never positive. The lower the discount rates from six percent the higher the profit from plantation compared to other land use systems. Similarly, the higher the discount rate from 6% the lower the profit from plantation compared to other land use systems. Therefore, six percent discount rate is the critical rate for the plantation to be profitable.

Chapter 9

Conclusions and Policy Implications

9.1 Introduction

This research identified some common and site-specific research issues with reference to carbon sequestration and land use systems, and addressed them by taking a case study of three competitive land use systems in Kingaroy, Queensland. This study first determined the optimal spacing level and optimal rotation age of the spotted gum plantations and then the study period for other land use systems was extended to the optimal rotation age of plantations (i.e., 34 years) for meaningful comparison of all land use systems. This study is comprehensive and necessarily a multidisciplinary work, as it has covered all variable costs and benefits of three land use systems. On top of that, it has considered different sources and sinks of three major greenhouse gases, i.e. carbon dioxide, methane and nitrous oxide, related to all land use systems. There were some studies partially related to this study, but most of them were more of a piecemeal approach. This thesis is comprehensive, but not fully based on primary data. Because of comprehensiveness, finance and time limitation, sole dependency on primary data was not possible. Therefore, some secondary data were used, where appropriate.

This chapter presents the summary of the whole thesis and then put forward some policy implications, research contributions and further researchable issues.

9.2 Summary

The primary purpose of this thesis was to compare a) peanuts-maize cropping, b) pasture and c) spotted gum plantations incorporating traditional tangible benefits and three major greenhouse gases. There were several specific objectives and their complementary research questions to address the aim of the research. Each results and discussions chapter (chapter 4 to 8) partly served the objective as a nested chapter. Many conclusions are drawn in each chapter. This section presents a summary of some of the major findings.

Soil carbon: This research demonstrated how a timeline of land use change might be useful to predict the soil carbon trends efficiently and reliably. The overall analysis of soil, surface litter and particulate organic matter's carbon in chapter four showed that the current peanut-maize cultivation in and around the research areas is a net source of soil carbon whereas pasture and plantations are a net sink, but the annual rates of soil carbon gain in pasture are lower than in plantations. The soil carbon level of cultivated land was lower than the global average for cultivated land, whereas the soil carbon level in plantations is higher than the global average for similar forests. The continuous traditional cultivation with heavy machinery and the removal of plants residues were found to be the major problem with cultivation. So, current cultivation practices are not favourable for carbon sequestration, while there is considerable potential for spotted gum plantations to sequester soil carbon when planted on ex-agricultural land. The predicted rate of change in soil carbon should be used cautiously as it applies only to Red Ferrosol soils in the research environment.

Biomass carbon: Grass biomass in pasture and grass and tree biomass in plantations are important components of carbon mass. Chapter four showed that the grass biomass in pasture (6.33 t ha^{-1}) would remain the same and would be always higher than in plantations. However, the tree biomass in a plantation would reach 498 t ha^{-1} at the 34th year. Therefore, plantations have considerable potential to earn carbon benefits, even if they are planted for timber, and there is some loss with end use.

Emissions from primary farm inputs: Chapter five showed that there is a large difference in greenhouse gas emissions due to the use of three primary farm inputs (agrochemicals, machinery and fuels) among the three land use systems. In 34 years, the amount of greenhouse gas emissions from primary farm inputs in cultivation is 4.2 times and 22.3 times higher than in plantations and pasture, respectively. This indicates that planting trees on ex-cultivated land has considerable greenhouse gas benefit but there would be a negative effect, if trees were planted on current pastureland while considering the primary farm inputs (only). However, the difference in emissions between plantations and cultivation is a good indication of the potential for achieving 'Vision 2020' anticipated by the Australian government for plantations. It would however, be unwise to draw a final conclusion without holistic analysis of all sources and sinks of greenhouse gases from all land use systems.

Emission of nitrous oxide (N_2O) from nitrogenous sources: The analyses in chapter five shows that a huge amount of N_2O emissions would occur from soil disturbance, nitrogenous fertilisers, cattle excretions and biologically fixed nitrogen in plantations and pasture and from all the above activities except cattle excretions in cultivation. Because of frequent cultivation, high use of nitrogenous fertilisers and the high proportion of legumes, cultivated land has a relatively higher amount of N_2O emissions, followed by pasture and plantations. Missing these N_2O emissions from any one of theses sources would have serious implications on the overall cost benefit analysis in all land use systems.

Emission of methane from pasture and plantations. The pasture and plantations both have a beef component, as the case study plantation has been managed as a silvipastoral system; however, the stocking rate of cattle in plantations would always be lower than in pasture. Therefore, methane emissions from pasture would be 3.1 times higher than from plantations in 34 years. An inclusion of a pasture component in plantations would increase the methane emissions but without analysing the other costs and benefits actual conclusions can not be drawn.

Optimal spacing for spotted gum plantation: This study demonstrated how an optimal spacing level can be determined by non-linear regression modelling in a limited data environment. In this regard, chapter six produced the growth models of spotted gum and estimated the mean diameter at breast height (DBHs) and total merchantable logs volume of four spacing levels by age. From analyses, the spacing level 'C' (5.4 m x 5.4 m = 343 trees ha^{-1}) was found to be better than the other spacing levels for maximising the logs' volume. Further analysis from spacing level 'C' revealed that the merchantable log volume could be maximised by keeping around 250 of the largest trees per hectare. This analysis is based on the current state of knowledge and limited data. If the full rotation data are available, a more reliable model could be produced by using similar principles.

Optimal rotation and net present value (NPV) of spotted gum plantations: The optimal rotation of plantation for maximum sustained merchantable logs yield was found to be 66 years. Since this rotation has no relation to costs and benefits and greenhouse gases, it is not influenced by a depreciation rate and demand and supply situations in the market. The optimal rotation to maximise just timber net present value (NPV) and timber plus grazing (stock) NPV was found to be the same at 31 years. If the greenhouse gas benefit is added to the timber and stock NPV, the optimal rotation age of plantations would increase by three years to 34 years. The business-a-usual-scenario (based on current practices and technologies) shows that the total NPVs from timber, stock and greenhouse gas would be around $3700 in 34 years. Pasture (~21%) and carbon (~23%) alone accounted for over 44% of the total NPV. Thus there is a considerable potential for increasing the total NPV by incorporating pasture and carbon benefits in plantations.

Currently, the sawmillers do not buy logs between 10 cm and 25 cm diameter, which are considered merchantable elsewhere in the world. A large amount of harvesting residues need to be left in the farm for this reason. The tidying-up operation for them adds some extra cost. Similarly, due to the small and fragmented nature of farm forestry, off-farm-time-cost of farm inputs may be very high. Therefore, there is a reasonable chance of increasing NPV by going towards commercialisation, utilising the logs between 10-25 cm diameter and producing renewable energy from harvestings and thinning residues.

Comparison of NPV from cultivation, pasture and plantation: Comparison of cultivation, pasture and plantation incorporating greenhouse gas value was the main goal of this study. All other conclusions drawn so far are complementary to this goal. Overall analyses in chapter eight shows that if the comparison of net present values was limited to traditional benefits (i.e. income from crops and hay in cultivation, beef in pasture and timber in plantation), cultivation was found to be the most profitable option, followed by pasture and plantations. Even after the inclusion of beef value, plantations could not compete with other land use systems. Plantation was found to be a net sink of greenhouse gases, while pasture and cultivation were found to be net sources. Cultivation lost a greater amount of net present value from greenhouse gases than did pasture. After the inclusion of greenhouse gas value, plantation was found to be the most profitable option, followed by pasture and cultivation. So, there is a resonable chance of land use transformation if carbon markets become reality. However, if the carbon price is reduced from the currently used price of $\$10.5\ t^{-1}$ to $\$4.3\ t^{-1}$, cultivation would be the most preferred option. Carbon price of $\$4.4\ t^{-1}$ is the threshold for plantations. The higher the carbon price from $\$4.4\ t^{-1}$ the more attractive would be the plantation.

The discount rate has a major impact on the optimal rotation length and net present value from plantations. If the currently used discount rate (six percent) increased to seven or eight percent, the optimal rotation of a plantation would reduce from 34 to 31 years and 29 years, respectively. At a seven percent discount rate, a plantation would be a less profitable option than pasture, but marginally more profitable than cultivation and if the discount rate were eight percent, a plantation would be less profitable than both pasture and cultivation. Therefore, a six percent discount rate is critical for a plantation. The lower the discount rate from six percent the more competitive would be the plantation and vice versa. If the recent trend of increasing interest and inflation rates is continued in Australia, plantations would not be an easy choice for farmers. This would have serious implications on the government's 'Vision 2020' target of increasing the plantation estate to three million hectares by 2020.

The finding of this analysis should be interpreted with caution. This study has social elements as it considered the greenhouse gas value to great length. However, the NPVs estimated in this study are neither profit nor private economic benefit, the focus was to compare the 'with project' and 'without project' scenarios. The analysis did not include overhead costs such as owner labour and permanent labour costs, rates and rents, insurance, living costs, taxation and lease payments etc. Similarly, it has not used a market price for fuel, a subsidised fuel price is used. As the objective of this study was to compare different land use systems, all sources of costs and benefits were treated in the same way to make them comparable. Therefore, the results from this study must be used in similar circumstances. If the overhead cost of all land uses were considered none of the three land use systems would show as profitable in a conventional economic on financial analysis.

9.3 Management and policy implications

This section comprises some recommendations for all land use systems.

Cultivation: If only the traditional tangible products are considered, cultivation is the most preferred option at six percent discount rate. However, when the greenhouse gas emission costs are included in the valuation, cultivation is the least preferred option. The higher amount of negative NPV from greenhouse gas is mainly due to the higher frequency of cropping and conventional tillage systems, and the removal of hay. One of the solutions for this problem could be zero tillage but this will cause water logging and may result in salinity problems in a low lying area. More importantly, zero tillage may reduce the cost of production and net greenhouse gas emissions but it may also reduce a significant amount of crop's yield.

The removal of hay is detrimental in different ways. First, it costs additional money for extra fertilisers. The production, packing, transportation and application of them emit significant amounts of greenhouse gases. Second, it helps to reduce the soil carbon level directly and indirectly. Third, it helps to damage the soil structure and thereby decreases the infiltration capacity of soil, which is a key for successful rein-fed cropping. Fourth, during the collection and transportation of hay, some greenhouse gas emissions would occur.

Trees in pasture: The soil carbon in pasture could be increased by planting a few trees around the pasture, as plantations of hardwood species are found to be better than pasture for soil carbon sequestrations. Trees also provide shade to the cattle during the hot season and also sequester large quantities of carbon in their biomass. If the trees are fodders, the benefit would be twofold. Therefore, farmers may consider this option, if carbon markets become a reality.

Plantation production efficiency: This study shows that the plantation is comparatively better than other land use systems at six percent discount rate, if stock and carbon value is considered. However, the recent trend of increasing interest rates in Australia is not encouraging for plantation. This would have serious implication on the government's '*Vision 2020*' target of increasing the plantation estate to three million hectares by 2020. Therefore, the following policy implications are made for getting more benefits from plantations.

Currently, small size logs (10 cm to 25 cm diameter), which are equivalent to 90 m^3ha^{-1}, are not acceptable at sawmills due to large processing costs. If farmers can use these logs, there is a good chance of increasing NPV. This can be achieved either by developing some efficient technology with the current sawmill or by using a portable sawmill on the spot. However, for this to happen either farmers should go for commercial scale of plantations or they have to adopt a co-operative farming system. This study suggests all levels of stakeholders to put their efforts in this direction. Especially, government should consider the processing limitation of current saw mills and develop some economic policy to address this issue.

The current recovery rate of logs is very low (average of 43%). As a result, around 178 t of residues would be lost from each ha in 34 years. To include the 90 m^3 of logs between 25 cm to 10 cm diameters, means another 68 t of biomass would be lost. Locking this whole biomass at least for 46 years would add around \$650 ha^{-1} as a carbon benefit to the combined NPV of plantation in 34 years. There is more benefit in using these residues for the replacement of the fossil fuels or production of bio-fuels (renewable energy). Moreover, by using the thinning, slash and other residues in plantation, there are further chances of increasing plantation benefit. Therefore, this study suggests for favourable policy to utilise these residues for the production of renewable energy.

Some value adding options on plantations could be possible, as some research shows that there is some medicinal benefits (perfume, curing food poisoning, leaf ant control etc) of spotted gum. If these benefits are commercialised, it would make plantations more attractive. Moreover, if markets for forest ecosystem services such as biodiversity, aesthetics, hunting etc. can develop, the plantation benefits could be much higher than the currently estimated amount. For that reason, this study suggests developing some concrete policies to commercialise the medicinal benefits of spotted gum.

The optimistic scenario of this study shows that there is a good chance of increasing total NPV from plantation, if farmers have a commercial scale of plantation and good farm forestry institutions. Moreover, on one hand, the hardwood supply from Malaysia and Indonesia is increasingly limited and on the other hand, China and India are looking for large volume of hardwoods. Among the competitor suppliers, Australia generally faces lower energy costs and has an overall capital cost advantage because of lower mill construction costs and costs of capital. Therefore, if farmers go for a commercial scale of plantation, there may be a good chance of spotted gum penetration in the international markets. However, without having a convincing demonstration, farmers may not change their land use, as they may perceive that the land use transformation to be a risky business. Extension activities may be beneficial. More importantly, a better incentive package from government would be very helpful. Once there is a commercial scale, the benefit of plantation would be realised for long run venture. Therefore, this study suggest government to work in that direction.

Forest certification is becoming increasingly popular in the developed world, especially in Europe, for sustainable forest management (SFM). There are several indicators of SFM that need to be audited while making certification. The certified forest products attract more market price than non-certified forest products. If the carbon focused plantations become one of the indicators of SFM, this sort of plantation will invite higher market prices. Therefore, this study suggests that the government has to make a stand in this direction in the national and international SFM policy formulation.

9.4 Research contributions

The overarching goal of the study was to compare plantation, cropping and pasture land use systems by incorporating traditional tangible products and greenhouse gas value. The strength of the study is its comprehensiveness, as it considered all variable costs and three major greenhouse gases associated with each land use system. This research contributes new knowledge in the following areas.

- This study demonstrated how optimum spacing and optimum rotation could be determined in a limited data environment. It analysed four different spacing levels by producing growth models— using a non-linear regression module. The best spacing level, which gave the highest merchantable volume in all ages, was further analysed for different thinning scenarios. Finally, the validity of the model was analysed by comparing the regression parameter (B0, maximum potential diameter) with the field measured value, along with the root mean square errors and coefficient of determination of the model.

- This study developed a conceptually rigorous framework of estimating optimum rotation of plantation by incorporating timber, stock and greenhouse gas values. Most of the literature around the world are not comprehensive in nature, only considering the biomass carbon and total costs and benefits. The consideration of carbon sequestration in standing biomass and total costs and benefits is not enough; an estimation of emissions of all greenhouse gases

(CO_2, CH_4 and N_2O) associated with primary farm inputs, cattle burping and excretion, biologically fixed nitrogen, and the sequestration of carbon in standing biomass and soil is necessary to account for optimal rotation of a plantation. This study achieved this important comprehensive mission.

- This study proved how a timeline of land use change could be used for efficient and effective estimation of soil carbon.

- Some of the sources of greenhouse gases are missing in many studies. For example, emission of greenhouse gases associated with the production, packaging and transportation of primary farm inputs, and biologically fixed nitrogen are poorly accounted for. This study identified all possible sinks and sources of greenhouse gases from all land use systems and demonstrated how they can be properly estimated.

- This study confirmed that the current cultivation practices in and around Kingaroy are likely to be degrading soil and are emitting more greenhouse gases relative to other land use systems.

- This study proved that the spotted gum plantation would be the most profitable land use option at the given discount rate (6%) and carbon price (\$10.5 $t^{-1}CO_2e$), if carbon and stock values are considered.

This research also identified some research gaps, which is discussed in the next section.

9.5 Suggestions for further research

From the overall discussions, it is obvious that the current cultivation practices in and around Kingaroy are not favourable for carbon sequestration. Several alternative cultivation (tillage) practices are recommended in the literature including reduced and zero tillage. Each cultivation practice has both negative and positive aspects. However, due to lack of comprehensive study they are poorly considered. Therefore, this study recommends a holistic analysis of all sources of costs and benefits at a landscape level before advocating any particular tillage system. The major consideration should be given to the impact on; low-land salinity, greenhouse gas emissions and crops yield at the landscape level.

The removal of peanuts hay for cattle feed has some financial benefits but there are several costs too. If all those costs associated with hay removal are considered, the current income from hay may not be profitable in the long-run. This study recommends further research on this issue. The major focus should be on: costs for extra fertiliser; the amount of greenhouse gas emissions associated with the production, packaging, transportation and application of extra fertilisers; the effect on soil structure, infiltration and crop production; effect on soil carbon; and greenhouse gas emissions during the collection and transportation of hay.

Although this research discussed all possible NPVs determining factors in some detail, it is static in nature as it assumes that all climatic variables are constant. However, in the context of climate change, climatic variables are dynamic in nature. The changing climatic variables could have a diverse effect on each land use system in time and space. Therefore, this study urges further research on the impact of climate change on the NPVs of all land use systems. For this, how different climatic variables could be changed in the given site should be estimated first. This can either be done by downscaling the general circulation model or consultation with the CSIRO climate team. After that, the effect of changing these climate variables to each of the NPV determining parameters should be analysed. This is the most difficult part. To simplify this problem a different scenario could be developed; alternatively, on the basis of the results of this thesis and other climatic data, a reliable ecosystem based model could be run. Finally, the total NPVs of each land use system could be determined by following the same principle of this thesis.

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Appendices

Table C-1: Coordinates of soil sampling plots of all land use types in Kingaroy

Name	Q	Easting (m)	Northing (m)	Error (±) m	C	Easting (m)	Northing (m)	Error (±) m
Taabinga 4 years plantation	1	375841	7050073		1	375845	7050070	
	2	375846	7050083	3.5	2	375854	7050091	3.5
	3	375827	7050093	4.6	3	375830	7050099	4.1
	4	375823	7050079	4.5	4	375816	7050077	4.4
Taabinga 11 month plantation	1	375988	7050047	3.4	1	375983	7050042	3.3
	2	375987	7050062	3.8	2	375985	7050067	3.2
	3	376002	7050056	3.2	3	376008	7050064	3.3
	4	376004	7050043	3.3	4	376007	7050039	3.0
Taabinga scrubland	1	375836	7050003	3.8	1	375842	7050004	3.7
	2	375831	7049990	5.0	2	375830	7049983	4.7
	3	375808	7049999	7.4	3	375815	7049984	4.5
	4	375823	7050006	4.2	4	375818	7050010	4.1
Taabinga pasture	1	376120	7050549	3.2	1	376126	7050545	3.0
	2	376107	7050552	3.6	2	376096	7050543	3.1
	3	376108	7050563	4.0	3	376103	7050568	3.8
	4	376120	7050568	3.3	4	376128	7050573	3.3
Peanut cropping	1	376372	7050450	3.2	1	376369	7050450	3.1
	2	376381	7050438	3.4	2	376380	7050428	3.2
	3	376391	7050443	3.0	3	376400	7050443	3.0
	4	376391	7050457	3.9	4	376389	7050463	3.8
Mature spotted gum	1	386529	7069795	4.0	1	386537	7069785	3.4
	2	386525	7069785	3.7	2	386517	7069774	3.6
	3	386517	7069796	4.2	3	386515	7069795	4.2
	4	386529	7069794	6.0	4	386537	7069799	4.5

Note: Q refer to quadrant number and C refer corner number of soil sampling plot

Table C-2 Large end and small end diameters and tapering of spotted gum logs

Large end diameter over bark (cm)	Small end diameter over bark (cm)	Length (m)	Taper (cm/m)
29	22.5	5.8	1.12
20	15	3.9	1.28
22.5	20	4.4	0.57
20	17.5	4.4	0.57
19.7	12.5	9.9	0.73
20	15	4	1.25
24.9	20	7.4	0.66
28.4	20	6.5	1.29
20.7	12.5	5	1.64
24.1	12.5	11.3	1.03
24	12.5	6.3	1.83
26.4	12.5	14.9	0.93
22	12.5	5.8	1.64
24.9	15	8.8	1.13
17.1	12.5	4.6	1.00
21.4	12.5	9.7	0.92
18.2	12.5	6.6	0.86
20	15	4.1	1.22
19.5	12.5	8.3	0.84
15	12.5	3.5	0.71
14	12.5	3.3	0.45
16.2	12.5	4.1	0.90
20	13	6	1.17
23.4	20.5	2.5	1.16
19	16.8	2.8	0.79
14.6	12.5	3.2	0.66
18.4	16.5	3.3	0.58
13	10.8	3.3	0.67
24.3	21.1	2.9	1.10
25.2	20	7.5	0.69
24.2	18.5	3.2	1.78
27.6	21.6	5.5	1.09
26.7	20.3	8.1	0.79
24.9	23	4.1	0.46
27.6	21.5	3.5	1.74
21.5	18.5	3.2	0.94
26.5	24.5	3.2	0.63
24.6	23.5	2.4	0.46
28.2	24.4	8.4	0.45
26.5	24	5.1	0.49
22.5	21.5	2.4	0.42
21.1	19.5	2.4	0.67
25.5	19.4	2.4	2.54
26.6	12.5	14.1	1.00
19.8	12.5	8.6	0.85
Average tapering (cm/m)			0.97
Length of log between (10cm to 25cm)			15.45
So volume of log (15.45mby17.5cm)			0.37162
So total volume of log between 10cm to 25cm diameter			92.905002

Table D-1 Average soil carbon (%) and $\delta^{13}C$ (‰) in different land uses and at different depths at Taabinga, Kingaroy

Land use types		Depth of soil in cm 0-5	5-10	10-20	20-30	30-50	50-70	70-90	90-110
Pasture	Ave C (%)	2.80 (0.25)	2.00 (0.16)	1.87 (0.04)	1.47 (0.08)	1.17 (0.18)	0.97 (0.14)	0.74 (0.14)	0.60 (0.10)
	$\delta^{13}C$ (‰)	-21.7 (0.48)	-21.7 (0.24)	-22.9 (0.34)					
Cultivation	Ave C (%)	1.01 (0.05)	1.00 (0.04)	0.97 (0.18)	0.72 (0.13)	0.53 (0.10)	0.41 (0.04)	0.33 (0.06)	0.23 (NA)
	$\delta^{13}C$ (‰)	-22.2 (0.17)	-22.3 (0.10)	-22.3 (0.41)					
Native Scrub	Ave C (%)	4.86 (0.38)	2.50 (0.51)	1.62 (0.46)	1.15 (0.32)	1.39 (0.48)	1.16 (0.12)	0.88 (0.04)	0.75 (0.05)
	$\delta^{13}C$ (‰)	-25.9 (0.21)	-25.5 (0.29)	-25.0 (0.30)					
Mature spotted gum	Ave C (%)	9.89 (0.71)	8.18 (1.54)	6.19 (0.99)	5.33 (0.95)	2.71 (0.65)	0.92 (0.23)	0.64 (0.18)	0.53 (0.34)
	$\delta^{13}C$ (‰)	-25.6 (0.41)	-25.1 (0.49)	-24.6 (0.51)					

Note: The figures in parentheses are standard deviation of soil C (%) and $\delta^{13}C$ (‰)
Total number of replicates for each depth is four except for 90-110 cm depth cultivation, which had only one replicate. Due to highly compacted soil it was not possible to have four samples.

Table D-2 Average bulk density (g/cm^3) of different land use systems at different depths, at Taabinga, Kingaroy

Depth of soil (cm)	Pasture (n = 4)	Cultivation (n = 4)	Native scrub (n = 4)	Mature spotted gum (n = 4)
0-5	1.13 (0.07)	1.62 (0.15)	1.16 (0.06)	0.62 (0.04)
5-10	1.30 (0.05)	1.60 (0.17)	1.31 (0.09)	0.76 (0.08)
10-20	1.20 (0.04)	1.42 (0.07)	1.39 (0.08)	0.71 (0.02)
20-30	1.25 (0.07)	1.38 (0.11)	1.56 (0.11)	0.96 (0.10)
30-50	1.18 (0.03)	1.28 (0.06)	1.55 (0.06)	1.09 (0.14)
50-70	1.26 (0.04)	1.13 (0.16)	1.55 (0.06)	1.19 (0.04)
70-90	1.23 (0.05)	1.08 (0.14)	1.55 (0.06)	1.14 (0.03)
90-110	1.30 (0.00)	1.29 (NA)	1.53 (0.06)	1.14 (0.07)

Note: The figures in parentheses are standard deviation of bulk densities. Total number of replicates for each depth is four except for 90-110 cm depth cultivation, which had only one replicate.

Table D-3 Surface litter and particulate organic matter (POM) in different land uses at Tabingaa, Kingaroy

Litter or POM type	fresh:dry wt ratio	Fresh wt ha^{-1}	Dry wt t ha^{-1}	Content types	Sampled DW	C (%)	t C ha^{-1}
Pasture surface litter	1.06	6.17	5.82	dirt	102.9	11.37	0.51
				grass	14.28	38.72	0.24
				misc.	5.19	40.68	0.09
				twigs	0.61	39.93	0.01
				leaf	2.35	38.83	0.04
				grass stem	1.63	39.40	0.03
				crust	5.14	32.76	0.07
				grass rhizome	0.47	38.79	0.01
				Total	132.57		1.01
Mature spotted gum surface litter	1.07	17.55	16.4	dirt	55.15	36.65	4.19
				misc.	2.51	18.05	0.09
				grass	0.15	37.61	0.01
				gum nuts	1.92	44.22	0.18
				bark	9.03	42.11	0.79
				twigs	7.42	44.03	0.68
				leaf	2.94	45.19	0.28
				Total	79.12		6.21
Mature spotted gum POM	1.06	31.95	30.14	dirt	102.88	21.46	4.51
				twigs	13.83	42.52	1.20
				bark	16.85	43.75	1.51
				leaf	5.49	45.36	0.51
				gum nuts	3.58	41.25	0.30
				grass	0.28	37.17	0.02
				insects	0.02	32.74	0.00
				stones	4.67	7.94	0.08
				Total	147.6		8.12
Native scrub POM	1.03	40.70	39.51	dirt	183.72	10.50	3.98
				bark	0.86	31.78	0.06
				twigs	0.66	35.89	0.05
				roots	0.04	29.64	0.00
				leaf	0.95	39.52	0.08
				stones	5.35	0.97	0.01
				Total	191.58		4.18
Native scrub surface litters	1.05	125.20	119.24	dirt	15.96	33.44	13.24
				leaf	14.67	42.77	15.56
				leaf twigs	4.26	42.28	4.47
				bark	3.74	38.94	3.61
				branch twigs	8.73	42.26	9.15
				misc.	0.71	24.48	0.43
				Total	48.07		46.46

Table D-4 Long-term trends of biomass of spotted gum plantation at Tabinga, Kingaroy

Age	Stem mass t ha^{-1}	Bark mass t ha^{-1}	Foliage mass t ha^{-1}	Branch mass t ha^{-1}	Bark, foliage & branch mass t ha^{-1}	Total AGBM t ha^{-1}	Total biomass t ha^{-1}
1	1.95 (48%)	0.31	0.65	1.08	2.04 (105%)	3.99	5.03
2	8.85	1.38	2.58	4.30	8.26	17.11	21.54
3	20.76	3.16	4.95	8.18	16.29	37.06	46.65
4	13.66	2.11	3.65	6.09	11.85	25.51	32.12
5	20.66 (56%)	3.14	4.94	8.16	16.23 (78%)	36.90	46.45
6	28.84	4.30	6.13	9.96	20.39	49.23	61.97
7	38.10	5.55	7.20	11.42	24.17	62.27	78.40
8	48.38	6.88	8.14	12.53	27.55	75.93	95.60
9	59.61	8.25	8.96	13.34	30.55	90.16	113.51
10	44.83 (63%)	6.43	7.84	12.20	26.46 (59%)	71.29	89.75
11	52.92	7.44	8.49	12.90	28.84	81.76	102.93
12	61.59	8.48	9.09	13.46	31.02	92.61	116.60
13	70.75	9.53	9.61	13.87	33.02	103.76	130.64
14	80.36	10.59	10.09	14.18	34.85	115.22	145.06
15	90.42 (71%)	11.64	10.51	14.40	36.55 (40%)	126.97	159.85
16	100.89	12.68	10.89	14.56	38.13	139.02	175.02
17	111.76	13.70	11.23	14.67	39.60	151.36	190.56
18	123.00	14.70	11.53	14.75	40.98	163.98	206.45
19	134.60	15.67	11.81	14.80	42.28	176.88	222.69
20	146.53 (77%)	16.62	12.06	14.83	43.51 (30%)	190.04	239.27
21	158.79	17.53	12.28	14.86	44.68	203.46	256.16
22	171.35	18.41	12.49	14.87	45.78	217.12	273.36
23	184.19	19.26	12.68	14.88	46.82	231.01	290.85
24	197.32	20.07	12.85	14.89	47.81	245.12	308.61
25	210.70 (81%)	20.84	13.00	14.89	48.74 (23%)	259.43	326.63
26	224.32	21.58	13.15	14.90	49.62	273.94	344.89
27	238.18	22.27	13.28	14.90	50.45	288.63	363.38
28	252.25	22.93	13.40	14.90	51.24	303.49	382.09
29	266.54	23.56	13.52	14.90	51.97	318.51	401.01
30	281.02 (84%)	24.15	13.62	14.90	52.67 (19%)	333.68	420.11
31	295.68	24.70	13.72	14.90	53.32	349.00	439.39
32	310.52	25.23	13.81	14.90	53.93	364.45	458.84
33	325.51	25.72	13.89	14.90	54.51	380.02	478.45
34	340.67 (86%)	26.17	13.97	14.90	55.04 (16%)	395.71	498.20
35	355.96	26.60	14.04	14.90	55.54	411.51	518.09

Note: Figures in parentheses under the column of bark, foliage & branch mass are percentage of them to the total stem biomass. Similarly, figures in parentheses under the stem mass are percentage of stem to the total aboveground biomass The total biomass includes root and aboveground biomass. Root biomass is considered as 25.9% of the aboveground biomass.

Table E-1 Greenhouse gas emissions (kgCO_2e ha^{-1}) from agrochemicals in different land use systems in Kingaroy

Chemical	CO_2e kg^{-1}	GHGs emission (kgCO_2e ha^{-1}) in different land use systems							
		Peanut yr^{-1}		Maize yr^{-1}		Pasture (34 yrs)		Plantation (34 yrs)	
		Kg ha^{-1}	total CO_2e	Kg ha^{-1}	total CO_2e	Kg ha^{-1}	total CO_2e	Kg ha^{-1}	total CO_2e
N	3.27	0	0	185	604.95	50	163.5	226	739.02
P	1.34	0	0	0	0	0	0	0	0
K	0.642	50	32.1	80	51.36	0	0	0	0
Lime	0.042	500	21	500	21	0	0	0	0
Insecticide	24.5	0.4	9.8	0	0	1	24.5	0.5	12.25
Herbicide	22.8	3.55	80.94	6.27	142.95	2.5	57	8	182.4
Fungicide	24.5	2.6	63.7	0	0	0	0	0	0
Boron	0.335	0	0	0	0	0	0	0	0
CK1, main P	1.34	100	134	0	0	0	0	0	0
			341.54		820.27		245		933.67
So, in 34 yrs		Peanut & maize (341.54+820.27)*17}			19751		245		933.67

Note: in case of mixed fertiliser CK1, P-value was taken

Table E-2 Estimation of GHG emissions due to use of farm machinery and fuel in different land use systems in Kingaroy

Activity in different land use systems	Vehicle	Wt (kg)	Working life (WL) hr	Worked hour per ha	wt of accessory	WL of accessory hour	Fuel L ha^{-1}	Emission of CO_2e Machine (kg/ha)	Emission of CO_2e Fuel (kg ha^{-1})
Peanut cropping									
Slashing	75KW (6403)	3880	12500	0.32	900	2000	6.00	2.34	20.10
Deep ripping	168KW (8330)	10771	12500	0.59	1180	2000	24.70	8.20	82.75
Chisel plough	92KW (8330)	6277	12500	0.47	2504	2000	10.81	7.91	36.21
Discing	92KW (8330)	6277	12500	0.47	2504	2000	10.81	7.91	36.21
Scarifier	92KW (8330)	6277	12500	0.41	1524	2000	9.51	5.02	31.86
Cultivating	92KW (8330)	6277	12500	0.41	1524	2000	9.51	5.02	31.86
Planting/seeding	92KW (7520)	6277	12500	0.41	1219	2000	9.51	4.41	31.86
Self propelled sprayer (4.2)	75KW (6403)	3880	12500	0.33	571	2000	6.22	1.90	20.84
Digging	168KW (8330)	10771	12500	1.41	1000	2000	59.10	18.39	197.99
Threshing (self propelled peanut combine)	183KW (AMADAS 9900)	14300	12500	0.35	1200	2000	16.07	5.86	53.83
Baling & transportation	92KW (7520)	6277	12500	0.70	1500	2000	16.07	8.40	53.83
Drying (15t @) 0.5% MC/hr, MC of 2 t peanut down from 18 to 12%	30KW (990)	1340	8000	1.60	250	2000	12.00	4.49	40.20
Freight (2t @17t @30min)	160KW (1710D)	8800	12500	0.03	6000	2000	1.18	1.05	3.95
Total emission of CO_2e (kg ha^{-1}) from peanut cropping in every cropping year							185.49	78.57	621.39
Maize									
Primary tillage	92KW (8330)	10771	12500	0.47	2504	2000	10.73	9.47	35.95
Inter-row tillage	92KW (8330)	10771	12500	0.41	2504	2000	9.54	8.42	31.96
Scarifier	92KW (8330)	6277	12500	0.41	1524	2000	9.51	5.02	31.86
Self propelled sprayer (5)	75KW (6403)	3880	12500	0.39	571	2000	7.40	2.26	24.79
Planting	92KW (7520)	6277	12500	0.41	1219	2000	9.51	4.41	31.86
Harvesting by contract header	193 KW (AMADAS9900)	14300	12500	0.25	1200	2000	12.10	4.19	40.54
Freight (3.5t@17ton@30min)	160KW (1710D)	8800	12500	0.05	6000	2000	2.07	1.84	6.93
Total emission of CO_2e (kg ha^{-1}) from maize cropping in every cropping year							60.86	35.60	203.88
Total emission of CO_2e (kg ha^{-1}) from peanut and maize cropping in 34 year							4187.95	1940.80	14029.63

Table E-2 continued

Activity in different land use systems	Vehicle	Wt (kg)	Working life (WL) hr	Worked hour per ha	Wt of accessory	WL of accessory hour	Fuel L ha^{-1}	Emission of CO_2e Machine (kg/ha)	Fuel ($kg\ ha^{-1}$)
Spotted gum plantation									
Deep ripping & hilling	168KW (8330)	10771	12500	1.25	1180	2000	52.50	17.42	175.88
Self propelled sprayer (4 at age 1 & 1 at age2)	92KW (7520)	6277	12500	0.32	571	2000	7.40	2.43	24.79
Seedling transport (@400gm,1000@17ton)	160KW (1710D)	8800	12500	0.07	6000	2000	2.96	2.63	9.92
Slashing (3 at age 1, 2 & 3)	75KW (6403)	3880	12500	0.32	900	2000	6.00	2.34	20.10
1st thinning (by saw)	3.3 KW engine (CS71)	6.63	8000	11.03	0	0	9.10	0.09	30.48
Pruning	3.3 KW engine (CS71)	6.63	8000	3.00	0	0	2.48	0.02	8.29
2nd thinning (felling, delimbing & bucking)	3.3 KW engine (CS71)	6.63	8000	14.7	0	0	12.13	0.12	40.63
Pruning	3.3 KW engine (CS71)	6.63	8000	7.00	0	0	5.78	0.06	19.35
Final Harvesting									
Felling (bouncher)	168KW (843J)	10771	12500	2.96	3012	2000	118.40	67.28	396.64
Delimbing & bucking (P saw)	3.3 KW engine (CS71)	6.63	8000	12.50	0	0	10.31	0.10	34.55
Skidding (grapple skidder with tractor)	168KW (548G)	10768	12500	10.42	0	0	437.64	86.17	1466.09
Cross cutting (chain saw)	3.3 KW engine (CS71)	6.63	8000	6.25	0	0	5.16	0.05	17.27
Loading/unloading transportation to mill	160KW (1710D)	8800	12500	30.20	6000	2000	1208.00	1073.86	4046.80
Total emission of CO_2e ($kg\ ha^{-1}$) from spotted gum plantation in 34 year							1877.85	1252.57	6290.78
Pasture									
Slashing (5.25 times, at age 1,8,16,24,32)	75KW (6403)	3880	12500	0.46	900	2000	10.50	3.33	35.18
Deep ripping (5.25 at age 1,8,16, 24, 32)	168KW (8330)	10771	12500	3.09	1180	2000	129.67	43.03	434.39
Discing (5.25 times, at age 1,8,16, 24, 32)	92KW (8330)	6277	12500	2.45	2504	2000	56.33	41.24	188.71
Self propelled sprayer (1 time)	92KW (7520)	6277	12500	0.06	571	2000	1.48	0.49	4.96
Planting/seeding (5.25 times, age 1,8,16, 24, 32)	92KW (7520)	6277	12500	2.17	1219	2000	49.93	23.17	167.27
Freight to selling yard (34 times)	160KW (1710D)	8800	12500	1.14	6000	2000	45.56	40.50	152.63
Electricity-H_2Opump ($1.66/0.1=16.6kwh *34)									231.96
Total emission of CO_2e ($kg\ ha^{-1}$) from pasture in 34 year							293.47	151.76	1215.08

Note: All machineries and accessory equipment, except where indicated, were from John Deere. [a] Refers vehicle and equipments from AMADAS. Fuel for self propeller (for agrochemicals) not considered (comes under agrochemicals). When the fuel consumption data was unavailable, it was derived from work hour & power of machine (fuel consumption = Power of machine in KW * 0.25 L $hour^{-1}$ * hour used) (Harris, 2004)

Table G-1 Different types of costs for spotted gum plantation in Kingaroy, Queensland

Year	Activity	Items	Cost/unit	Quantity	Tot Val ($/ha)
1	Site survey	Consulting hour	60		60
1	Ripping and hilling	Machine hire	150	1	150
1	Pre-planting weed control	*Roundup* (lt)	5	3	15
		Fuel and oil	0.41	3	1.23
		Parts & repairs	1.5	3	4.5
1	Planting	Seedlings	0.75	1000	750
		Transport seedling	0.25	1000	250
		labour (Pottiputki)	17	10	170
		Fertiliser (BigN,kg)	0.606	226	137
1	Post plant slashing	Fuel and oil	0.41	3	1.23
		Parts & repairs	1.5	3	4.5
1	Weed spraying (spot spray from 4w motorbike)	labour (hr)	17	2	34
		Roundup (lt)	5	2	10
	Cost of motorbike operation	Fuel and oil	0.41	3	1.2
		Parts & repairs	1	3	3
1	Form pruning	labour	17	4	68
Total yr 1 cost					1659.66
2	Weed spraying (spot spray from 4w motorbike)	labour (hr)	17	2	34
		Roundup (lt)	5	2	10
	Cost of motorbike operation	Fuel and oil	0.41	3	1.2
		Parts & repairs	1	3	3
	Maintenance slashing	Fuel and oil	0.41	3	1.23
		Parts & repairs	1.5	3	4.5
Total yr 2 cost					53.93
4	Maintenance slashing	Fuel and oil	0.41	3	1.23
		Parts & repairs	1.5	3	4.5
4	Thinning-1 (800 to 400 trees)	labour-thinning	17	11.03	187.5
4	Low pruning	labour	17	10	170
Total yr 3 cost					363.23
7	Carry-up pruning	labour	17	16	272
10	Thinning-2 (400 to 150 trees)	labour-marking			50
	Felling, delimbing & bucking (saw)	labour	17	14.70	205.8
	Tidying operation	labour	17	8	136
Total yr 12 cost					391.8
Vary, Ex. for 34 yr	Final Harvesting				
	Felling (Bouncher)	Hired bouncher (hr)	155	2.96	458.8
	Delimbing & bucking (saw)	labour	17	12.5	212.5
	Skidding (grapple skidder with tractor)	Skidder	110	10.42	1146.2
	Cross cutting (chain saw)	labour	17	6.25	106.25
	Loading/unloading transportation to mill	Hired-truck ($/m3)	9.4325	352.36	3324
	Tidying operation	labour	17	10	170

Note: Most of the values for year 1 to 4 were taken from Cockfield (2005) and Venn (2005). Fuel costs are based on year 2001, as it was the year of plantation. The same rate is used for all land uses.

Table G-2 Estimation of net present value from timber and livestock in Kingaroy (based on business-as-usual scenario)

Age	Timber Volume (m3/ha)	Timber Value ($/ha)	NPB of timber ($/ha) A	Cum.NP cost for timber ($/ha) B	Stock Rate ha^{-1}	Net benefit (stock) ($/ha)	Cum.NPV of stock ($/ha) C	NPV Timber (A-B)	NPV T+Stock (A-B+C)
1	0.00	0.00	0.00	1565.72	0.00	-72.07	-67.99	-1565.72	-1633.71
2	0.00	0.00	0.00	1613.71	0.00	0.00	-67.99	-1613.71	-1681.70
3	0.00	0.00	0.00	1918.69	0.00	0.00	-67.99	-1918.69	-1986.68
4	0.00	0.00	0.00	1918.69	0.29	100.32	11.47	-1918.69	-1907.22
5	0.00	0.00	0.00	1918.69	0.28	97.59	84.40	-1918.69	-1834.29
6	0.00	0.00	0.00	1918.69	0.27	93.03	149.98	-1918.69	-1768.71
7	0.00	0.00	0.00	2099.58	0.26	88.48	208.82	-2099.58	-1890.76
8	0.00	0.00	0.00	2099.58	0.26	88.00	264.04	-2099.58	-1835.55
9	0.00	0.00	0.00	2099.58	0.25	83.92	313.71	-2099.58	-1785.88
10	0.00	0.00	0.00	2099.58	0.24	79.36	358.02	-2099.58	-1741.56
11	0.00	0.00	0.00	2099.58	0.24	77.00	398.59	-2099.58	-1701.00
12	0.00	0.00	0.00	2294.30	0.29	100.32	448.44	-2294.30	-1845.86
13	0.00	0.00	0.00	2294.30	0.27	93.03	492.06	-2294.30	-1802.24
14	28.93	2396.45	1059.95	2369.49	0.26	88.48	531.19	-1309.54	-778.34
15	43.09	3588.91	1497.53	2365.23	0.25	83.92	566.21	-867.71	-301.50
-	-	-	-	-	--	-	--	--	-
25	200.70	17630.11	4107.79	2333.91	0.15	37.00	740.43	1773.88	2514.32
26	217.40	19196.59	4219.60	2331.67	0.14	33.79	747.86	1887.94	2635.80
27	234.18	20721.67	4297.01	2329.55	0.14	33.79	754.87	1967.46	2722.33
28	251.03	22258.21	4354.38	2327.55	0.14	33.79	761.48	2026.82	2788.30
29	267.91	23804.51	4393.28	2325.67	0.14	33.79	767.71	2067.61	2835.33
30	284.81	25359.13	4415.28	2323.90	0.14	33.79	773.60	2091.39	2864.98
31	301.72	26920.69	4421.85	2322.22	0.14	33.79	779.15	2099.63	2878.78
32	318.62	28487.91	4414.41	2320.64	0.14	33.79	784.38	2093.77	2878.16
33	335.51	30059.56	4394.29	2319.15	0.14	33.79	789.32	2075.14	2864.47
34	352.36	31634.51	4362.76	2317.74	0.14	33.79	793.98	2045.02	2839.01
35	369.17	33211.67	4321.01	2316.42	0.14	33.79	798.38	2004.60	2802.98
--	-	-	-	-	--	-	--	--	-
65	818.45	74397.01	1685.29	2298.15	0.14	33.79	858.89	-612.86	246.03
66	831.02	75539.29	1614.31	2297.93	0.14	33.79	859.62	-683.62	175.99
67	843.41	76666.27	1545.65	2297.72	0.14	33.79	860.30	-752.07	108.22
68	855.64	77777.98	1479.31	2297.53	0.14	33.79	860.94	-818.23	42.71
69	867.71	78874.44	1415.24	2297.35	0.14	33.79	861.55	-882.10	-20.56
70	879.60	79955.72	1353.44	2297.18	0.14	33.79	862.12	-943.74	-81.62

Table G-3 Estimation of net present value from timber and stock in Kingaroy (based on optimistic scenario)

Age	Timber Volume (m3/ha)	Timber Value ($/ha)	NPB of timber ($/ha) A	Cum.NP cost for timber ($/ha) B	Stock Rate ha^{-1}	Net benefit (stock) ($/ha)	Cum. NPV (stock) ($/ha) C	NPV Timber (A-B)	NPV T+Stock (A-B+C)
1	0.00	0.00	0.00	1565.72	0.00	-72.07	-67.99	-1565.72	-1633.71
2	0.00	0.00	0.00	1613.71	0.00	0.00	-67.99	-1613.71	-1681.70
3	0.00	0.00	0.00	1918.69	0.00	0.00	-67.99	-1918.69	-1986.68
4	0.00	0.00	0.00	1918.69	0.29	100.32	11.47	-1918.69	-1907.22
5	0.00	0.00	0.00	1918.69	0.28	97.59	84.40	-1918.69	-1834.29
6	0.00	0.00	0.00	1918.69	0.27	93.03	149.98	-1918.69	-1768.71
7	0.00	0.00	0.00	2099.58	0.26	88.48	208.82	-2099.58	-1890.76
8	0.00	0.00	0.00	2099.58	0.26	88.00	264.04	-2099.58	-1835.55
9	0.00	0.00	0.00	2099.58	0.25	83.92	313.71	-2099.58	-1785.88
10	0.00	0.00	0.00	2099.58	0.24	79.36	358.02	-2099.58	-1741.56
11	0.00	0.00	0.00	2099.58	0.24	77.00	398.59	-2099.58	-1701.00
12	0.00	0.00	0.00	2294.30	0.29	100.32	448.44	-2294.30	-1845.86
13	0.00	0.00	0.00	2294.30	0.27	93.03	492.06	-2294.30	-1802.24
14	28.93	4421.45	1955.61	3341.07	0.26	88.48	531.19	-1385.46	-854.26
-		-	-	-	-	--	-	-	-
27	234.18	37114.33	7696.32	3186.55	0.14	33.79	754.87	4509.77	5264.64
28	251.03	39829.98	7791.94	3167.14	0.14	33.79	761.48	4624.80	5386.28
29	267.91	42558.22	7854.41	3147.12	0.14	33.79	767.71	4707.28	5475.00
30	284.81	45296.44	7886.57	3126.61	0.14	33.79	773.60	4759.96	5533.56
31	301.72	48042.19	7891.16	3105.70	0.14	33.79	779.15	4785.47	5564.61
32	318.62	50793.16	7870.78	3084.47	0.14	33.79	784.38	4786.31	5570.69
33	335.51	53547.19	7827.86	3063.03	0.14	33.79	789.32	4764.83	5554.15
34	352.36	56302.25	7764.73	3041.44	0.14	33.79	793.98	4723.29	5517.27
-	-	-	-	-	-	--	-	-	-
65	818.45	131688.44	2983.09	2516.61	0.14	33.79	858.89	466.48	1325.37
66	831.02	133710.37	2857.45	2506.56	0.14	33.79	859.62	350.88	1210.50

Table G-4 Costs and benefits due to addition of pasture in plantation, in Kingaroy, Queensland

Description	Example for fourth yr	Cost/Benefit ($\$ha^{-1}$)
Stocking rate varies	Fourth year = $0.286ha^{-1}$	
Gross weight gain (250 kg/head) in 12 months	250*0.287=71.5 kg	
Gross gain in price ($2/kg)	$2.0*71.5kg	143.00
Selling cost ($13.49/head): It includes yard dues ($3.28/head), MLA Levy ($5/head), average freight costs to sale yard ($5/head), tail tags $0.11/each, NLIS tag @ 2.9 for all sold cattle (27 Cattle)	$13.49/head*0.286 head	3.86
Commissions (4%)		5.72
Annual income (Net of selling price) (143-3.86-5.72)		133.42
Annual health cost ($5.87/head)		1.68
Annual ear tag cost ($2/head)		0.57
Annual electricity ($1.66/0.56head)		0.85
Annual maintenance ($30/ha)		30.00
Total annual benefit for fourth year		100.32
1st yr establishment cost, other than plantation costs		
Seed costs (legumes & others)		25.00
Planting/seeding (1 time x $10/ha)		10.00
Water boring ($1500) pumps and pipes (2000) for 27 Cattle for 50 years) ($129.62/head)		37.07
Total of first year cost		**72.07**

Note: On the basis of stocking rate of that year total annual benefit for that year is estimated

Table G-5 Estimation of net present value from timber and stock in Kingaroy, Queensland (based on business-as-usual scenario)

Age	Tree biomass (t/ha) (A)	Gained soil C (t/ha) (B)	Grass biomass (t/ha) (C)	Cattle N excretion CO_2e (t/ha) (D)	Cattle CH_4 emission CO_2e (t/ha) (E)	N emission from land (CO_2et/ha) (F)	Net GHG value $/ha (AtoF)	Cumulat NP GHG Val($/ha) (AtoF)	Emission (Fertiliser) (CO_2et/ha) (G)	Emission (Machine) (CO_2e/ha) (H)	Emission Fuel (CO_2et/ha) (I)	Cum NPV of GHI ($/ha)	Cum NPV of all GHG ($/ha)	NPV T+S+C
1	5.03	1.42	0.00	0.00	0.00	1.37	-11.09	-10.46	0.83	0.03	0.21	-10.51	-20.97	-1654.68
2	21.54	2.83	2.30	0.00	0.00	1.27	-0.98	-11.33	0.09	0.00	0.00	-10.51	-21.84	-1703.55
3	46.65	4.25	3.00	0.00	0.00	1.27	11.02	-2.08	0.00	0.00	0.00	-10.51	-12.59	-1999.27
4	32.12	5.66	4.48	0.11	0.36	1.27	1.82	-0.64	0.00	0.00	0.03	-10.81	-11.45	-1918.67
5	46.45	7.08	4.35	0.11	0.35	1.27	9.10	6.16	0.00	0.00	0.00	-10.81	-4.65	-1838.94
6	61.97	8.49	4.24	0.10	0.34	1.27	16.86	18.04	0.00	0.00	0.00	-10.81	7.23	-1761.48
7	78.40	9.91	4.13	0.10	0.33	1.27	25.00	34.67	0.00	0.00	0.00	-10.81	23.86	-1866.90
8	95.60	11.32	4.03	0.10	0.32	1.27	33.46	55.66	0.00	0.00	0.00	-10.81	44.85	-1790.70
9	113.51	12.74	3.93	0.10	0.31	1.27	42.22	80.65	0.00	0.00	0.00	-10.81	69.84	-1716.04
10	132.00	14.16	3.83	0.09	0.31	1.27	51.21	109.25	0.00	0.00	0.00	-10.81	98.44	-1643.12
11	151.00	15.57	3.73	0.09	0.30	1.27	60.42	141.08	0.00	0.00	0.00	-10.81	130.27	-1570.73
12	116.60	16.99	4.48	0.11	0.36	1.27	46.69	164.28	0.00	0.05	0.92	-15.87	148.41	-1697.44
-	-	-	-	-	-	--	-	-	--	--	-	--	-	-
30	420.11	42.47	2.18	0.05	0.17	1.27	196.73	755.16	0.00	1.01	4.79	-26.48	728.68	3593.67
31	439.39	43.88	2.18	0.05	0.17	1.27	205.99	789.00	0.00	1.06	4.99	-26.30	762.70	3641.48
32	458.84	45.30	2.18	0.05	0.17	1.27	215.32	822.36	0.00	1.11	5.18	-26.11	796.25	3674.41
33	478.45	46.72	2.18	0.05	0.17	1.27	224.72	855.21	0.00	1.16	5.38	-25.90	829.31	3693.78
34	498.20	48.13	2.18	0.05	0.17	1.27	234.18	887.51	0.00	1.21	5.57	-25.69	861.82	3700.82
35	518.09	49.55	2.18	0.05	0.17	1.27	243.70	919.22	0.00	1.26	5.76	-25.47	893.75	3696.73

Note: Price of carbon=$10.5t^{-1}$$CO_2$e, Discount rate = 6%, Carbon mass=biomass *0.5, CO_2 mass=3.67*carbon mass

Net greenhouse gas value ($ ha^{-1})=[[{(A + C) * 0.5 + B}*3.67]/46]- (D+E+F)]*10.5 and NPV of GHI = $-\{(G+H+I)*10.5\}/(1.06)^{age}$

Table G-6 Estimation of net present value from timber, stock and carbon in Kingaroy, Queensland (optimistic scenario)

Age	Tree biomass (t/ha) (A)	Gained soil C (t/ha) (B)	Grass biomass (t/ha) (C)	Cattle N excretion CO_2e (t/ha) (D)	Cattle CH_4 emission CO_2e (t/ha) (E)	N emission from land (CO_2et/ha) (F)	Net GHG value $/ha (AtoF)	Cumulat NP GHG Val($/ha) (AtoF)	Emission (Fertiliser) (CO_2et/ha) (G)	Emission (Machine) (CO_2e/ha) (H)	Emission Fuel (CO_2et/ha) (I)	Cum NPV of GHI ($/ha)	Cum NPV of all GHG ($/ha)	NPV T+S+C
1	5.03	1.42	0.00	0.00	0.00	1.37	-11.09	-10.46	0.83	0.03	0.21	-10.51	-20.97	-1654.68
2	21.54	2.83	2.30	0.00	0.00	1.27	-0.98	-11.33	0.09	0.00	0.00	-10.51	-21.84	-1703.55
3	46.65	4.25	3.00	0.00	0.00	1.27	11.02	-2.08	0.00	0.00	0.00	-10.51	-12.59	-1999.27
4	32.12	5.66	4.48	0.11	0.36	1.27	1.82	-0.64	0.00	0.00	0.03	-10.81	-11.45	-1918.67
5	46.45	7.08	4.35	0.11	0.35	1.27	9.10	6.16	0.00	0.00	0.00	-10.81	-4.65	-1838.94
6	61.97	8.49	4.24	0.10	0.34	1.27	16.86	18.04	0.00	0.00	0.00	-10.81	7.23	-1761.48
7	78.40	9.91	4.13	0.10	0.33	1.27	25.00	34.67	0.00	0.00	0.00	-10.81	23.86	-1866.90
8	95.60	11.32	4.03	0.10	0.32	1.27	33.46	55.66	0.00	0.00	0.00	-10.81	44.85	-1790.70
9	113.51	12.74	3.93	0.10	0.31	1.27	42.22	80.65	0.00	0.00	0.00	-10.81	69.84	-1716.04
10	132.00	14.16	3.83	0.09	0.31	1.27	51.21	109.25	0.00	0.00	0.00	-10.81	98.44	-1643.12
11	151.00	15.57	3.73	0.09	0.30	1.27	60.42	141.08	0.00	0.00	0.00	-10.81	130.27	-1570.73
12	116.60	16.99	4.48	0.11	0.36	1.27	46.69	164.28	0.00	0.05	0.92	-15.87	148.41	-1697.44
-	-	-	-	-	-	--	-	-	--	--	-	--	-	-
30	420.11	42.47	2.18	0.05	0.17	1.27	196.73	755.16	0.00	1.01	4.79	-26.48	728.68	6262.24
31	439.39	43.88	2.18	0.05	0.17	1.27	205.99	789.00	0.00	1.06	4.99	-26.30	762.70	6327.31
32	458.84	45.30	2.18	0.05	0.17	1.27	215.32	822.36	0.00	1.11	5.18	-26.11	796.25	6366.94
33	478.45	46.72	2.18	0.05	0.17	1.27	224.72	855.21	0.00	1.16	5.38	-25.90	829.31	6383.46
34	498.20	48.13	2.18	0.05	0.17	1.27	234.18	887.51	0.00	1.21	5.57	-25.69	861.82	6379.09
35	518.09	49.55	2.18	0.05	0.17	1.27	243.70	919.22	0.00	1.26	5.76	-25.47	893.75	6355.90

Note: Price of carbon=$10.5t$^{-1}CO_2e$, Discount rate = 6%, Carbon mass=biomass *0.5, CO_2 mass=3.67*carbon mass
Net greenhouse gas value ($ ha^{-1})=[[{(A + C) * 0.5 + B}*3.67]/46]- (D+E+F)]*10.5 and NPV of GHI = -{(G+H+I)*10.5}/(1.06)^{age}

Table H-1 Estimation of cost, benefit and gross margin of peanut cropping in Kingaroy, Queensland

Description	Cost ($ ha^{-1})
Machinery Operations (exclude GST)	
Slashing	5.73
Deep ripping (1 time x $20/ha)	20
Chisel plough (1 time x $15/ha)	15
Discing (1 times x $15/ha)	15
Scarifier (1 time x $13/ha)	13
Cultivating (1 time x $10/ha)	10
Planting (1 time x $10/ha)	10
Self propelled spraying (4.2 time x $5.78/ha)	24.28
Seed (60 kg/ha x $2.9/kg)	174
Inoculants	3.27
Fertiliser	
Lime (1 in 5 yrs) (0.20 x 2.5 t/ha x $65/ton)	32.5
CK1 (100 kg/ha x $0.55/kg)	55
MOP (KCl) (50kg x $0.51/kg)	25.5
Herbicide	
Treflan (1.7 lt/ha x $8.6l/lt)	14.62
Gramoxone (1 in 2 yr) (0.7lt/ha x 0.5 x $9.68/lt)	3.39
Basagran (1 in 2 yr) (1 lt/ha x 0.5 x $34.27/lt)	17.14
Uptake oil (1 lt/ha x $5/lt)	5
Fungicide	
Folicur (2 times x 0.3 lt/ha x $94/lt)	56.4
Plus Agridex (2 times x 1lt/ha x $6.09/lt)	12.18
Insecticide (Lannate) (1 in 5 yr) (2 lt/ha x 0.2 x $13/lt)	5.2
Chipping	80
Harvesting	
Digging (own machine) (1 times x $50/ha)	50
Threshing/cleaning (contract) (2 t/ha x $79/ton)	158
Drying (2 t/ha x $15/ton)	30
Freight to PCA (2t/ha x $10/ton)	20
Balling & transportation cost (1 in 4 yr) (0.25 x $40/ha)	10
Total Variable Cost (per ha)	865.21
Income from bale (1 in 4 yr) (effective wt 2t) (2t x 0.25 x $150/t)	75
Income from peanut (yield 2t/ha x $600/ton)	1200
Total Gross Income	1275
Gross Margin (per ha)	409.79

Table H-2 Estimation of cost, benefit and gross margin of maize cropping in Kingaroy

Activities	Cost ($ ha^{-1})
Machinery operations	
Primary tillage (1 x $13/ha)	13
Inter-row tillage (1 x $ 8/ha)	8
Scarifier (1 time x $13/ha)	13
Planting operation (1 x $ 10/ha)	10
Self propelled spraying (5 x $ 5.78/ha)	28.9
Seed (10 kg/ha x $6.51/kg)	65.1
Fertiliser cost	
DAP (125 kg/ha x $0.48/kg)	60
Lime (1 in 5 yrs) (0.20 x 2.5 t/ha x $65/ton)	32.5
Urea (60 kg/ha x $0.5/ton)	30
MOP (80 kg/ha x $0.51/kg)	40.8
Herbicide cost	
Amicide 500 (3 times x 0.4lt/ha x $6.05/lt)	7.26
Kamba 500 (3 times x 0.28lt/ha x $39/lt)	32.76
Roundup CT (2 times x 1.7 lt/ha x $4.75/lt)	16.15
Surpass 300 (2 times x 0.4 lt/ha x $4.65/lt)	4.65
Express (25gm x 1 x $0.48/gm)	12
Harvesting and post harvesting costs	
Contract header (4ha/hr x $250/hr)	62.50
Freight to market centre (3.5 t/ha x $10/t)	35
Total variable costs	471.62
Total income on-farm (3.5 t/ha x $160/ton)	560
GROSS MARGIN ($/ha)	88.38

Table H-3 Estimation of NPV from peanut-maize cropping system in 34 years in Kingaroy

Age	Soil Carbon tC/ha	Net loss of soil C CO_2t/ha	GHG from agrochemical, fuel & machine (tCO_2e/ha)	N from land, soil disturbance & BFN (tCO_2e/ha)	NPV loss from GHG ($/ha)	Net benefit crops ($/ha)	NPV from crops ($/ha)
1	76.69	4.50	1.05	1.50	69.86	249.09	234.99
2	75.48	4.43	1.05	1.50	65.22	249.09	221.68
3	74.30	4.32	1.05	1.50	60.56	249.09	209.14
4	73.15	4.21	1.05	1.50	56.22	249.09	197.30
5	72.02	4.14	1.05	1.50	52.47	249.09	186.13
6	70.92	4.03	1.05	1.50	48.68	249.09	175.60
7	69.85	3.92	1.05	1.50	45.16	249.09	165.66
8	68.80	3.84	1.05	1.50	42.12	249.09	156.28
9	67.77	3.77	1.05	1.50	39.28	249.09	147.43
10	66.77	3.66	1.05	1.50	36.42	249.09	139.09
11	65.79	3.59	1.05	1.50	33.95	249.09	131.21
12	64.83	3.51	1.05	1.50	31.65	249.09	123.79
13	63.89	3.44	1.05	1.50	29.49	249.09	116.78
14	62.98	3.33	1.05	1.50	27.32	249.09	110.17
15	62.08	3.29	1.05	1.50	25.61	249.09	103.93
16	61.21	3.18	1.05	1.50	23.71	249.09	98.05
17	60.36	3.11	1.05	1.50	22.08	249.09	92.50
18	59.52	3.07	1.05	1.50	20.69	249.09	87.27
19	58.71	2.96	1.05	1.50	19.14	249.09	82.33
20	57.91	2.93	1.05	1.50	17.94	249.09	77.67
21	57.13	2.85	1.05	1.50	16.70	249.09	73.27
22	56.37	2.78	1.05	1.50	15.54	249.09	69.12
23	55.63	2.71	1.05	1.50	14.46	249.09	65.21
24	54.90	2.67	1.05	1.50	13.54	249.09	61.52
25	54.19	2.60	1.05	1.50	12.60	249.09	58.04
26	53.50	2.53	1.05	1.50	11.72	249.09	54.75
27	52.82	2.49	1.05	1.50	10.97	249.09	51.65
28	52.16	2.42	1.05	1.50	10.20	249.09	48.73
29	51.52	2.34	1.05	1.50	9.48	249.09	45.97
30	50.89	2.31	1.05	1.50	8.88	249.09	43.37
31	50.26	2.31	1.05	1.50	8.38	249.09	40.91
32	49.67	2.16	1.05	1.50	7.66	249.09	38.60
33	49.07	2.20	1.05	1.50	7.29	249.09	36.41
34	48.50	2.09	1.05	1.50	6.71	249.09	34.35
Total NPV in 34 years					921.71		3578.89
Net NPV gain after deducting NPV lost from GHGs							2657.18

Table H-4 Estimation of cost, benefit and gross margin of pasture in Kingaroy

Activities	Price ($ ha^{-1})
Selling price of weaners	$2/kg
Gross weight gain (250 kg/hd x 0.56hd) in 12 months =140kg	
Total gross gain in price (140kg x $2/kg)	280.00
Selling Costs	
Yard dues (3.28/head * 0.56head)	1.84
MLA Levy ($5/head * 0.56 head)	2.80
Average freight costs to sale yard $ 5/head	2.80
Tail tags $0.11/each	0.06
NLIS tag @ 2.9 for all sale cattle (27 Cattle)	0.06
Commission 4%	11.2
Total selling cost ($/ha)	18.7
Net selling price ($280-$18.7=$161.3)	261.3
Annual health cost	
1 fluke drench ($/head)	1.72
Misc. vet costs ($/head)	2.5
7-in-1 vaccine ($/head)	1.2
3 times sprays @ $0.15/head	0.45
Total health costs of 0.58 beef ($5.87/head*0.56 head)	3.29
Annual other cost	
Ear tags @$2/head	1.12
Annual maintenance cost ($30/ha improved, NSW)(herbicides (Grazon 75ml/lt), weed control etc)	30.00
Electricity used for water pumping ($20/3month/27 cattle)	1.66
Total annual cost	36.06
Total annual benefit ($261.3 – $36.06)	225.24
Costs (initial establishment)	
Slashing	5.73
Deep ripping (1 time x $20/ha)	20
Seed costs (legumes & others)	25
Urea (50 kg/ha x $0.5/kg)	25
Planting/seeding (1 time x $10/ha)	10
Water boring ($1500) pump & pipes ($2000) for 27 cattle (per 0.56 cattle)	72.59
Costs in 8th, 16th, 24th & 32nd years	
Slashing ($5.73)	5.73
Deep ripping (1 time x $20/ha)	20
Seed costs (legumes & others) ($25)	25
Planting/seeding (1 time x $10/ha)	10
Total cost in 8th, 16th, 24th & 32nd years	60.73
Costs in 33rd & 34th years	
Slasher ($5.73 x 1/8)	0.72
Deep ripping (1 time x $20/ha x 1/8)	2.5
Seed costs (legumes & others) ($25 x 1/8)	3.12
Planting/seeding (1 time x $10/ha x 1/8)	1.25
Total cost in 33rd & 34th years	7.59

Table H-5 Estimation of NPV from pasture system in 34 years in Kingaroy

Age	Soil C tC/ha	Cum. gain in soil C tCh^{-1} (A)	Grass bio-mass (t/ha) (B)	GHG from agrochemical, fuels & machines tCO_2e/ha	N urine, faeces tCO_2ha^{-1}	N soil dis. & BFN $tCO2eha^{-1}$	CH4 cattle $tCO_2 h^{-1}$	NPV gain from A + B	NPV lost from other GHG	Net benefit from stock	NPV from stock
1	145.23	0.78	6.33	0.44	0.21	1.37	0.77	3.12	27.72	152.64	144.00
2	145.98	1.53	6.33	0.01	0.21	1.23	0.77	3.50	20.84	225.23	200.45
3	146.7	2.25	6.33	0.01	0.21	1.23	0.77	3.81	19.66	225.23	189.11
4	147.41	2.96	6.33	0.01	0.21	1.23	0.77	4.06	18.54	225.23	178.40
5	148.1	3.65	6.33	0.01	0.21	1.23	0.77	4.26	17.50	225.23	168.30
6	148.77	4.32	6.33	0.01	0.21	1.23	0.77	4.42	16.50	225.23	158.78
7	149.43	4.98	6.33	0.01	0.21	1.23	0.77	4.53	15.57	225.23	149.79
8	150.08	5.63	6.33	0.19	0.21	1.37	0.77	4.62	16.79	164.5	103.21
9	150.71	6.26	6.33	0.01	0.21	1.23	0.77	4.67	13.86	225.23	133.31
10	151.34	6.89	6.33	0.01	0.21	1.23	0.77	4.70	13.07	225.23	125.77
11	151.95	7.50	6.33	0.01	0.21	1.23	0.77	4.70	12.33	225.23	118.65
12	152.56	8.11	6.33	0.01	0.21	1.23	0.77	4.69	11.64	225.23	111.93
13	153.15	8.70	6.33	0.01	0.21	1.23	0.77	4.66	10.98	225.23	105.60
14	153.74	9.29	6.33	0.01	0.21	1.23	0.77	4.61	10.36	225.23	99.62
15	154.32	9.87	6.33	0.01	0.21	1.23	0.77	4.55	9.77	225.23	93.98
16	154.89	10.44	6.33	0.19	0.21	1.37	0.77	4.48	10.53	164.5	64.75
17	155.45	11.00	6.33	0.01	0.21	1.23	0.77	4.40	8.69	225.23	83.64
18	156.01	11.56	6.33	0.01	0.21	1.23	0.77	4.32	8.20	225.23	78.91
19	156.55	12.10	6.33	0.01	0.21	1.23	0.77	4.22	7.74	225.23	74.44
20	157.1	12.65	6.33	0.01	0.21	1.23	0.77	4.13	7.30	225.23	70.23
21	157.63	13.18	6.33	0.01	0.21	1.23	0.77	4.02	6.89	225.23	66.25
22	158.16	13.71	6.33	0.01	0.21	1.23	0.77	3.92	6.50	225.23	62.50
23	158.68	14.23	6.33	0.01	0.21	1.23	0.77	3.81	6.13	225.23	58.96
24	159.19	14.74	6.33	0.19	0.21	1.37	0.77	3.70	6.61	164.5	40.63
25	159.70	15.25	6.33	0.01	0.21	1.23	0.77	3.59	5.46	225.23	52.48
26	160.20	15.75	6.33	0.01	0.21	1.23	0.77	3.48	5.15	225.23	49.51
27	160.69	16.24	6.33	0.01	0.21	1.23	0.77	3.37	4.85	225.23	46.71
28	161.18	16.73	6.33	0.01	0.21	1.23	0.77	3.26	4.58	225.23	44.06
29	161.66	17.21	6.33	0.01	0.21	1.23	0.77	3.15	4.32	225.23	41.57
30	162.14	17.69	6.33	0.01	0.21	1.23	0.77	3.04	4.08	225.23	39.21
31	162.61	18.16	6.33	0.01	0.21	1.23	0.77	2.93	3.85	225.23	37.00
32	163.07	18.62	6.33	0.19	0.21	1.37	0.77	2.83	4.15	164.5	25.49
33	163.52	19.07	6.33	0.02	0.21	1.25	0.77	2.72	3.47	217.64	31.82
34	163.96	19.51	6.33	0.02	0.21	1.25	0.77	2.62	3.27	217.64	30.02
Total NPV								132.9	346.88		3079.1
Net loss from greenhouse gases in 34 yrs									213.99		
NPV from crops in 34 years after deducting the NPV loss from greenhouse gases											2865.1

Appendix J Description of peanut, maize, pasture grasses and spotted gum species found in the research site

The land uses in the selected sites are cropping, pasture and spotted gum. For economic and environmental reasons, peanuts are usually alternated with maize. Since both are summer crops, the land is fallowed for around seven months in every winter season. This section describes the general characteristics of peanut, maize, spotted gum and major pasture species.

Peanut (*Arachis hypogaea*) belongs to the Leguminaceae family. It grows in the form of a bush or vine. It produces yellow flowers on the axils of its leaves, which after self-fertilisation grow down to soil and become a pod. Planting timing is strongly guided by soil temperature (minimum of 18°C at nine o'clock) and preferred harvesting time. In the study area, people normally plant peanuts from November to December and harvest from April to May. The peanut industry can generally be categorised into three production systems: extensive rain-fed, intensive irrigation and intensive high rainfall systems. Three different types of peanut (Virginia, Runner and Spanish) are grown in the region. As the research site receives low rainfall and has no irrigation facility, it falls into the first category where the Streeton variety of the Virginia type was found to be the best. This is because of its high yielding and drought tolerant capabilities, and it is less susceptible to aflatoxin than other varieties (QDPIF, 2004).

Maize (*Zea mays*), a gigantic domesticated grass, belongs to the Gramineae family. It is the third most planted field crop (after wheat and rice) in the world. It is used for feed, silage, and for the breakfast food and processing markets. In the study area, it is mostly planted between mid September and mid October when the minimum soil temperature is around 12°C. Harvesting time depends on grain moisture content. Harvesting above 13% grain moisture and then drying reduces losses from lodged plants, insects and cob rots (DPI&F, 2000), but it adds to energy consumption and greenhouse gas emission operations. Recently, there has been more interest in maize cultivation, mainly due to declining interest in cotton and sorghums because they fetch lower prices and have lower water use efficiency than maize (Birch *et al.,* 2003). The expansion of the feedlot beef and dairy industries in the region (Robertson *et al.,* 2003), new market of maize for ethanol production (Birch *et al.,*

2003) and increased demand in Japan for Australian processed maize which is not contaminated with genetically modified organisms, are other encouraging factors.

The main grass species in pasture and plantation on the study sites were varieties of native grasses and Rhodes grass (*Chloris gayana*) and the dominant legume species were burr medic (*Medicago polymorpha*) and Siratro (*Macroptilium atropurpureum*). Rhodes grass is a tufted perennial grass whose runners cover the ground surface and produce plantlets. It can tolerate salt and moderate frost and complements many legumes. There are two varieties of Rhodes, Pioneer and Katambora, with the latter more popular in the research site for its later flowering and leafing time, higher adoptability in clay and clay loam soil and palatability. Burr medic is a smooth-leafed small annual medic. It grows well in pH neutral soil with a moderate phosphorus level. It has naturalised over some two million hectares of southern Queensland. It is an excellent feed for cattle in `medic years' when good autumn and winter rainfall follow a dry summer.

Siratro is a perennial twining legume established from seed and plant nodules. It is losing its favour in phosphorus poor soil, as it demands high phosphorus (Brown, 1983) but it is still popular in the study areas, as it fixes large amounts of nitrogen and passes quickly to companion grasses. Sowing this legume in native pasture has doubled the stocking rate and increased the annual live weight gain per animal of some 50 kg (Beek, 1983). In the study areas, cattle producers have generally adopted a crossbreed of *Bos indicus* and *Bos taurus*. The former tropical breed was chosen for heat and tick resistant behaviours and the latter British breed was chosen for good marbling content, which has significant appeal in the Japanese market (C. Marshall, 2005, pers.com., 7 April).

Small plantations were started on private farms following the SEQRFA program. Spotted gum is one of the recommended species in the research area. The word ‘spotted’ for the spotted gum refers to the ‘spots’ on the bark. The species is widely distributed in south east Queensland. Naturally, they predominate between 25°S to 38°S latitude. In Queensland, distribution extends up to 400 km inland and up to 950m altitude from sea level (Boland *et al.,* 1984). Trees attain heights of 35-45 m and diameter at breast height of 1-1.3 m (Boland, 1984); the greater dimensions being reached towards the southern limits of its range in New South Wales (Huth *et* *al.,* 2004). Trees may grow up to 20-35 m in height and 0.7-1.2 m in diameter even in dryer and poorer sites (Boland, 1984). Spotted gum has good adaptive behaviour and it copes with soils that have low to high fertility; annual rainfall exceeds 600 mm; low to medium salinity; low to moderately high pH and sites that experience a moderate frequency of non-severe frost (DPI&F, 2004). In a native forest environment, it is usually found with many associates, such as narrow-leaved red iron bark (*Eucalyptus crebra*), black butt (*E. pilularis*), tallowwood (*E. microcorys*), grey gums (*E. propinqua*), and grey iron box (*E. paniculata*) (Boland, 1984). The timber is hard, durable and resistant to decay (DPI&F, 2004c; Lee, 2005) and is used for heavy and general building construction, decking and flooring. The species is also used for preservative-treated poles and handles (Queensland CRA/RFA Steering Committee, 1998).