The *FullCAM* Carbon Accounting Model: Development, Calibration and Implementation

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ABSTRACT

In developing Australia's National Carbon Accounting System (NCAS) the Australian Greenhouse Office (AGO) has undertaken ambitious national resource and activity inventories within an accounting framework that benefits from a comprehensive and integrated suite of remote sensing and carbon modelling activities. The result is a fine scale spatial application of a comprehensive carbon cycle model which is an integration of a range of existing models.

The model developed, named *FullCAM*, is an integration of biomass, decomposition, soil carbon models and accounting tools to provide a single model capable of carbon accounting in transitional (e.g. afforestation, reforestation and deforestation) and mixed (e.g. agroforestry) systems.

The *FullCAM* model can be run in point, estate (a mix of areas by age by activity types) and a spatial mode which will integrate information drawn from the remotely sensed land-cover-change program, productivity and climate surfaces and other ancillary data to perform the various accounting routines capable of meeting the various reporting requirements of the UN Framework Convention on Climate Change, and more specifically, the Kyoto Protocol.

Keywords: FullCAM, NCAS, carbon

INTRODUCTION

The National Carbon Accounting System (NCAS) has been established by the Australian Government to provide a complete carbon accounting and projections capacity for land based (agricultural and forestry) activities.

Early in the development of the NCAS it was recognised that carbon accounting at both continental and project scales was going to rely on both the collation and synthesis of resource information and the calibration and verification of a model framework. The vast land areas in Australia under extensive forest and agricultural management demand an approach founded on modelling. Purely measured approaches were shown to be impractical, particularly for differential land based accounting systems such as Article 3.3 of the Kyoto Protocol.

An overall system framework (AGO, 2000a) guided the development of data gathering, projects and programs which could then be integrated using spatial modelling approaches. Various models were selected calibrated and verified through these programs, and a range of related projects were undertaken to provide the additional data needed to operate the models continent-wide at a fine resolution. *FullCAM* is an integrated compendium model that provides the linkage between the various sub-models.

FullCAM has components that deal with the biological and management processes which affect carbon pools and the transfers between pools in forest, agricultural, transitional (afforestation, reforestation, deforestation) and mixed (eg. agroforestry) systems. The exchanges of carbon, loss and uptake, between the terrestrial biological system and the atmosphere are also accounted for.

The integrated suite of models that comprise *FullCAM* are: the physiological growth model for forests, *3PG* (Landsberg and Wareing, 1997; Landsberg *et. al*., 2000; Coops *et. al.* 1998; Coops *et. al.,* 2000); the carbon accounting model for forests developed by the Australian Greenhouse Office (AGO), *CAMFor* (Richards and Evans, 2000a), the carbon accounting model for cropping and grazing systems – *CAMAg* (Richards and Evans, 2000b), the microbial decomposition model *GENDEC* (Moorhead and Reynolds, 1991; Moorhead *et. al.,* 1999) and the Rothamsted Soil Carbon Model – *Roth C* (Jenkinson, *et. al.,* 1987, Jenkinson *et. al.,* 1991).

These models have been independently developed for the various purposes of predicting and accounting for:

- soil carbon change in agriculture and forest activities (in the case of *Roth C*);
- the determination of rates of decomposition of litter (in the case of *GENDEC*); and
- the prediction of growth in trees (in the case of *3PG*).

CAMFor and *CAMAg* are carbon accounting tools developed by the Australian Greenhouse Office through which it is possible to apply management impacts such as fire, harvest, cropping, and grazing, to externally generated growth and decomposition rate inputs.

To prepare these models for integration into *FullCAM*, each model (except for *CAMAg*) was translated to a common Microsoft Excel spreadsheet format. The Excel workbooks used only sheet based formula. No 'Macros' or other code were applied. This provided a consistent and transparent model platform from which to review and integrate the various models. This developmental Excel version was named GRC3. Having a consistent structure and format for the models allowed for the independent calibration of various models while providing for ease of later integration. The transparency of the development process also facilitates review at a detailed level.

The integration of the models serves two primary goals. The first is to provide a capacity to be able to operate at a level of conservation of carbon at a site or other specified area. This includes all pools and transfers (net of atmospheric uptake and emissions) between pools to ensure that there are no significant instances of double counting or omissions in accounting. Potentially, this could occur if each of the dominant carbon pools – soil carbon, biomass and litter – were considered independently. The second is to provide the capacity to run the model continentally as a fine resolution grid-based spatial application. A single efficient model is required to analyse the large input data sets in a spatial context.

MODEL SELECTION

The need to develop an integrated model was highlighted during the International Review of the NCAS Implementation Plan for Phase 1 of the 1990 Baseline. The Review report is contained in the NCAS Technical Report No. 11 (AGO, 2000b). Most germane among the Review recommendations was a need to take a holistic approach, with modelling and measurement continuous across all carbon pools and cognisant of the transfers between pools.

Other recommendations from the Review which had direct implications for the development of the NCAS, and therefore *FullCAM* were:

- the adoption, within the NCAS suite of tools, of a generic and widely applicable physiological growth model;
- the adoption of a microbial litter decomposition model, with a direct suggestion to consider the *GENDEC* model of Moorhead *et. al*. (1999); and,
- support for the national calibration of the *Roth C* soil carbon model.

The selection and development of the models for integration to *FullCAM* arose from early analysis carried out in developing the system framework for the NCAS. Various strategies for data accumulation and assimilation into models capable of continental and project scale carbon accounting (largely directed at satisfying the requirements of the Kyoto Protocol) were developed. Strategies were developed to guide the fundamental data collections, research program and model calibration.

The rationale for the selection of the models that were integrated in *FullCAM* can be found in the various NCAS Technical Reports (Turner *et. al*., 1999; AGO, 2000a–c; Webbnet, 2000).

CAMFor (carbon accounting model for forests) (Richards and Evans, 2000a) was developed within the NCAS to provide capacity for both project and continental scale accounting. *CAMFor* is an Excel based model which has its conceptual foundations in the CO_2 *Fix* model of Mohren and Goldewijk (1990).

CAMAg (carbon accounting model for agriculture) was also developed for the NCAS (Richards and Evans, 2000b). *CAMAg* performs similar functions to *CAMFor,* but operates in agricultural systems. *CAMAg*, unlike *CAMFor*, was developed with direct integration of the *Roth C* model.

Copies of the original models and User Manuals can be found in the following publications or distributed on the following websites:

- *CAMFor* User Manual - http://www.greenhouse.gov.au/ncas
- *Roth C* - http://www.iacr.bbsrc.ac.uk/res/treshome.html
- *3PG* - http://www.landsberg.com.au

MODEL DEVELOPMENT

The component models are being independently calibrated for the NCAS through a variety of programs. This activity provides for considerable investment into the calibration of each of the models for the range of conditions and management practices present throughout Australia. Over a 2–3 year period, the total investment in the data collection and process understanding for model calibration will be the order of $9M.

Model calibration includes the collation of a series of previous (quality audited) site measurements and the undertaking of additional field work and laboratory analyses. Independent data sets are maintained for the model calibration and verification of model results. The subsequent integration of the range of calibrated models into a spatial version of *FullCAM* will rely on interpolation across a range of spatially continuous input data layers. This includes data such as that on climate, soil type, biomass and land cover change.

Such a comprehensive approach to carbon accounting was made possible by the NCAS having sole responsibility for the development of carbon budgets across the forest and agriculture sectors, including both the biomass and soil carbon pools. This allowed for alignment of program activities for the calibration of each component model. Data collection and model calibrations could then be easily transferred into the calibration and verification of the *FullCAM* model in both its plot and spatial versions.

THE COMPONENT MODELS

3PG

The adopted version of *3PG* is that described as Version 3-PGpjs 1.0 (Sands, 2000).
In its original form, this is an Excel version of the model supported by Visual Basic Macros. This was translated into a consistent sheet based and formula driven (no Macros) model. Subsequent

changes were made to this model to enable spatial application reflecting the previous version development by Coops and Wareing (2000) and Landsberg and Kesteven (2001).

The principal work required to implement this model was the compiling of the fundamental input data. This entailed:

- the development of a slope and aspect corrected solar radiation surface on a 250m grid;
- the use of Digital Elevation Model (DEM) of AUSLIG – Geodata 9 second DEM (version 2);
- the provision of access by CSIRO Division of Land and Water to their Fertility and Soil Moisture Continental Surfaces (Mackenzie *et. al.,* 2000);
- the derivation of soil surfaces from the Atlas for Australian Soils (Northcote*,* 1979);
- use of the rainfall, temperature and radiation surfaces from ANUCLIM (software package) (McMahon *et. al*., 1995);
- derivation of a Normalised Difference Vegetation Index (NDVI) 10-year average by ERIN for the NCAS; and
- development of a frost surface by the NCAS.

CAMFor

CAMFor has its origins in the 1990 *CO_2 Fix* Model of Mohren and Goldewijk (1990). The published Fortran code for this model was converted to an Excel spreadsheet (sheet based, formula driven) format as reported in Richards and Evans (2000a). A subsequent series of modifications were made including:

- the introduction of an inert soil carbon pool recognising the nature of the carbon in Australian mineral soils, the high charcoal content and the potential long term protection of fine organic matter through encapsulation and absorption by clays;
- a fire simulation capacity was added to the model that could deal with stand replacing and/or regenerating fires, being either forest floor fires largely removing litter or crown fires affecting the whole tree;
- the wood product pool structures and lifecycles were modified to reflect those cited in the NCAS Technical Report Number 8 (Jaakko Pöyry, 1999);
- greater resolution was added to the component distinctions of the standing tree material, splitting coarse and fine roots, branch and leaf material;
- the potential to override the soil carbon model component by directly entering either field data or externally modelled inputs, and
- an added capacity to account from a primary data input of above-ground mass increment as an alternative to stem volume increment.

Within *FullCAM*, the *CAMFor* sub-component can take its growth information from any one of three sources:

- net primary productivity (NPP) derived from *3PG* with feedback from management actions (thinnings, etc.) specified in *CAMFor*;
- information entered from external models; and
- measures of either above-ground mass increment or stem volume increment.

Material entering the debris pool (that is the above-ground coarse and fine litter) and the decay (the root material below ground shed by live biomass) is accounted in either a decomposable or resistant fraction, with the potential to apply separate decomposition rates to each.

A series of defaults were developed for *CAMFor* using the growth rates and management descriptions drawn from the work of Turner and James (1997*)*. Under contract to the AGO, Turner and James converted wood flow estimates for typical silvicultural regimes, growth rates and harvest rates – prepared through survey of forest growers for the National Forest Inventory (NFI) – to standing volumes and volume increments. Wood densities were available from the work of Ilic *et. al.* (2000).

The information flowing from *3PG* to *CAMFor* is simply that of total NPP, as reflected in whole tree productivity/growth. Rules for the allocation to various tree components and for the turnover rates that will affect the standing mass increment at any one time (change in mass as opposed to a total productivity change) are either specified within a *CAMFor* table or driven by formula common to *3PG* and *CAMFor*.

Neither *CAMFor* nor *3PG* (in this form) deal with a number of stems, but work on proportional change to mass per unit area. Thinning activities, such as harvest or fire, which are specified in *CAMFor* are treated as a proportional decrease of biomass and are reflected as an equivalent proportional decrease in canopy cover within *3PG*.

CAMAg

Within *FullCAM*, *CAMAg* serves the same roles for cropping and grazing systems as *CAMFor* does for forests. The *CAMAg* model reflects the impacts of management on carbon accumulation and allocates masses to various product pools within plants and to decomposable and resistant organic residues. Yields need to be prescribed in the model – as either above-ground, total or product mass – as do above- and below-ground turnover rates.

With both *CAMFor* and *CAMAg* embedded within *FullCAM*, it is possible to represent the transitional afforestation, reforestation and deforestation (change at one site) or mix of agricultural and forest systems (discrete activities at separate sites). Under afforestation and reforestation there is a gradual change from the characteristics of the original pasture or cropping system, with the mass of organic matter derived from those systems decomposing and decreasing with declining input. For deforestation, the same applies, but with a large residual of decomposing woody material being the primary change remaining within *CAMFor*.

Within *FullCAM*, *CAMFor* and *CAMAg* can be proportionally represented (as under afforestation, reforestation and deforestation) according to the relative proportions of canopy cover under each of the woody (*CAMFor*) and non-woody (*CAMAg*) categories. This provides capacity for ongoing mixed systems such as agroforestry.

GENDEC

GENDEC is a microbial decomposition model, developed by Moorhead *et. al.(1999),* which considers the environmental and biological drivers of microbial activity, namely temperature, moisture and substrate quality.

GENDEC addresses both carbon and nitrogen, relying on nitrogen to carbon ratios throughout the decomposition process, and using available nitrogen as a factor which may constrain the rate of microbial activity. When *GENDEC* is brought into operation with *FullCAM*, it can replace the empirical decomposition routines which deal with the resistant decomposable fraction of each above-ground tree component embedded within either or both the *CAMFor* and *CAMAg* components of the model.

The inclusion of *GENDEC* within the NCAS suite of models, and its subsequent inclusion in *FullCAM*, arose from the recommendations of the International Review Panel of the NCAS (AGO, 2000b). The rationale of this recommendation was that the calibration to Australian conditions of a generic decomposition model such as *GENDEC* would allow for extrapolation and interpolation over a broad range of environmental situations and forest types.

A particular constraint to understanding of decomposition rates is that long-term field trials are not possible given the need to produce initial results for the NCAS by mid to end 2001. This period of time is far too limited to develop any long term temporal trials and only allows for the development rates of change in mass through chronosequence investigations. The inherent limitations that lie within that approach are recognised and will be addressed over time through long term trials.

The impact of invertebrate activities on the breakdown of debris is addressed within *FullCAM,* whereby the microbial decomposition of *GENDEC* is paralleled by a breakdown factor which can account for losses in above-ground litter due to factors such as macro-invertebrate activity. Root material is incorporated directly into the soil carbon pools, and therefore is subject to the decomposition activities of the *Roth C* component of the *FullCAM* model.

Roth C

The Rothamsted soil carbon (*Roth C*) model accepts pre-determined masses of plant residues which are then split into decomposable and resistant plant material. Required model inputs include the fractionation of soil carbon into various soil carbon pools, generally defined by classes of resistance to decomposition. Turnover rates for each fraction are determined by rainfall, temperature, ground cover and evaporation. The *Roth C* source code was made available to the NCAS in two versions, 26.3 and 26.5. Version 26.3 is the more recent ‘release’ version while 26.5 is a developmental version yet to be fully tested.

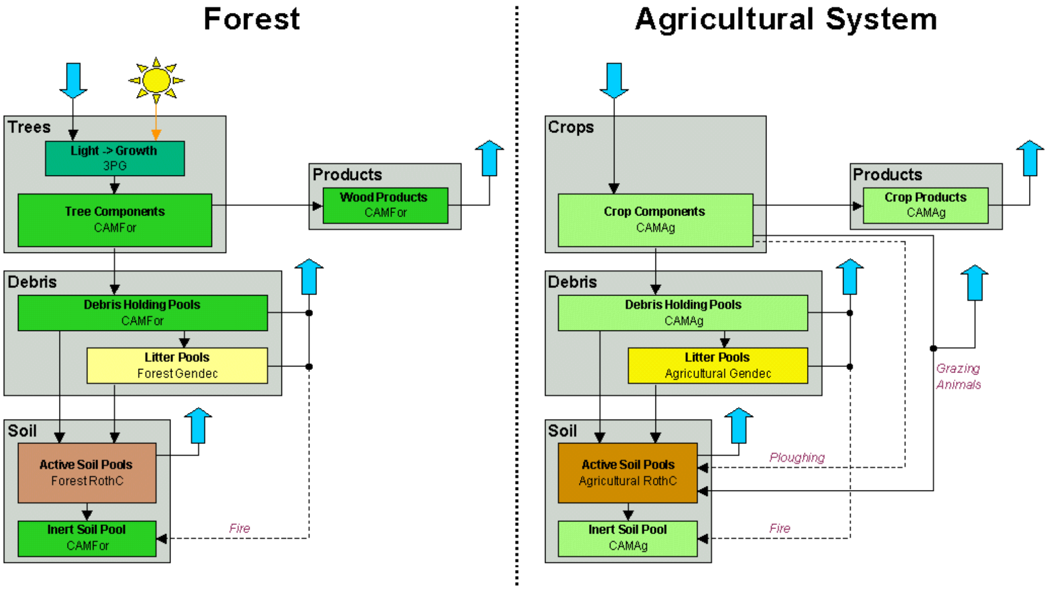
It is recommended that, if calibration data is available, then the *Roth C* model should be used in conjunction with *CAMFor*. It is a more robust soil model than the soil carbon routines contained within *CAMFor*. As calibration data is more readily available for agricultural systems, *Roth C* has already been directly integrated into *CAMAg*. *CAMAg* must be operated in conjunction with the *Roth C* model.

MODEL INTEGRATION

The initial integration was performed on a Microsoft Excel developmental version of the forest component of *FullCAM* and linked with the Excel versions of the models *3PG*, *CAMFor*, *GENDEC* and *Roth C*. The resultant developmental model named *GRC3*, was used to test and refine the linkages between the models. It formed a 10 megabyte Excel workbook, which could be used for developmental purposes, but was not a realistic option for general or routine application.

No equivalent developmental Excel version of *CAMAg* and its integration with *GENDEC* and *RothC* in the agricultural suite of models was created because the linkages in this integrated model would mirror those in the forest sector model being tested in *GRC3*. As the developmental work on linkages was not required specifically for the agricultural suite of models, and with the Excel based models being unsuited to general application, a decision was taken to move directly to the C code based application of the agricultural component of *FullCAM*. This is far more efficient and transportable (e.g., Mac, PC or Unix environments), and is capable of continental scale spatial application.

Figure 1. Overview of the *FullCAM* model



MODEL CALIBRATION

FullCAM provides a mix of accounting tools and empirical and process modelling. Many of the options are at the discretion of the user and reflect management decisions, such as forest harvest and ploughing. A further set of required inputs, particularly in *CAMFor* and *CAMAg*, determine the empirical rates of transfer between pools or to the atmosphere. Unlike the 'process' elements of the model, these components need to be user-defined, based on rates determined from sources such as field trial, literature or third party models.

The final components of the model are the process elements, generally contained within the *3PG*, *GENDEC* and *Roth C* model components. The distinguishing feature of the process and empirical components is that the empirical rates are static in that they do not respond to changes in environment. Each of the process components of the model (*3PG*, *GENDEC* and *Roth C*) are dependent on inputs such as temperature and rainfall in various ways.

Soil Carbon

Agricultural Soils

One of the most significant calibration exercises being pursued is that for the *Roth C* model in land clearing systems. A full description of this exercise can be found in the NCAS Technical Report No. 2 (Webbnet, 1999) and Swift and Skjemstad (1999).

The calibration (as opposed to preparing data inputs) is concentrated around defining the various soil fractions, and determination of rates of decomposition under a range of climates, soil types and management actions. Model calibration is largely provided for through a series of chronosequence paired sites and through changes measured in long-term field trials. Paired sites, independent of the calibration sites, are also being used to verify modelled results. There are a range of projects in place for the calibration and verification of the model. This includes approximately 70 new paired sites, sampled according to a standardised protocol (McKenzie *et. al.* 2000).

In addition to the soil pairs, soil fractionation is required to establish the inert, resistant and decomposable fractions of various soils. This project involves the analysis of soil samples from a variety of Commonwealth and State soil archives.

Related projects include the development of correction factors to standardise data to a single analytic method. The standard chosen for this project is the LECO dry combustion method. The results of this project are reported in the NCAS Technical Report No. 15 (Skjemstad *et. al.,* 2000).

Pre-clearing (initial) soil carbon condition is also a required model input. To obtain this, an extensive program involving various State and Territory Governments was coordinated by Webbnet Land Resource Services Pty Ltd for NCAS Technical Report No. 12 (Webbnet, in prep). The best available soil landscape units were mapped and attributed with the pre-clearing soil carbon condition according to the best available soil carbon data, supplemented with expert judgement to infer across soil types where no data is available.

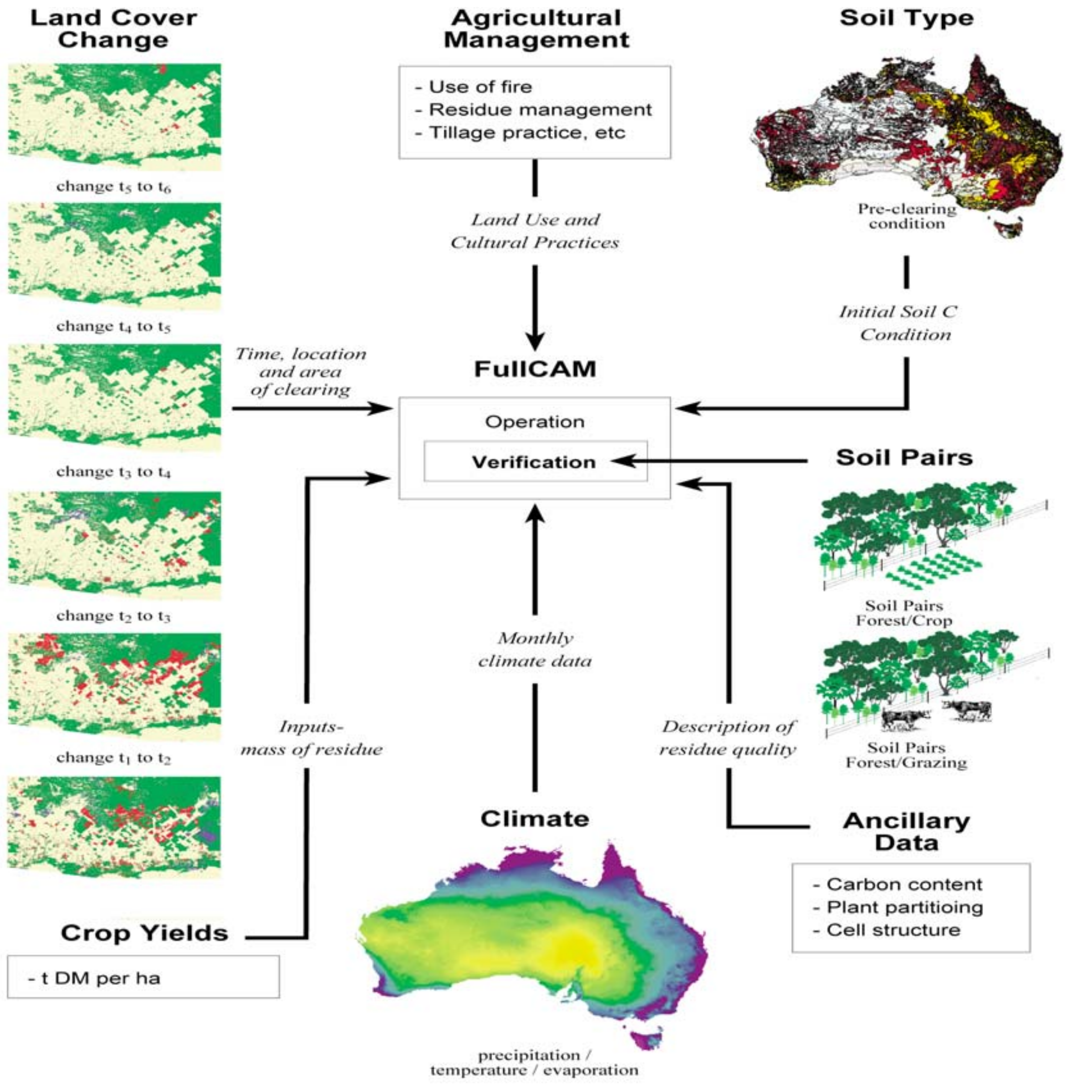
Various management actions are applied post land clearing and this is often closely related to soil type and climate. Acting for the NCAS, CSIRO Land and Water, through a variety of agents dispersed through the States and Territories, prepared a detailed report on the management actions (type and preparation) applied to various soil types for each land use within each Interim Biogeographic Regions of Australia (IBRA) (Thackway and Cresswell, 1995) over time intervals between 1970–2000 (Swift and Skjemstad, 2001).

This survey work by Swift and Skjemstad included estimates of the residue inputs for each activity over time. However, little information on pasture production was provided in this report and further yield modelling, plus the collection of yield data, will be carried out for the NCAS by CSIRO Sustainable Ecosystems using the *APSIM* model.

To provide climate data for a fine scale spatial operation of the *Roth C* model, monthly rainfall and temperature surfaces for the continent are being prepared. These monthly surfaces will cover the years 1970–2000 and be derived using the *ANUCLIM* software (McMahon *et. al.,* 1995)

The enormity of the information management task involved in presenting this data to a spatial model led to the development of the *CAMAg* component of the *FullCAM* model. The spatial components of the input data, rainfall, temperature, pre-clearing soils carbon condition can be automatically extracted as relevant to a particular grid. However, yield and management tabular information will need to be assigned according to a series of ‘rules’ to allocate various actions such as ploughing.

Figure 2. The Agricultural Soil Carbon Program



A series of long-term and ***Soil Paired*** *sites will be used in model calibration and verification. The* ***Land-Cover-Change*** *results will provide the time, location and area of clearing. The 'initial' soil carbon description for that location will be drawn from the* ***Soil Type Pre-clearing Condition*** *map. Monthly climate data/rainfall, temperature and evaporation will be extracted from* ***Climate*** *surfaces. Residue inputs will be estimated from modelled or measured* ***Crop Yields. Agricultural Management*** *information will be drawn from the tables of the NCAS land use and management survey.* ***Ancillary Data*** *such as carbon content, plant partitions, etc., will be drawn from a variety of sources. The FullCAM modules of CAMAg and RothC will be used in conjunction to model carbon budgets at a 1ha resolution, extracting information from the above-mentioned surfaces and tables relevant to each 1ha grid within a model run.*

Forest Soils

A program has also been developed for the modelling of soil carbon change under afforestation, reforestation and forest management. Conceptually, the program has many similarities to the previously described land use change soils program, relying on measured changes in long-term trials or differences between paired sites to calibrate and verify model results. However, there are some significant differences brought about by a need to understand more about above- and below-ground plant turnover (and the fate of each pool of material). These are far more difficult to quantify and there is a paucity of data compared to the residue estimation required for cropping systems.

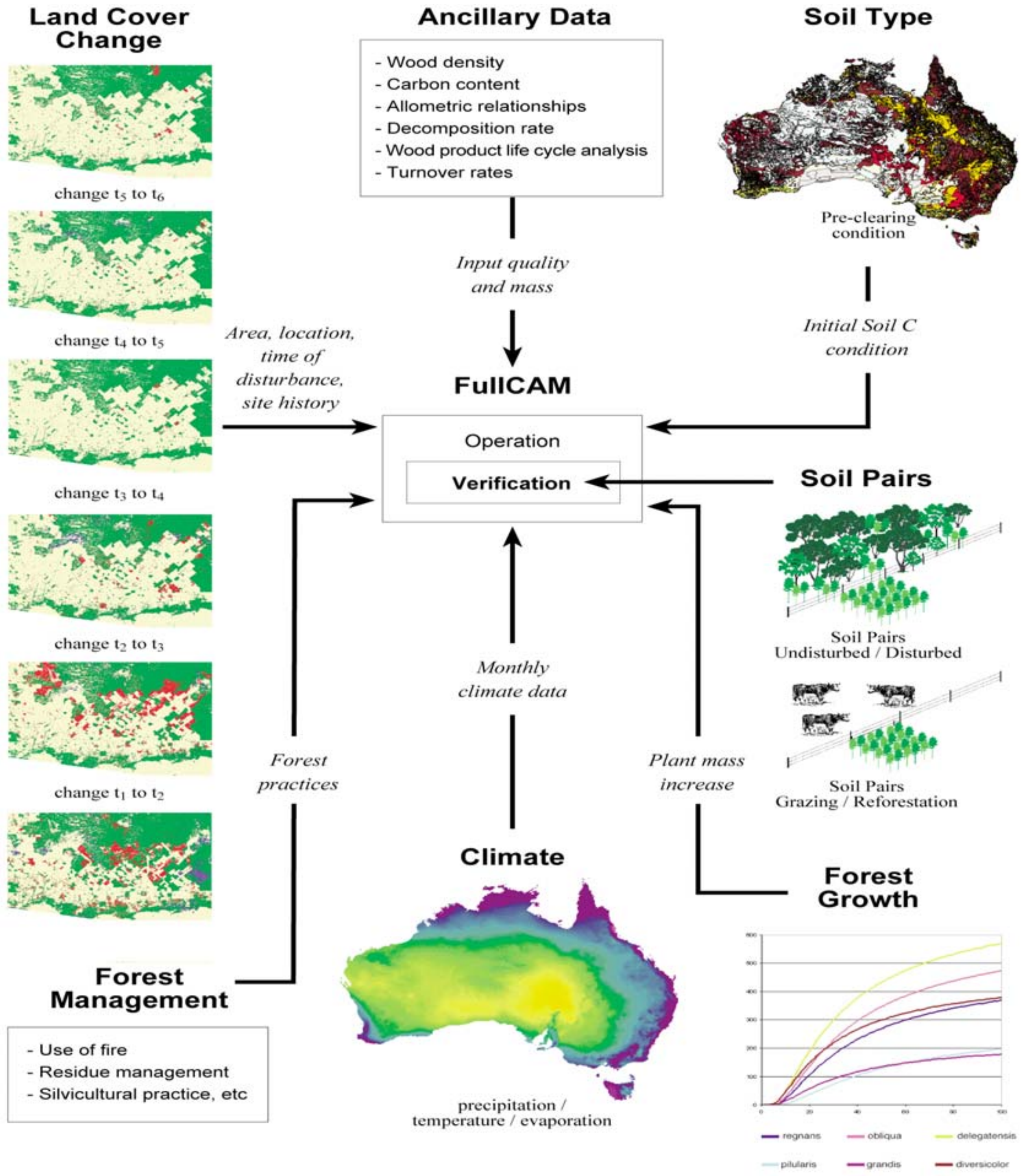
Another complexity is the fact that afforestation and reforestation systems may have many years in a transitional state between the residual effect of the original crop or pasture system and the eventual tree system (Polglase et. al. 2000). *FullCAM* has been designed to operate parallel agricultural and forest versions of soils and decomposition models in conjunction with *CAMFor* and *CAMAg* to allow for the separate calibration of models for each type of system. The proportion of the 'area' designated for agricultural and forest inputs will be determined on the basis of percent canopy. Outputs will reflect the 'lag' in changed input regimes and will be the sum of carbon attributable to each system. The proposed forest soil carbon program contains elements that will detect, via isotope analysis, the components of soil carbon input from C3 and C4 plants (non-woody, woody) in a variety of transitional (afforestation and reforestation) systems.

The forest soils program also contains proposals to determine the decomposition characteristics of coarse and fine litter to calibrate and verify the *GENDEC* model across a range of systems. In addition, the project contains elements of physiological growth modelling in order to derive rates of turnover of above- and below-ground plant material. This work will be carried out using the *3PG* model component of *FullCAM*.

Access to a 'whole-of-system' model like *FullCAM* provides an opportunity to model changes in soil carbon from growth, through turnover and decomposition within the one framework. Much of the calibration data for models provides considerable additional information and already exists through other, related NCAS projects. For example, the land use change soils project will provide pre-clearing soil carbon contents and soil landscape mapping, the 'condition' of soil at the time of transition from agriculture to forest use, the soil fractionation and rainfall and temperature data.

Work has already been completed for the NCAS carbon contents (NCAS Technical Report No. 7; Gifford, 2000a) and on C:N ratios of a variety of forest materials (NCAS Technical Report No 22; Gifford, 2000b). NCAS Technical Report No. 6, (Mackensen and Bauhus, 1999) provides a state-of-knowledge assessment on the decomposition of coarse woody debris. A set of three NCAS Technical Reports No.s 5a, 5b and 17 (Eamus *et. al*., 2000; Keith *et. al*., 2000; Snowdon *et. al*., 2000) are studies on allometry that provide assessments of the allocation of mass to various tree components. When combined with information obtained from a detailed forest management practices study (eg., post harvest burn, wood chip) this information will be capable of determining the amount of material entering litter pools due to forest harvest activities. The *CAMFor* components of the *FullCAM* model will play a needed information management role capable of interfacing the tabular and formula based information, such as allometric equations, with the *GENDEC* and *Roth C* model components.

Figure 3: The Forest Soil Carbon Program



*A series of long term and **Soil Paired** sites will be used in model calibration and verification. The **Land-Cover-Change** results will provide the area, location and timing of disturbances as well as site history. The 'initial' soil carbon description for the site will be drawn from the **Soil Type Pre-clearing Condition** map. Monthly climate data (rainfall, temperature and evaporation) will be extracted from **Climate** surfaces. Inputs will be determined via **Growth** estimates and turnover rates. **Forest Management** will be extracted from relevant NCAS surveys. **Ancillary Data** will be drawn from a number of sources. The FullCAM modules of CAMFor and Roth C will be used in conjunction to model carbon budgets at a 1ha resolution, extracting information from the above-mentioned surfaces and tables relevant to each 1ha grid in the model run.*

The final required element for the use of *FullCAM* within the NCAS soils work is the timing of the activity. This information can be drawn from the NCAS multi-temporal land-cover-change analyses. *FullCAM* will interface with the spatial layers (1ha grids) to determine the timing of afforestation, reforestation and deforestation events.

Biomass

As described in the approaches to biomass estimation for the NCAS (Richards, 2001) there are multiple constraints to consider in terms of accounting requirements. The following sections review approaches to data collation and collection and model calibration for the *FullCAM* model in response to this complex accounting requirement.

The most significant accounting requirement variation is that a continental account is the only requirement for the 1990 Baseline. This demands quite different data and methods from those used for the activity (project) scale accounting required post-1990. The following discussion describes the use of *FullCAM* as separate implementations for the 1990 and post-1990 accounting. Despite the differences in overall approach, there is much common data, and therefore considerable commonality in data sources and proposed programs.

Plantations

Carrying on from the work of the Forest Resources Committee (1989) the National Forest Inventory (NFI) has maintained a record of plantation areas by State (1995–99) and by region across State borders (1990–94). This record provides approximate age classes and areas of plantations from 1940. Since the work of the Forest Resources Committee, the record of plantation ages and areas (in total by region) has been maintained by periodic survey of public and private growers with estates of larger than 1,000ha. A report of these areas can be found in NFI (1997, 2000).

Turner and James (1997) developed indicative wood yield estimates for major plantation types and silvicultural regimes for each of the NFI's 14 regions. The AGO subsequently commissioned Turner and James (2001) to convert this information into current annual increments (CAI) for each possible permutation of plantation type, silvicultural regime and region. This included typical responses in growth and management to differing site qualities.

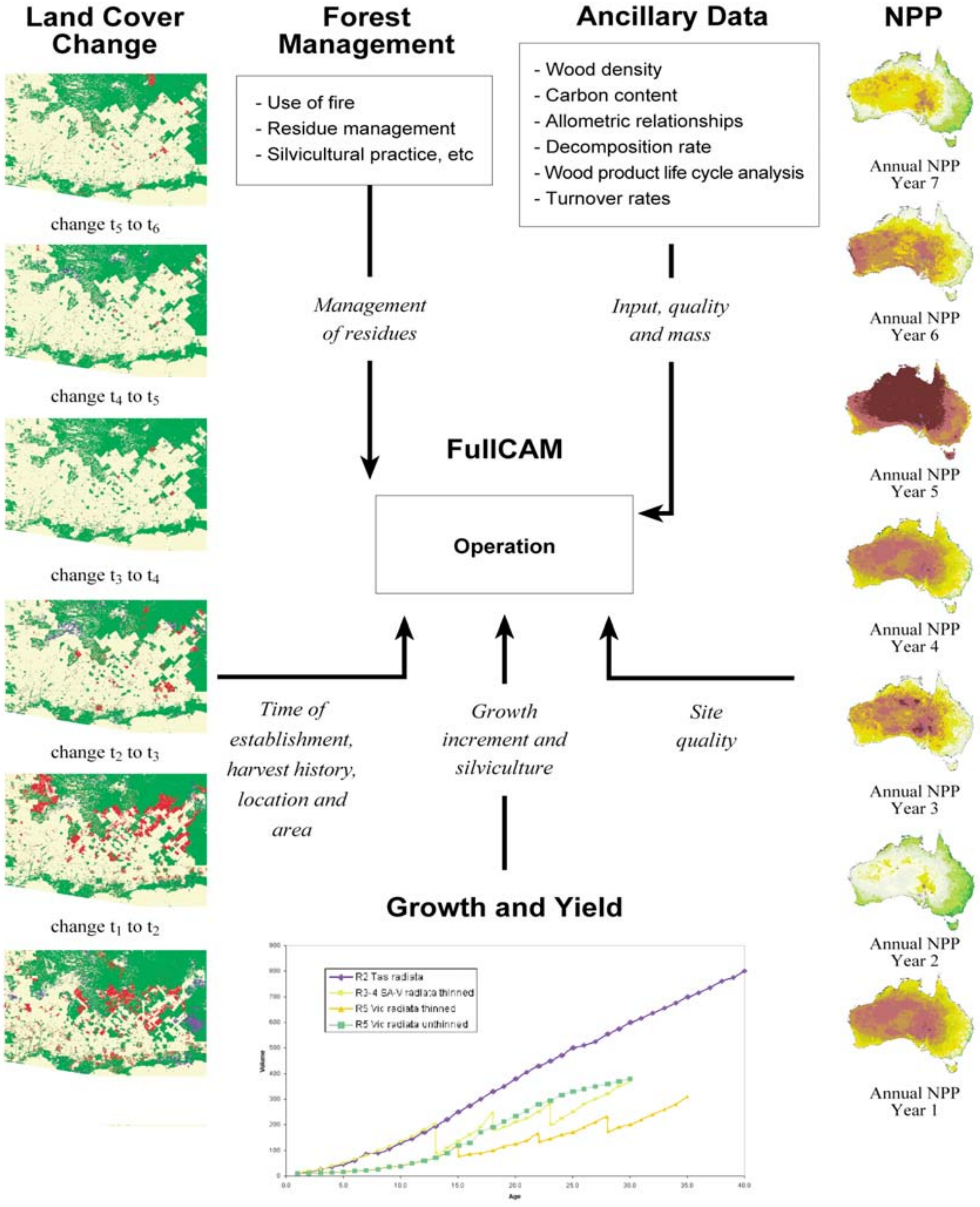
The indicative yields (CAI) of Turner and James (2001) and the age class and area data of the NFI were used as inputs to develop a national account for the plantation sector using the *CAMFor* (Excel version) of Richards and Evans (2000a), Brack and Richards (2001). This Excel version of the national account in *CAMFor* will be translated into the *CAMFor* component of *FullCAM* and provides the basis of a continental baseline estimate for 1990.

To develop this national model, considerable ancillary data, beyond that of age class, area, growth and silvicultural regime, is also required. Wood density information was drawn from the NCAS Technical Report No. 18 (Ilic *et. al.,* 2000) and carbon contents from the NCAS Technical Reports Nos. 7 and 22 (Gifford, 2000a and 2000b). Calculations for the ratios of commercial to non-commercial tree components were drawn from NCAS Technical Reports 5a, 5b and 17 (Eamus *et. al*., 2000; Keith *et. al*., 2000; Snowdon *et. al*., 2000)

The *CAMFor* based analysis of Brack and Richards (2001) represents the integration of the best available national understanding and state of knowledge on allometry, wood density, growth, carbon contents, and age and area of plantations and their management.

The greatest uncertainty in the areas of established plantations lies in the non-commercial species and areas belonging to estates of less than 1000ha that have not been considered in the NFI. These are largely environmental and small commercial plantings that form only a small component of the total plantation area and are generally slower to accumulate carbon than commercial species. Regional sub-sampling of the establishment of non-commercial species will be extracted from the NCAS remote sensing multi-temporal land-cover-change analyses. This will provide the area and age of plantings in a range of systems. The limited contribution of these types of plantings to the national carbon account, especially prior to 1990, would make full census (as opposed to sub-sampling) a potentially unnecessarily time consuming and expensive exercise (Turner *et. al*., 1999). To provide more resolution in terms of age of planting and areas of planting than is currently available, the age and area of commercial species (mostly coniferous pre-1990) will be extracted from the land-cover-change analyses. When prepared this enhanced information can be used in the national forest model developed by Brack and Richards (2000).

Figure 4. The Plantations Program



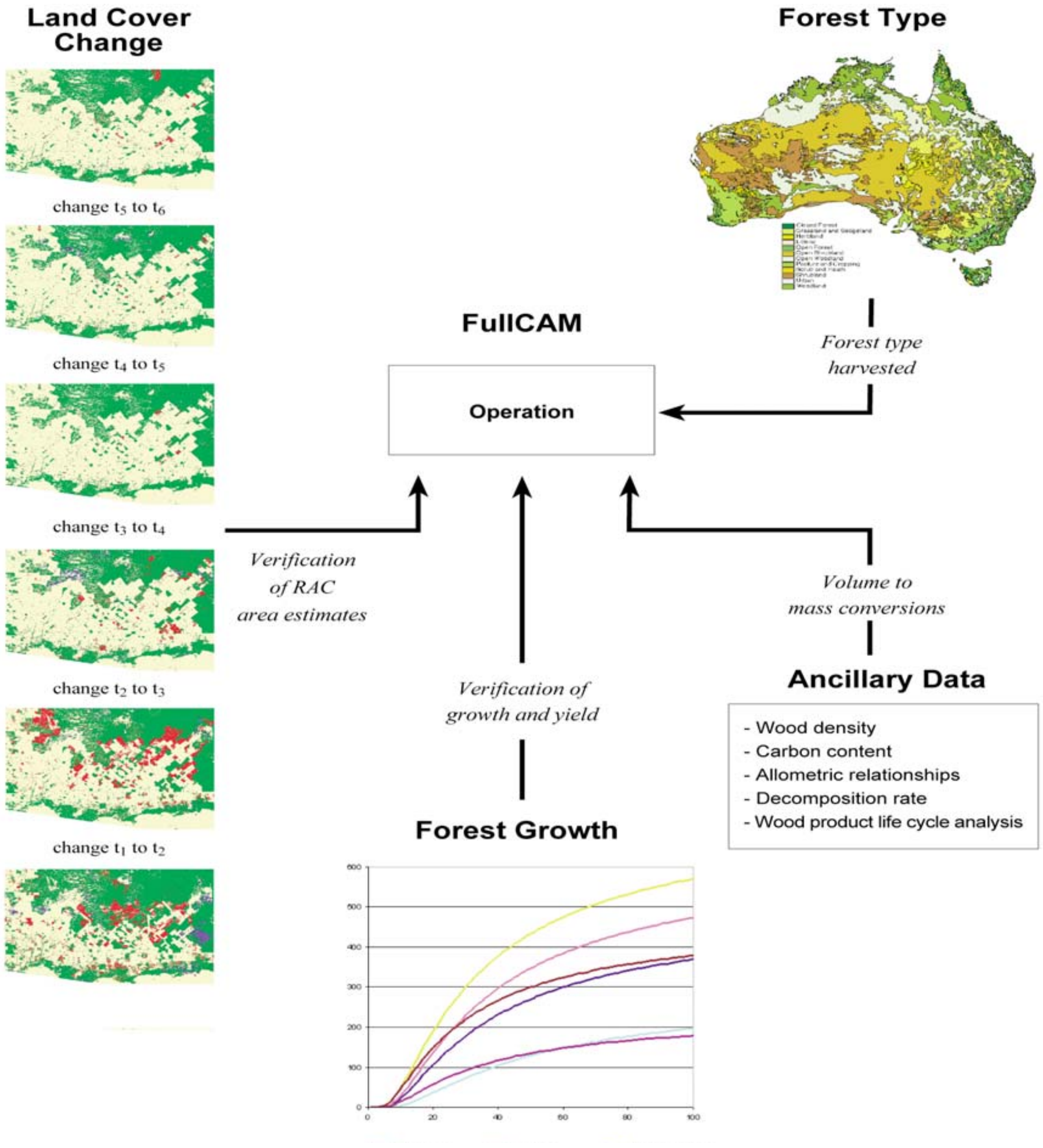
The time of establishment, harvest history, location and area can be taken from the ***Land-Cover-Change*** *results. Relevant site quality can be taken from the long-term (250m)* ***NPP Surface***. ***Growth and Yield*** *can be taken from the results of Turner and James (2000) and residue management from the* ***Forest Management*** *survey of the NCAS.* ***Ancillary Data*** *such as carbon content etc. can be drawn from a variety of sources. As soil carbon is not reported here, only the CAMFor module of FullCAM will be used.*

Managed Native Forests

Much of Australia's knowledge of native forests and their management arises from the work of the Resource Assessment Commission's (RAC) Forest and Timber Inquiry (1991). This represented a major national undertaking in the collection and synthesis of forest related information. Work was largely completed between 1989 and 1991, with the publication of results in 1992.

Information of particular importance to carbon accounting includes the areas, harvest intensities and growth rates of various commercially exploited forest types in each State and Territory. This information from the RAC has been combined with the ancillary data extracted from the same sources as presented in the preceding discussion on plantations. The *CAMFor* model (in its Excel version) was again used by Brack and Richards (2001) as the accounting base. This information, as contained in the Excel version of *CAMFor,* will be transferred into *FullCAM* for future implementation and refinement.

Figure 5. The Managed Native Forests Program



The RAC area estimates can be verified by the ***Land-Cover-Change*** *results. These areas by forest type can then be verified against forest type mapping such as the NVIS.* ***Forest Growth*** *estimates* *contained in the RAC reporting can be verified against available growth models.* ***Ancillary Data*** *will be drawn from a variety of sources.*

Land Clearing Biomass

The multi-temporal land-cover-change analyses currently being implemented by the NCAS will be able to identify the area, location and timing of clearing events between 1972 and 2000. To estimate the biomass at the time of clearing it is important to understand the rates of growth of various vegetation types in addition to the time of clearing and age since last disturbance or clearing.

The NCAS commissioned URS Consulting (with Landsberg Consulting) to identify and assess any available data on the growth in non-commercial species. Initially it was intended to consider the potential application of various stratifications and classifications into which to attribute generalised biomass increments. Surveys of experts quickly identified that site productivity, and not vegetation type, was the main determinant of rate of growth.

In a parallel project with URS (and Landsberg Consulting) and CSIRO (Drs Neil McKenzie and Nicholas Coops), the NCAS (through Dr Jenny Kesteven) undertook the development of a continental productivity surface (Landsberg and Kesteven, 2001) to test the possible derivation of spatial strata to guide the estimation or attribution of growth rates to various regions. The development of this productivity surface also allows for the application of techniques such as multi-phase sampling for the estimation of biomass at fine grid scales. This provides an alternate approach should spatial variability prove confounding to logical stratification and, therefore, to reliable stratified random or set grid sampling. The results of tests of spatial variability showed productivity to be highly variable over short distances. This spatial variability, combined with variability introduced by disturbance suggests the use of a multi-phase, continuous variable approach is required.

The potential stratifications tested for their utility were the Interim Biogeographic Regionalisation of Thackway and Cresswell (1995) and the Carnahan Vegetation Map (AUSLIG, 1990). In both instances it was found that the variation within strata was large enough that it would not be feasible to sample (for total biomass) enough sites to provide for a rigorous sample approach that was capable of removal of potential error introduced by undersampling or bias by, for example, selective sampling of the more productive components.

Following on from these findings the NCAS convened an experts workshop to consider other potential means of stratification at a finer scale and potentially more homogenous than those tested previously. A preference for a stratification based on vegetation structure, as the surrogate for total biomass, was put to the workshop.

The workshop, with a mix of expertise in remote sensing and inventory design among participants recommended that, in the absence of techniques to provide a consistent and relevant continental stratification in the short to medium term that would enhance existing stratifications, the NCAS adopt a multi-phase approach to biomass estimation. Multi-phase sampling represents a major departure from the stratified random sample approaches previously envisaged for use in the NCAS. It is a move away from the large forest inventory datasets (usually limited to merchantable volume and therefore requiring variable corrections to total biomass which introduces potentially significant bias), generally compiled via random sampling, to fewer high quality total biomass measures. It also provides a significant step forward in the spatial application of *FullCAM,* as both disturbance history and biomass estimation can be extracted from high resolution spatial surfaces.

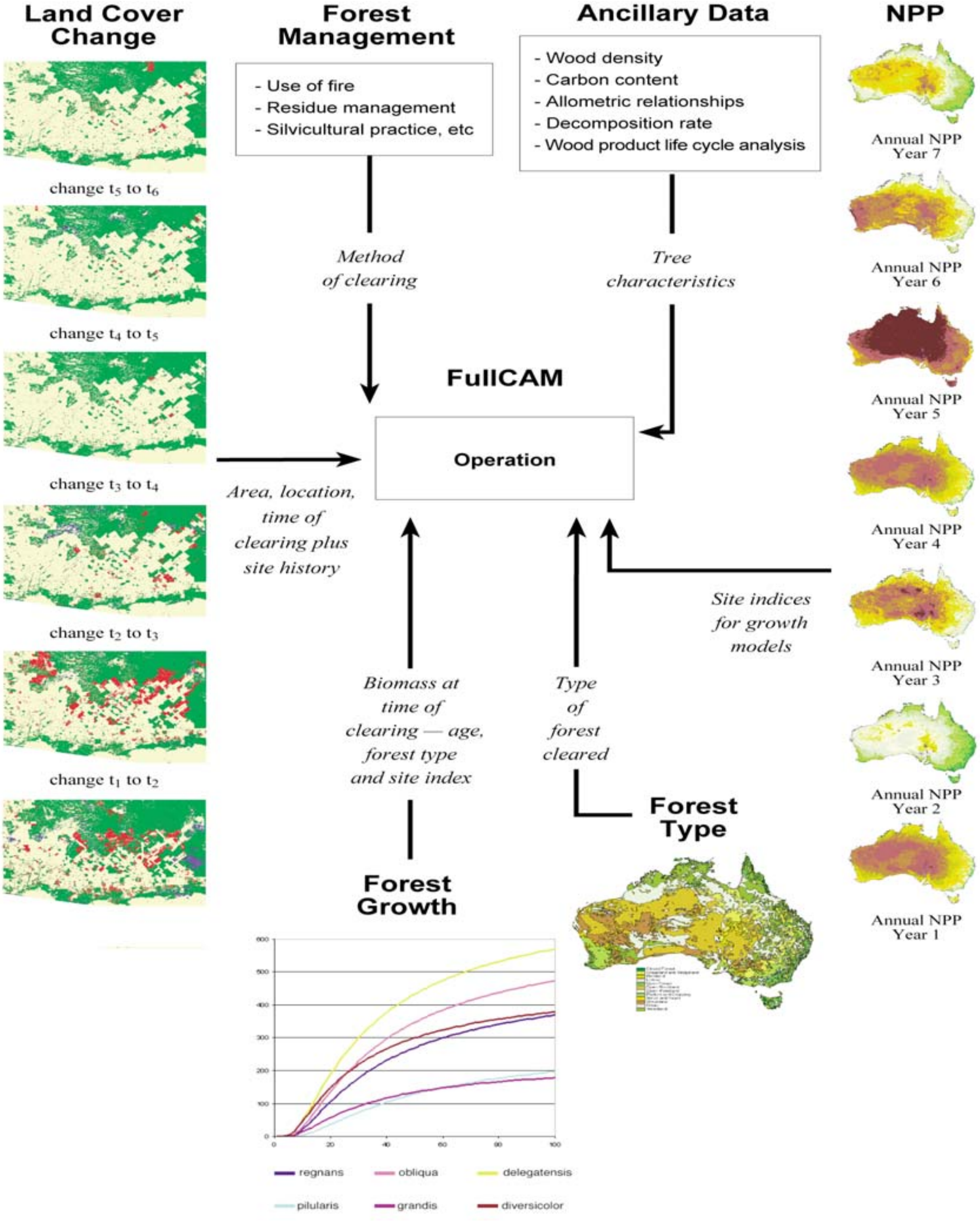
In response to the need for a grid-based continuous value productivity surface for multi-phase sampling, the NCAS has undertaken the development of a fine scale (250m) productivity grid. Unlike the 1km grid used in the initial analysis, which showed no response to slope and aspect correction for incoming solar radiation, it was presumed that slope and aspect correction is relevant on the finer 250m grid and a slope and aspect correction for solar radiation has been applied.

In multi-phase sampling, known reliable measures of total biomass can be located against known site values (of a continuous value variable) on the productivity surface. Through spatial regression techniques, it is possible to 'correct' the continuous index of productivity values across the entire surface against the known measures of biomass. Using this method, corrected indices of productivity can be developed for 'mature' forest systems. The age classes of sample locations are available from the NCAS multi-temporal land-cover-change program.

The availability of total biomass estimates across all woody vegetation systems, and the need for and potential to derive new total biomass estimates, was the subject of a further expert workshop and a program of recommended activities was derived (see Raison, 2001).

The age and intensity of disturbance can be extracted from the land-cover-change record and rates of regrowth can be derived using the productivity surface as described for regrowth forests. Appropriate growth equations, such as those of West and Mattay (1993) for regrowth forests, would need to be developed. These could be based on long-term permanent plots with known histories and calibrated against the land-cover-change record and the productivity surfaces.

Figure 6. The Land Clearing Biomass Program



The ***Land-Cover-Change*** *results can be used to identify the area, location and time of clearing as well as the disturbance history (which will give age of forest). The* ***Forest Type*** *can be used to select the appropriate* ***Forest Growth*** *model, which can be used to make a biomass estimate given age and site index (****NPP****).* ***Ancillary Data*** *can be drawn from a variety of sources, while* ***Forest Management*** *information is needed on method clearing, use of fire, etc.*

One of the main advantages of the use of a multi-phase sample approach is that modelling is carried out directly on total biomass and is not reliant on the potentially variable conversions from the merchantable volume or single tree measures to estimation of site (stand) based total biomass. Such conversions are much more variable than even those of total stem volume to total mass. The approach can also be extended across all forest systems, independent of vegetation type, whereas forest inventory information is likely to only be capable of sustaining commercial forest activity. This approach to biomass estimation is also independent of commercially sensitive merchantable volume estimates, which are required if an approach based on forest inventories is used.

Confirmation of the ability to apply multi-phase sampling across differing tenures (presumed to have different management regimes applied) was required. The effect of tenure on total biomass (through total volume) was tested by Brack (2001) using the Tasmania PI typing (Stone, 1998), which uses air photographs to stratify forest condition and inventory information on total volume from inventories of private and public forests. From the results of this work, Brack (2001) found that, while merchantable volumes vary by tenure, this variation could not be established for total volume. He concluded that the crown cover and height of the dominant eucalypts explained the majority of the variation in total volume, whereas tenure made no consistent difference.

The likely explanations for this are that there is a higher proportion of 'defect' trees in the private estate and that total biomass is determined by site productivity and not by management or disturbance (which is likely to vary by tenure). While management and disturbance may cause massive changes in wood quality, they do not impact on total stand stem volume and thus the manner in which crown and height is achieved. Because total biomass is largely unaffected by land use, multi-phase sampling can be applied independent of tenure. This is particularly significant given that inventory information for verification purposes on private tenures is very limited.

Key areas of improvement to enhance the current application of this approach to biomass estimation accounting for land use change are to:

- refine the modelling of plantations and native forests in *FullCAM* through improved inputs of allometry, density, carbon content, turnover etc.;
- assemble relevant total biomass data for multi-phase sampling and implement the proposed biomass sample program; and
- refine the 250m grid resolution productivity surfaces.

Additional work underway within the NCAS will also be useful in informing these approaches. These projects include:

- the development of a standardised protocol for the destructive sampling of biomass used to develop total biomass estimates; and
- descriptions of the management practices applied to various harvest and forest types since the 1950s.

Total biomass measures will also need to consider non-tree biomass in undergrowth. As suggested in the NCAS biomass sampling program, there is a need to develop appropriate correction factors to account for undergrowth components. Different corrections will need to be applied according to situation, which is likely to be defined by vegetation structure.

Forest floor litter can also represent a significant store of carbon. Litter generation, as post-harvest slash, depends on ratios of merchantable to non-merchantable material within harvested trees. Merchantable to non-merchantable ratios at the tree level are available for a range of forest systems.

Litter inputs arising from both tree mortality and branch and leaf turnover could, with the development of physiological growth models, be estimated. However, in the short term, coarse litter estimates will need to be derived according to survey of on-site litter masses and the application of empirical decay functions derived from chronosequence studies such as that of Mackensen and Bauhus (1999). More commonly, estimates of fine litter input and decomposition rates are made and these should be available.

As reported by Turner *et. al.* (1999), fuelwood is extracted from both private and public forests, and from scattered trees on agricultural land. This is likely to be a minor amount of material, almost always taken from already dead trees, thereby effectively only increasing the rate of decomposition through combustion. The suggested approach of Turner *et. al.,* of survey of fuelwood merchants, is likely the most effective method of addressing this issue.

Grazing Lands

The accounting for carbon change in woody vegetation in grazing lands (the grazed woodlands) needs to be able to identify both the agent of change and impact of change. It is useful to consider the points in terms of Articles 3.3 and 3.4 of the Kyoto Protocol. Under Article 3.3, change crosses a threshold which defines the condition describing forest or non-forest systems. These are the deforestation (clearing or re-clearing), afforestation and reforestation (establishment of a forest) events.

Article 3.4 does not require that a change (movement over a threshold) occurs, and considers the variability in a forest that remains a forest. Article 3.3 therefore tracks the change in carbon stock associated with a movement over a threshold definition of a forest, whereas Article 3.4 tracks changes in carbon stock within a system defined as a forest.

For woodland systems, the determination of ‘causes’ of afforestation, reforestation or deforestation as an initial ‘trigger’ activity to bring an area of land into the accounting framework is readily achievable from the multi-temporal land-cover-change program. As ‘fire’ events can also be readily identified, it will be possible to segregate this ‘natural’ cause of change from land clearing events. Regrowth post-clearing can be identified and, if the land is within the accounting framework, can be attributed to a change in biomass carbon. Two methods, using canopy- or age-based models, are feasible for the allocation of growth increment related models. However, early saturation of cover, at maximum detectable limits, means that this canopy based method is only appropriate for detection in early years.

The preferred approach is to use the multi-phase biomass sample for ‘mature’ systems to cap a maximum biomass capacity, and to then ‘grow’ the forest using age based growth trajectories with site indices determined from the annual productivity layers. This would require the use of site indice based growth equations with age determined from the multi-temporal land-cover-change analyses. To deal with incremental change (aggradation and degradation) from major identifiable disturbance it would be possible to establish canopy to mass relationships (which appear to be reasonable for sparse tree systems) and to then proportionally adjust the mass estimate. This adjustment is a relatively simplistic in approach but, with a better understanding of stand dynamics (their causes and impact on carbon density), it could be upgraded to respond to changes due to mortality, recruitment and tree ‘soundness’.

Wood Products

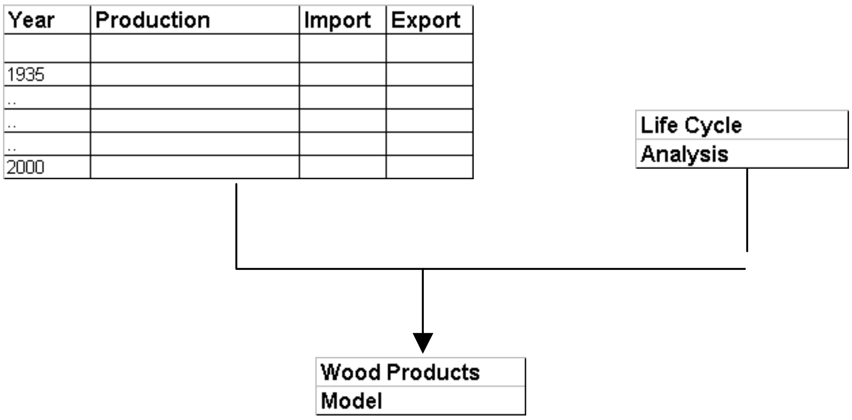
In 1999 the NCAS commissioned Jaakko Poyry to prepare a life cycle analysis of the Australian wood products sector (Jaakko Pöyry, 1999). This initial report considered only the 1998 wood product profile and provided the basis for further development of a time series wood products model. Later work between the NCAS and Jaakko Pöyry (Jaakko Pöyry, 2000) incorporated forest production data since 1944 into the life cycle analysis. This production data has been continuously and consistently collected and is currently maintained by the Australian Bureau of Agricultural and Resource Economics (ABARE, 2000). The data includes domestic production and import and export quantities.

The NCAS Wood Products Model, jointly developed by the NCAS and Jaakko Pöyry is a part of work investigating differing accounting options in the treatment of imported and exported materials. It is now a flexible and best practice model for the carbon accounting of wood products, constructed as a transparent sheet based and formula driven (no macros) Microsoft Excel spreadsheet model.

Along with the published input data, life cycle analysis and report on model development, the model provides a robust and transparent approach to accounting for wood products at a national level.

The life cycle analysis has been adapted to the *FullCAM* model wood products accounting component to provide mechanisms for wood product accounting at a project scale.

Figure 7. Wood Products



MODEL VERIFICATION

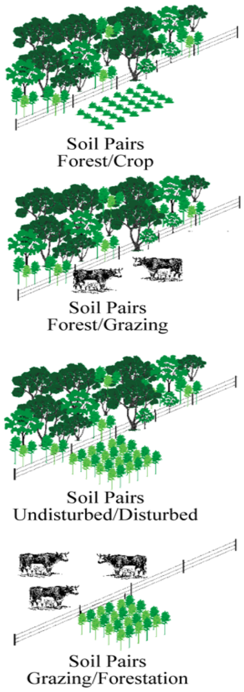
Programs undertaken for model verification are largely independent replicates of programs undertaken for model calibration. The principal difference between calibration and verification is that the ongoing verification can draw information from long-term (permanent) plots, either established or adopted as part of the program. Calibration, on the other hand, has been largely restricted to previously available, long-term and paired, chronosequence studies. Data used for model verification will be completely independent of that used for model calibration.

The various verification activities include permanent plot, long-term trials with internal measurement, landholder survey, ongoing chronosequence pairs activity, and comparison with other reliable, independent methods and models.

Any verification sites or data that may in future be used in model calibration or operation will be deleted as part of verification activities. Thus, the ongoing monitoring activities of the operational program will be able to use the verification sites and data as properly independent tests.

Figure 8. Verification Activities

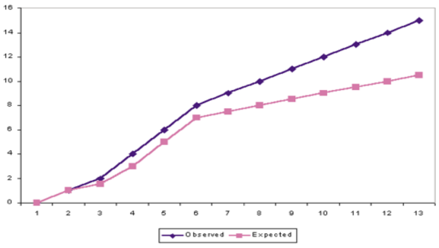
Chronosequence Set
Pairs as model targets



Long term measurement to validate
growth model results

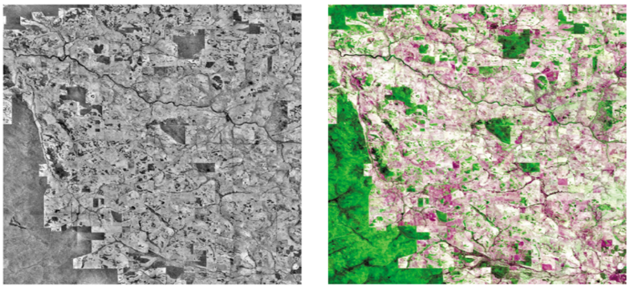
Ongoing survey of management activity

Verification of models
against measured data



Chronosequence decomposition studies

Air photographs used to verify
satellite interpretation



air photograph satellite image

CONCLUSIONS

To meet its objective of providing a comprehensive carbon accounting and projections capacity for land based activities, the National Carbon Accounting System has required the strategic development of several key datasets and modelling and accounting tools. Early reviews made it clear that approaches based on measurement were infeasible and that the calibration of relevant models would be required.

A series of programs were put in place to provide the input data and model calibration and verification to support fine resolution national scale accounting. These programs have been largely independent, although the need to integrate an overall information system was recognised (NCAS Technical Report No. 21, 2000a).

The development of the integrated *FullCAM* model has furthered this synthesis by providing an ability to operate a singular centralised model. This avoids the potential for errors of omission or double counting that could arise from multiple carbon pools and transfers being accounted for independently and subsequently summed, with little opportunity for reconciliation across or between pools.

FullCAM provides the capacity for national scale modelling at a fine spatial resolution (grids) of 1 hectare. Prior to the development of *FullCAM* it was anticipated that the NCAS would operate on a series of regional strata with a set of conditions derived by the intersects of layers of spatial data. The ensuing array of conditions and polygons defined by the intersects would then have been allocated a 'best-fit' time course of carbon change from look-up tables of pre-derived model results.

This initially envisaged approach relied on the use of averaged model inputs (conditions) over both space and time. Testing indicated that there was likely to be both a loss of resolution through averaging data and potential for 'spurious' results formed by the unrealistic arrays of conditions generated by averaging the data. This highlighted the need for an integrated model framework capable of operation at a fine grid scale, and accelerated need for the development of the *FullCAM* model.

While the approach taken in *FullCAM* relies on data of mixed resolutions, the use of such a comprehensive framework allows for strategic testing of potential improvements and development of finer resolution inputs in various data elements.

However, probably the most significant impact of *FullCAM* is that it allows for an ongoing evolution in the quality of any data inputs, be they for future accounting periods or improvements in fundamental input data or model calibration. Such ongoing improvements were not as readily made under the regional approaches envisaged formerly.

FullCAM also provides for greater responsiveness to the various reporting demands under the Kyoto Protocol. The fine spatial resolution, activity-driven and time-based modelling provides a capacity to report at both project and continental scales, in response to specific activities, and with sensitivity to the timing of an activity.

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Development of a 'Toolbox' for Carbon Accounting in Forests

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ABSTRACT

The National Carbon Accounting System (NCAS) of the Australian Greenhouse Office has joined with CSIRO and the Australian National University's Department of Forestry to prepare a 'toolbox' for carbon accounting in forests. The toolbox will represent an evolving 'best practice' approach and available data and will be made available as a public domain product.

The central carbon accounting model will be the *CAMFor* (carbon accounting model for forests of Richards and Evans 2000). Much of the data needed to operate the model has been collected for the NCAS and is reported in the NCAS Technical Report Series. As a part of the development of the toolbox this information will be extracted and placed into a single compendium default data table.

Other elements of the toolbox will include descriptions of appropriate methods for the gathering and analysis of field data. These measurement guides have largely been completed as agreed protocols and have been published in the NCAS Technical Report Series. The final element of the toolbox will describe appropriate methods for risk and uncertainty analysis.

Risk and Uncertainty in a Forest Carbon Sequestration Project

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ABSTRACT

The prediction of the quantity of carbon sequestered during the Kyoto Commitment Period (2008-2012) is subject to uncertainty and risk. This presentation uses CAMFor to model the sensitivity of the estimated sequestration of carbon to uncertainties in growth models, relative allocation of biomass increment, weather, decay of litter, debris and soil carbon, and harvesting of wood products. The uncertainty in wood density, equations used to predict tree growth and in the expected weather are shown to be highly influential in the uncertainty of the overall estimate of sequestration. Uncertainties in the relative allocation to leaves, twigs and bark are shown to be less important. Management decisions on the intensity and timing of harvesting and establishment regimes are subject to risk as they depend on political and unpredictable considerations. The decision to harvest or not will introduce more variance into the prediction of carbon sequestration than does the uncertainty that surrounds the estimates of weather and model estimates.

Keywords: Carbon sequestration, sensitivity, risk, carbon accounting model, Kyoto Commitment Period

INTRODUCTION

Commercial organisations are increasingly interested in potential investment in forest plantations as a means of offsetting carbon emissions. These investors need to weigh up the potential value of future carbon credits and other products against the cost of plantation establishment and maintenance. However there are uncertainties and risks associated with the estimation of the quantity of carbon sequestered in a plantation and these need to be considered before optimal investment decisions can be made.

Risks in carbon estimation are introduced by sampling errors around inputs, coefficients and model parameters - multiple estimates around the 'true' value with known (or reasonable) probability density functions. Uncertainties on the other hand, include an unknown range of outcomes for which there is no reliable probability density function. Uncertainty is introduced into investment decisions from external sources, like changes in the desired state or in the specifications of returns, new management orientation or the preference function. These changes do have probability functions associated with them.

An estimate of the quantity of carbon sequestered during the first Kyoto commitment period (2008 - 2012) incorporates a number of sources of risk and uncertainty. These sources may impact directly and indirectly on the estimates as they interact with each other. The uncertainty is extremely difficult to quantify and investors often try to minimise potential impact by diversifying to cover a range of preference functions. Simulation models, incorporating the best probability density functions and interactions available, are commonly used to investigate the impact of risk on investment decisions. This presentation summarises the derivation of appropriate probability density functions, sources of risk, and a sensitivity analysis model for estimating carbon sequestration in the first Kyoto commitment period.

METHOD

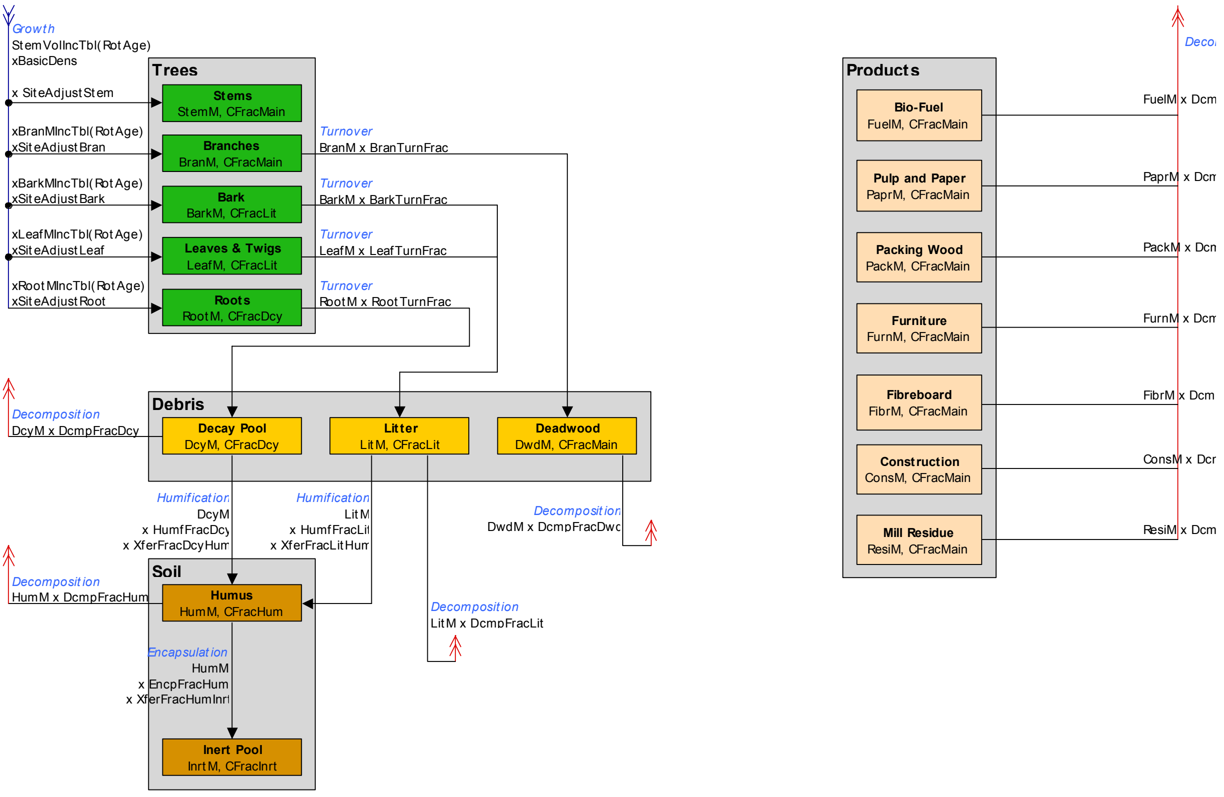
CAMFor - Carbon Account Modelling for Forests - developed by Richards and Evans (2000) was used to provide the sensitivity model framework. CAMFor tracks carbon equivalents in and through various pools on an annual basis:

- Biomass (stem wood, branches, bark, fine and coarse roots, leaves and twigs)
- Soil (active humus and inert charcoal)
- Debris pool (coarse and fine litter, below ground dead material)
- Products (dead wood, sawn timber, paper, biofuel, reconstituted wood products)

The user provides an estimate of the current annual increment (CAI) and the relative distribution of this increment to the stem wood, branches, etc. This is most commonly achieved by a predictive model of the annual stem-wood growth in volume and a series of coefficients and ratios to convert volume into carbon mass and relative growth of the other biomass pool components. Transfer or turnover of the carbon between the various biomass pools and the soil, debris, product pools and atmosphere is modelled by user nominated ratios that reflect death, decay, fire and product harvest (Figure 1). The pools and transfers can be tracked through thinnings, multiple rotations and fires.

Best estimates of the CAI, conversion and turnover coefficients for a medium site quality plantation of Eucalyptus grandis (flooded gum) were drawn from the literature. Realistic probability density functions and correlations were also drawn from the literature and the author's experience as the basis for the sensitivity analysis. These probability density functions were embedded into the CAMFor spreadsheet using @Risk probability density variables (Palasade Corporation, 1997).

Figure 1: Schematic of CAMFor



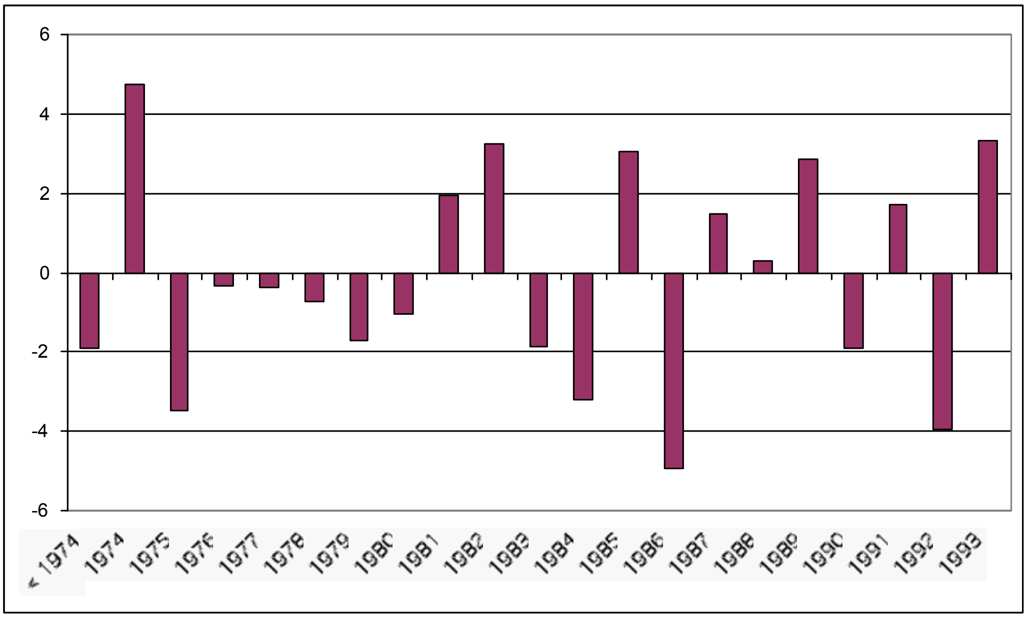
STEM-WOOD INCREMENT

The CAI (m3/ha/yr) for the stem-wood increment of initial or base model was based on the growth model developed by West (1999). It was assumed that this model was an unbiased estimator of the stem volume growth for a medium site quality over a full rotation of 30 years.

Sensitivity to the correct determination of site quality and growth model parameter estimation was modelled through the introduction of six @Risk probability density variables - model-1991, -1996, -2001, -2006, -2011 and -2016. The model1991 correction was applied to the 5 years of growth between 1991 and 1995, model1996 the next 5-years, etc. These variables were defined as a triangular probability density function with minima and maxima estimated as the ratio of average growth between a medium site quality plantation and a plantation of the same age but one site quality class lower or higher.

Temporal variations, for example caused by patterns in the weather, could cause a model to have localised bias and imprecision even though the overall rotation estimates were unbiased and relatively precise. An examination of the differences between the modelled growth and inventory-based estimates of change for Pinus plantations in NSW between 1974 and 1993 demonstrated these localised problems (Figure 2). For any 5-year period, the coefficient of variation for the difference between the modelled and the inventory-estimate of growth was about 18%. However there was a consistent pattern in the localised bias for these 5-year intervals - if one 5-year period grew below the average modelled increment, then the next 5-year period was likely to grow at above the average. To model this variation, six @Risk probability density variables - weather-1991, -1996, -2001, -2006, -2011 and -2016 - were developed. These variables were used as multipliers to the base model for consecutive 5-year periods. They were defined as being normally distributed around 1.0 with a CV of 18%. Every second variable was also weakly and negatively correlated with the preceding variable, thus an overestimate in the first period would be 'balanced' by an underestimate in the next period.

Figure 2 Differences between model-based prediction of growth and change in sampled inventory demonstrating localised bias and imprecision.

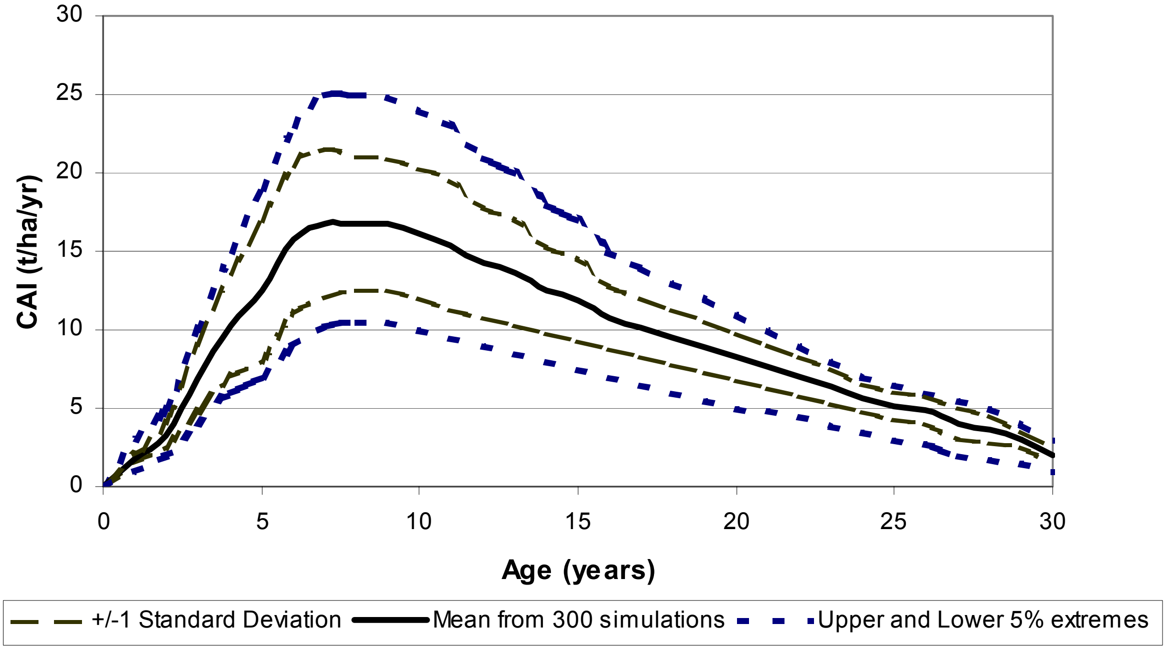


Density and Carbon Content

Base-case density data for plantation grown E. grandis, provided by State Forests of NSW, is 500 kg / m3. Greenhill and Dadswell (1940) indicate that the CV% in density across stands is in the order of 11%. Therefore density sensitivity is modelled by an @Risk variable - Density - with a normal distribution, mean of 500.0 and a standard deviation of 56. This analysis assumes variation in carbon content within the biomass is incorporated in the density variation.

Figure 3 summarises the mean and sensitivity range for the annual increment of stem-wood mass of the representative E. grandis plantation.

Figure 3: Annual increment in stem-wood mass (and sensitivity range) modelled *E. grandis* plantation**.**



Allocation of biomass between pools

Allocation of growth to branches, bark, twigs, leaves and roots (fraction increase relative to stem increase) was based on data derived from coefficients used in CO2Fix (Mohren et al 1990). These fractions were ratio adjusted so that the derived expansion factor (total above ground mass divided by stem mass) and root:shoot ratios agreed with the mean values reported by Snowdon et al (2000). The @Risk variables for modelling were modelled iteratively using variables - Expansion1991 - Expansion2016 and Root1991 - Roots2016 - that adjusted the allocation in 5-year periods for the above- and below- ground components respectively. The @Risk variables were defined as a triangular distribution with mean of 1.0 and minimum and maximum iteratively selected to mimic the range of expansion and root:shoot values reported by Snowdon et al (2000) (Figures 4 and 5). The distributions are weakly correlated with the corresponding weather variable when the weather distribution indicates above average stem growth, there is also likely to be above average growth of leaves, twigs and bark, but a below average growth of roots.

Figure 4: Expansion factors (and sensitivity range) modelled from CAMFor allocation and @Risk variables

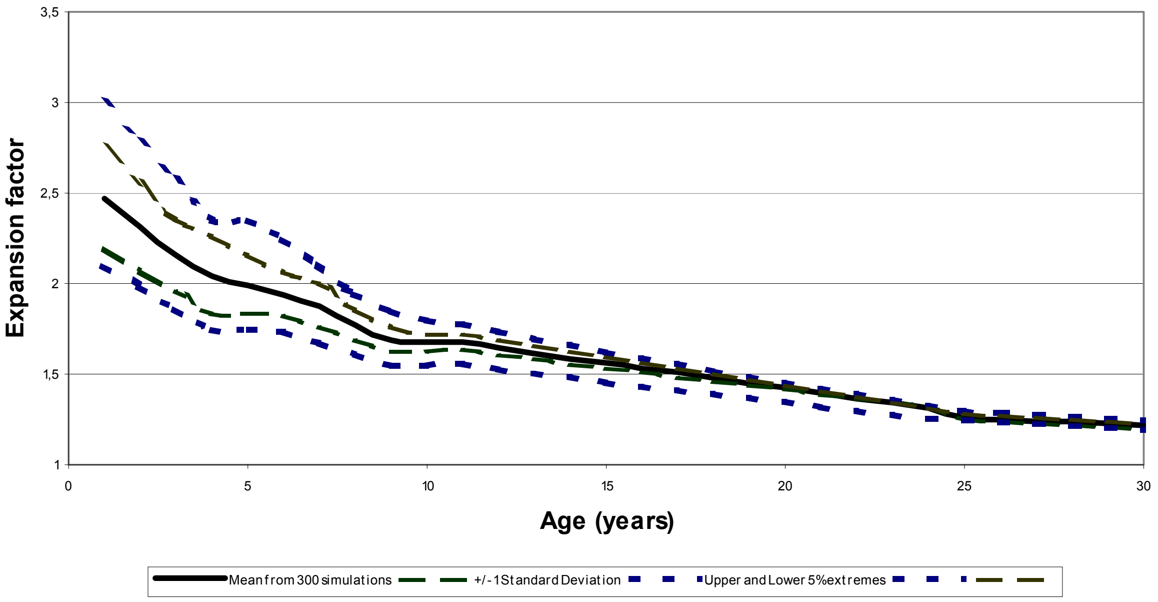
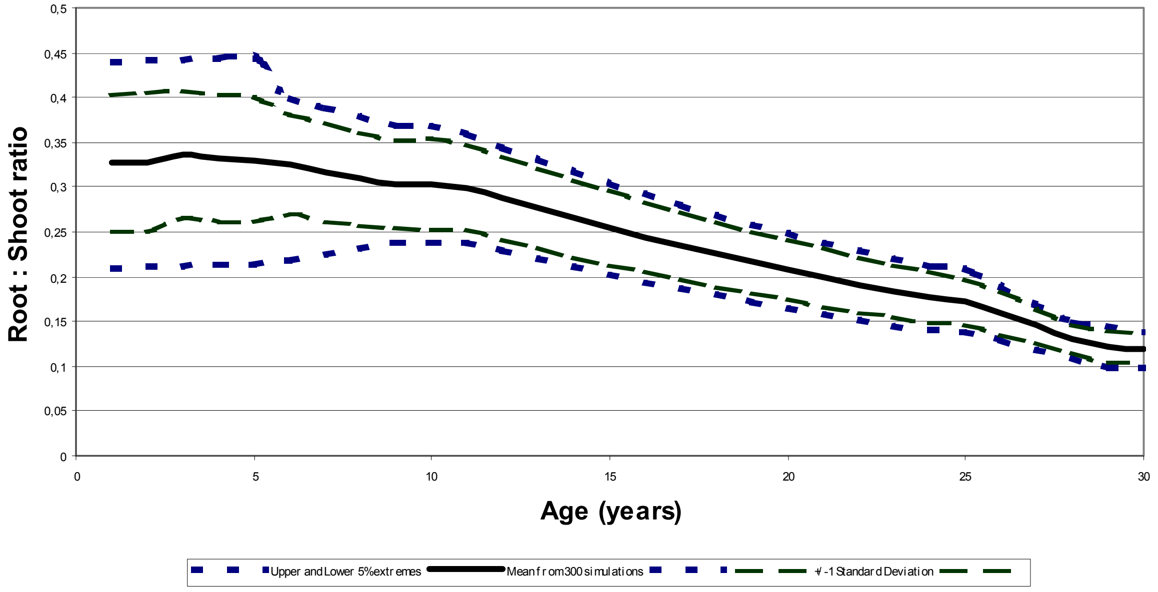


Figure 5: Root:Shoot ratios (and sensitivity range) modelled from CAMFor allocation and @Risk variables.



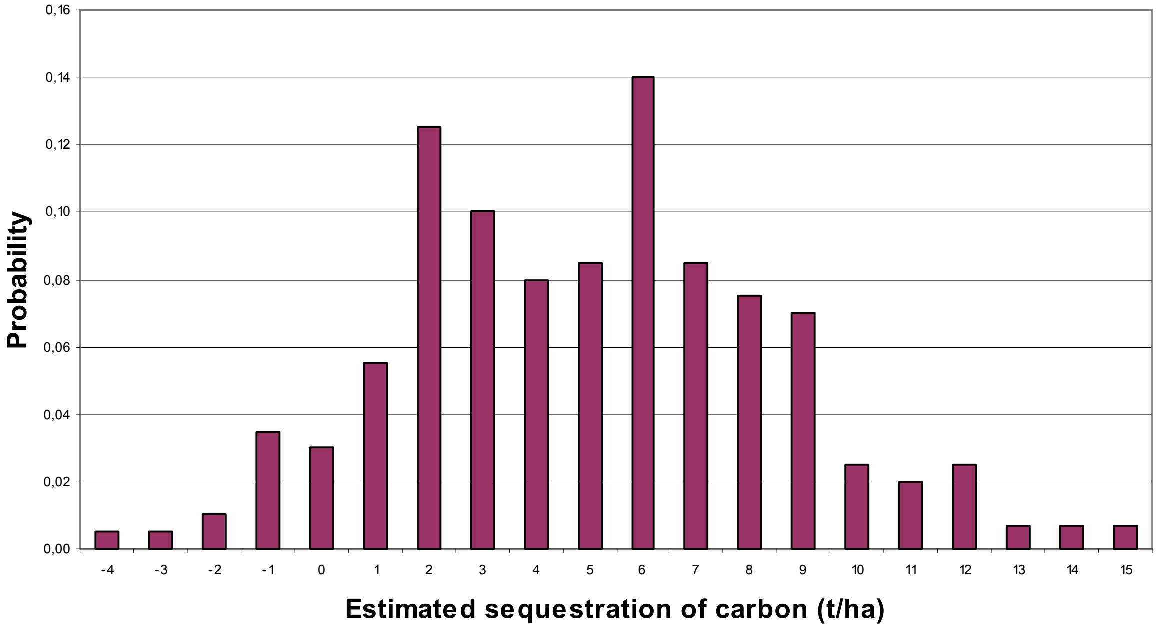
Soil carbon pool

There was little data available on the soil carbon pool for Eucalyptus plantations in northern NSW. Suggested values estimated by State Forests of NSW were that the soil carbon at the start of a rotation would be about 200 t/ha (varying between 100 300 t/ha), reducing by about 10% over the 5 years after conversion, after which it would reach a steady state. This was modelled using two @Risk variables with triangular distributions: Soil modelled the initial soil carbon pool size and had mean value of 200 with a minimum and maximum of 100 and 300 respectively. Soil-Chg modelled the annual fraction of soil carbon that remained in the soil for the first 5 years with a mean, minimum and maximum values of 0.97, 0.94 and 1.0 respectively.

RESULTS AND DISCUSSION

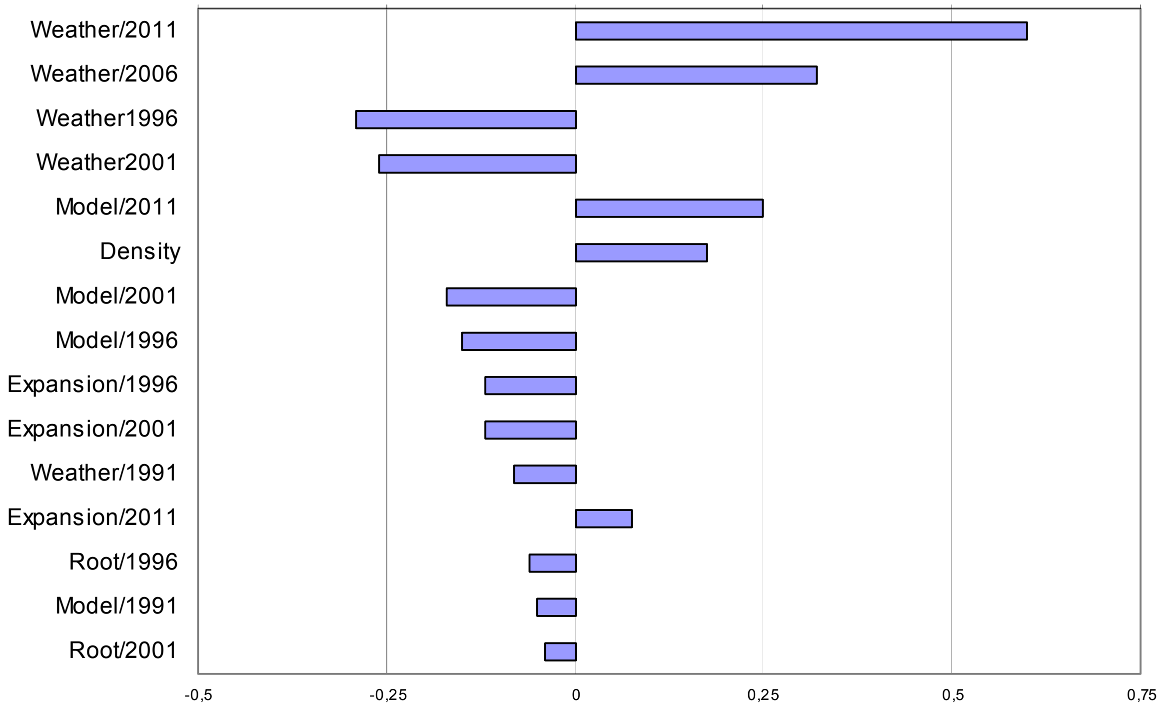
An initial sensitivity analysis was consisted of 300 simulations using the @Risk probability variables and a 1 ha plantation established in 1990. This plantation was assumed to be on 'bare earth', ie the initial biomass, litter and product pools were empty, The output of interest was the mass of carbon sequestered by this plantation during the Kyoto commitment period, 2008-2012 (Figure 6). The frequency distribution is distinctly bimodal which may reflect the weather pattern introduced by the assumptions of negative correlation between consecutive 5-year periods. A small fraction of simulations predicted an emission of carbon as more mass decayed than was sequestered during the Commitment Period.

Figure 6: Frequency of estimates for the net carbon sequestered (t) during the Kyoto Commitment Period by 300 sensitivity simulations of a 1 ha Eucalyptus plantation.



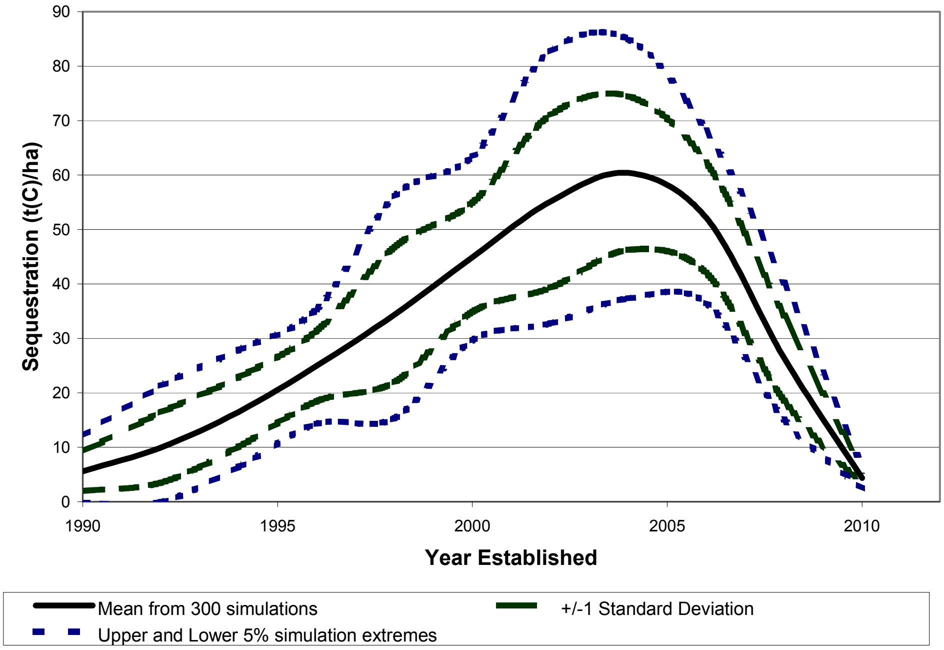
A tornado diagram (Figure 7) which ranks the strength of the correlation between the @Risk input variables and the carbon sequestered supports this idea. The most influential @Risk variables were weather2006 and weather2011 - if the weather promotes above (below) average growth during the Kyoto Period, the amount of carbon will increase (decrease) from the mean estimate. The weather variables prior to the Commitment period were negatively correlated - above average growth caused by "good" weather in 1996 - 2005 is correlated with smaller amounts of carbon being sequestered. This negative correlation may be due to the increased mass of leaves and twigs being produced prior to 2008, which subsequently decay and emit carbon during the Commitment period. Density and growth model estimates were the next most influential variables. The influence of risk in the allocation of growth to the leaves, twig, branches and roots was relatively unimportant with a correlation coefficient of less than 0.2.

Figure 7: Tornado diagram of correlation between input variables and carbon sequestered during the Kyoto Commitment Period.



A series of sensitivity analyses for plantations established between 1990 and 2010 indicates that the carbon sequestered in the biomass tends to increase to a maximum when established between 2002 - 2006 (Figure 8). This corresponds to plantations that will be about 5 to 10 years of age during the Commitment Period, which is the age range where CAI is at a maximum (Figure 3). Note also that the distribution of estimates is not equal around the mean - the upper 95% range is further from the mean than the lower 95% range.

Figure 8: Summary of carbon sequestered during the Kyoto Commitment Period in the biomass of plantations established between 1990 and 2010.



Routine management would allow a partial harvest or thinning for this type of plantation at age 12 years. Upon thinning, about 50% of the aboveground biomass pool would be turned over to debris or product pools. The impact of this thinning on the carbon sequestered depends on how close it is to the Commitment Period (Figure 9). A plantation established in 1996 and thinned in 2008, for example, would emit a large amount of carbon during the Commitment Period as the thinning debris and products harvested have their maximum rates of decay immediately after the operation. However this emission is balanced by the net growth of the plantation during this period. Plantations established earlier and therefore thinned before 2008 do not emit as much carbon from the remaining debris and product decay during the Commitment Period, but nor do the trees grow as fast.

A final simulation examined the carbon sequestration of a 5,500 ha estate of E. grandis where 500 ha were planted every two years from 1990 onwards (Figure 10). The emission of carbon from the soil is only significant for plantations established within 5 years of the Commitment Period. Age classes established in about 2002 to 2004 appear to maximise the sequestering of carbon. These plantations are growing relatively quickly, do not emit any carbon due to losses incurred due thinning and may only loose a minor amount of carbon from the soil. Age classes thinned within the Commitment Period may be net emitters of carbon due to their relatively slow growth and high quantities of slash and wood product. However there is a chance that even these plantations could requester significant quantities of carbon if the weather conditions during the Commitment Period are favourable. Age classes established at the end of the Commitment Period are likely to be net emitter of carbon as the soil carbon is released.

Figure 9: Impact of thinning on carbon sequestered during the Kyoto Commitment Period by biomass, debris and wood products

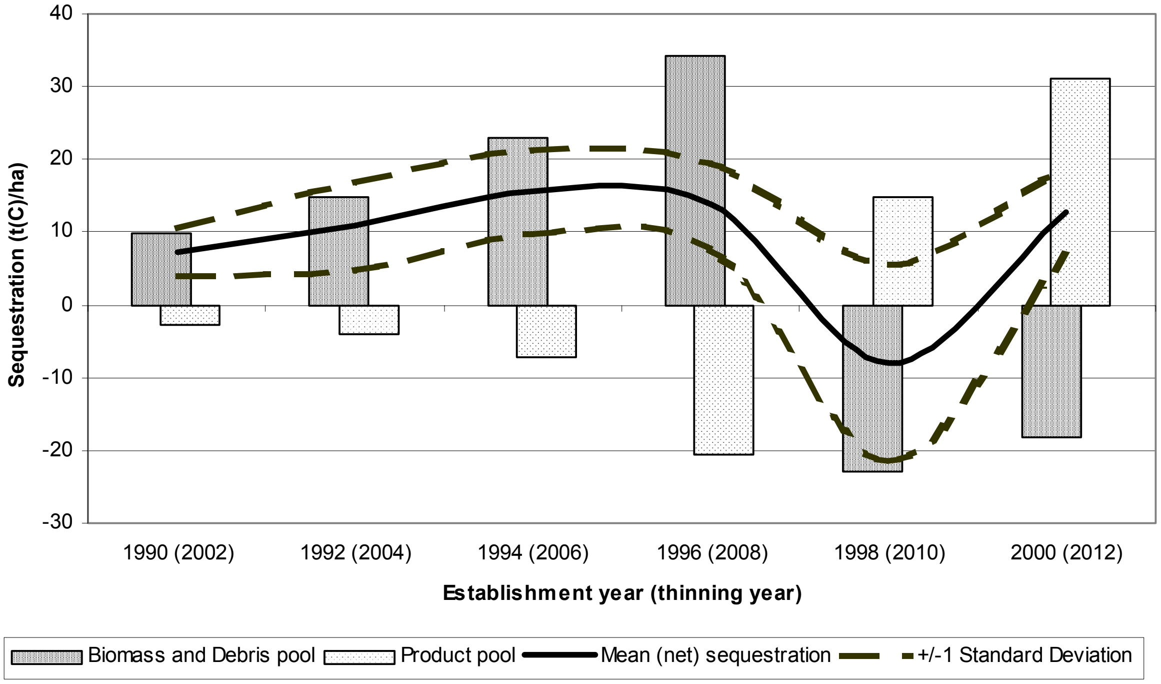
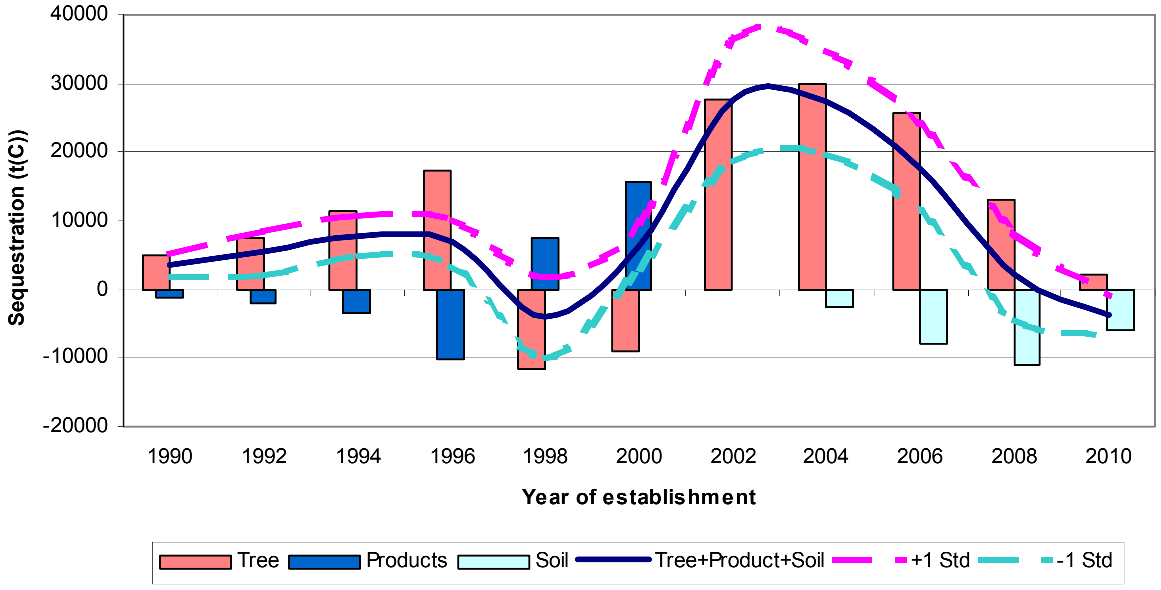


Figure 10: Summary of carbon sequestered by each age class during the Kyoto Commitment Period of a 5,500 ha plantation estate established between 1990 and 2010.



CONCLUSIONS

The influential sources of uncertainty in modelling for carbon sequestration vary with plantation age and proximity to the Kyoto Commitment Period. When the age is within the period of maximum CAI, errors in the model parameters and predictions of the weather will result in a high degree of uncertainty. When the CAI in the Commitment Period is low, eg very young or old stands, then uncertainty in estimating soil carbon emission and product decay becomes more important.

Management decisions, eg thinning or establishment, within the Kyoto Commitment period will have a much greater impact on the estimates of carbon sequestration than decisions prior to that Period. Therefore the ability to predict the management decision is very important. However, management decisions are also risky. Options to harvest prior or during the Kyoto Commitment Period may be influenced by unpredictable changes in management goals or objectives. Thus the uncertainty in the sequestration estimates introduced by weather and model variations may be completely dominated by political and management decisions of a 'risky' nature.

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Modelling Carbon Sequestration following Afforestation or Reforestation: Preliminary Simulations using GRC3

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ABSTRACT

The Australian Greenhouse Office (AGO), as part of its National Carbon Accounting System, is developing a capability to predict the change in carbon in Australian forests. To meet this objective a new model, GRC3, has been developed for forests combining four existing models: 3PG (growth of trees, allocation of carbon, and turnover of residues), GENDEC (litter decomposition), RothC (soil carbon turnover), and CAMFor (integrative tracking of carbon in managed plantations). Although each of these has been separately calibrated and validated under some systems, the integrated model has not been tested. In particular the GENDEC and RothC models need testing for plantations in Australia. The model, when calibrated and verified, would also form the basis of a 'carbon accounting toolkit' being developed by the AGO and others.

Keywords: Afforestation, Australia, carbon, GRC3, modelling

INTRODUCTION

In Australia, the area of plantation is expected to increase by about 2 million ha by 2020 compared to that existing in 1996. Most of these new plantations will be on agricultural land, and may provide an effective and practical contribution towards meeting Australia's international commitments to address climate change.

At a broad scale the effect of forest establishment on carbon stocks is best predicted through a verified modelling approach. A new model, GRC3, has been designed to track carbon transfer and turnover in forest establishment systems. This model combines four existing models: 3PG (growth of trees, allocation of carbon, and turnover of residues), GENDEC (litter decomposition), RothC (soil carbon turnover), and CAMFor (integrative tracking of carbon in managed plantations).

GRC3 has been developed in Microsoft Excel, and is expected to be superceded by FullCAM, prepared in C++ code. The two models are essentially the same, although FullCAM has additional features including an agricultural equivalent and ability to operate in a spatial mode. It is envisaged that FullCAM will provide the basis of an Australian carbon accounting system.

Although the submodel components of GRC3 have been separately calibrated and validated under some systems, the integrated model is currently untested. Prior to the collection and collation of data for broad application, testing is required to ensure that GRC3 is suitable for tracking of carbon through plantations via accurate simulation of dynamics of plantation growth, litter layer, and soil.

CSIRO is testing GRC3 for its ability to predict change in carbon under afforestation under Article 3.3 of the Kyoto Protocol, and specifically developing its ability to predict change in soil carbon. Here we:

- calibrate the model to various components of growth for seven select case studies of plantation establishment and management - land-use history, plantation productivity, soil type, climate and harvesting, and
- predict the cumulative change in carbon within tree biomass, debris, soil and total ecosystem pools for each study.

The objective is to quantify potential change in ecosystem carbon for seven case studies of plantations, and to identify important controlling processes that may need special attention for subsequent verification of the model.

MODEL DESCRIPTION AND METHODS

The integrated suite of models that comprise GRC3 are:

- 3PG, physiological growth model for forests (Landsberg and Waring 1997);
- CAMFor, Australian Greenhouse Office carbon accounting model for forests (Richards and Evans 2000);
- GENDEC, litter decomposition model (Moorhead and Reynolds 1991; Moorhead et al. 1999), and;
- RothC, soil carbon decomposition model (Jenkinson et al. 1991).

Each of these models have been independently developed and are suited to run on a monthly time-step.The model is represented diagrammatically in Figure 1.

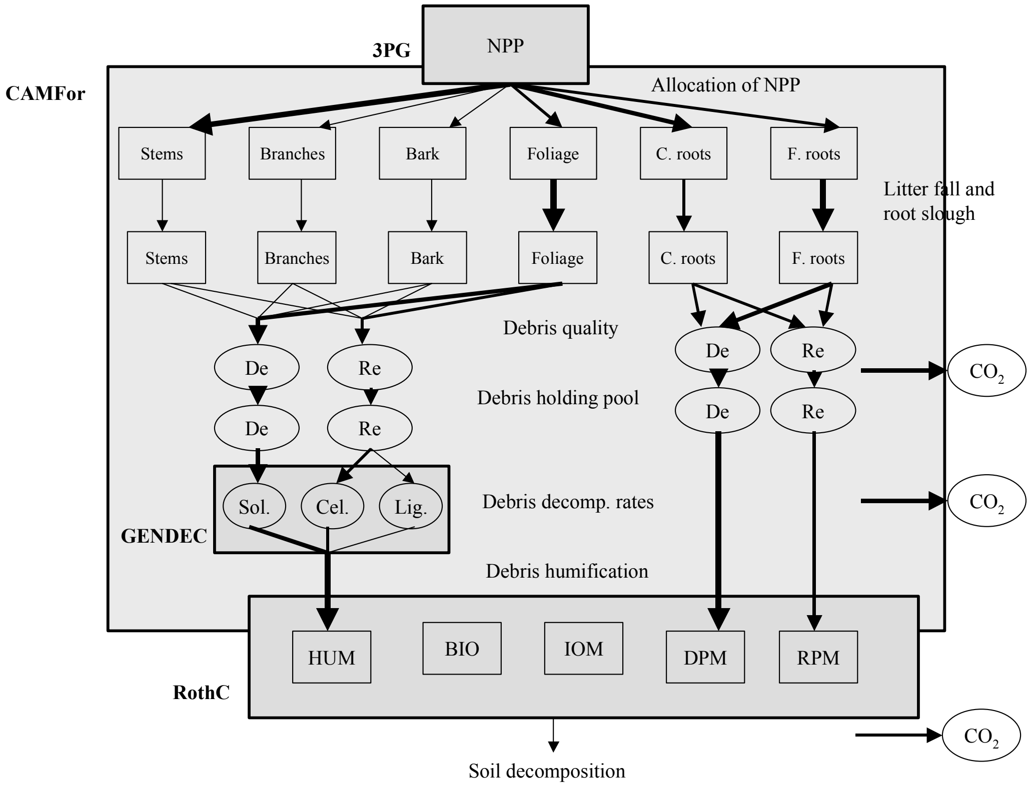


Figure 1: Basic structure and flows of carbon in FULLCAM. Boxes distinguish submodels. Arrows represent the main flows of carbon between submodels.

Seven regions and plantation management systems were chosen to provide the first test of GRC3, being selected on the basis that:

- they were one of the main forest establishment regions in Australia;
- at least one detailed growth study had been conducted in the region, and
- information on soil carbon content under pastures was available.

These regions and some of their characteristics are listed in Table 1.

Table 1: The seven sites, plantation species, and climatic data for case studies analysis.

Case study regions	Species	Abbreviation	Annual rainfall (mm)	Average temp. (^{o}C)
Low rainfall, south-west WA	*E. globulus*	LRWA	632	15.7
High rainfall, south-west WA	*E. globulus*	HRWA	1,022	14.9
Green Triangle, SA/Vic.	*P. radiata*	SA	704	13.4
South-east Q'land/North-east NSW	*E. grandis*	QLD	1138	20.4
South-east highlands, NSW/Vic.	*P. radiata*	NSW	791	13.5
South-east Vic.	*E. globulus*	VIC	1039	13.3
Florentine Valley, Tas.	*E. nitens*	TAS	1215	10.2

For each of the case studies listed in Table 1, there were between 4 and 27 sites where measurements of one or more of the following were made:

- mean annual increment
- stem volume
- leaf area index
- root mass
- litter fall
- litter layer mass.

It was assumed that all of these plantations were established on improved pastoral land and thus were relatively fertile.

As far as possible, GRC3 was calibrated to the observed above- and below-ground components of growth (i.e. mean annual increment, stem volume, leaf area index), and to litterfall and accumulation of the litter layer. This was done by 'tuning' the allocation of NPP to the various tree components such that the predicted growth and litter layer accumulation matched that observed. The model outputs presented in this report form part of a sequential strategy to develop capability in predicting soil carbon change following afforestation. However, it is important to note that results for changes in soil carbon remains unverified.

E. globulus plantation, LRWA region scenario

The National Plantation Inventory (Bureau of Rural Resources, March 2000) indicated that Western Australia (WA) had 33% of all the new plantations established in Australia in 1999. It was projected that this would increase to 39% by 2000. In 1999, 88% of all the new plantations in WA were hardwoods, mostly *Eucalyptus globulus* planted in the south-west of the state. This region is represented by the LRWA case study. General inputs are shown in Table 2. Table 3 details studies of plantation in the LRWA region from which growth, biomass, litter fall, and litter layer accumulation data was collated for preliminary model calibration.

Table 2: General inputs used for simulation of the LRWA region.

	Value	Reference
Latitude (^{o})	33.69	
Soil type	Sandy loam	Hingston et al. (1998)
Initial soil C content (0-30 cm, t C ha^{-1})	31.7	Grove et al. (2000); Mendham pers. com. (2000)
Available soil water capacity (mm)	232	Hingston et al. (1998)
Clay content (%, 0-30 cm)	7	Hingston et al. (1995)
Average rotation length (yrs)	10	O'Connell (2000) pers. com.
Initial stocking (stems ha^{-1})	787	Hingston et al. (1998)
Thinning operations	None	O'Connell (2000) pers. com.

Table 3: Plantation experiments in the LRWA region and age (years) at which data was collected for MAI (mean annual increment), SV (stem volume), ABG (above ground biomass), BGB (below ground biomass, LAI (leaf area index), LF (litter fall), and LLM (litter layer mass).

Site	MAI	SV	AGB	BGB	LAI	LF	LLM	Reference
Mumbulup	5	5-8	2-5	~	6-8	6, 7	~	Hingston et al. (1995; 1998)
Darkan	6, 9	6-12	3-9	~	7-12	7-11	~	Hingston et al. (1995; 1998)
Gibbs	10	0-4	~	~	~	~	~	Grove et al. (2000)
Cox	~	~	~	~	3	~	H*	O'Connell (2000) pers com.

*represents stand at harvest

E. globulus plantation, HRWA region scenario

Most of the 27,500 ha of new *E. globulus* plantations established in WA in 1999 were planted within the high rainfall region in the south-west. The HRWA case study represents the high annual rainfall (900-1,500 mm) zone in south-western WA. It is the area of WA where *Eucalyptus globulus* plantations are most productive, and provides a useful comparison with the LRWA case study described above. General inputs used are shown in Table 4. Table 5 details studies of plantation in the LRWA region from which growth, biomass, litter fall, and litter layer accumulation data was collated for preliminary model calibration.

Table 4: General inputs used for simulation of the HRWA region.

	Value	Reference
Latitude (^{o})	33.69	
Soil type	Sandy loam	Hingston et al. (1998)
Initial soil C content (0-30 cm, t C ha^{-1})	49.8	Aggangan et al. (1998, 1999); Grove et al. (2000); Mendham pers. com. (2000)
Available soil water capacity (mm)	232	Hingston et al. (1998)
Clay content (%, 0-30 cm)	7	Hingston et al. (1995)
Average rotation length (yrs)	10	O'Connell (2000) pers. com.
Initial stocking (stems ha^{-1})	787	Hingston et al. (1998)
Thinning operations	None	O'Connell (2000) pers. com.

Table 5: Plantation experiments in the HRWA region and age (years) at which data was collected for MAI (mean annual increment), SV (stem volume), ABG (above ground biomass), BGB (below ground biomass, LAI (leaf area index), LF (litter fall), and LLM (litter layer mass).

Site	MAI	SV	AGB	BGB	LAI	LF	LLM	Reference
Northcliffe	7	7-10	4-7	~	10-12	8, 9	~	Hingston et al. (1995; 1998)
Manjimup	9	9-12	6-9	~	6-8	10,11	~	Hingston et al. (1995; 1998)
Moltoni	11	0-4	~	~	~	~	~	Grove et al. (2000)
Windfield	~	~	~	~	~	~	H-1	Shammas (1999)
Carpenters	1-5	~	~	~	1-5	~	H	O'Connell pers com. (2000)

Where H represents stand at harvest

Pinus radiata plantation, SA region scenario

The National Plantation Inventory (Bureau of Rural Resources, March 2000) indicated that in the years 1999 and 2000, the Green Triangle region of South Australia and Victoria contained 9-12% and 20-28% of all the new plantations established in Australia, respectively. In temperate regions, *Pinus radiata* is the most common softwood species. General inputs are shown in Table 6. Table 7 details studies of plantation in the SA region from which growth, biomass, litter fall, and litter layer accumulation data was collated for preliminary model calibration.

Table 6: General inputs used for simulation of the SA region.

	Value	Reference
Latitude (°)	37.75	
Soil type	Sand	Carlyle (2000) pers com.
Initial soil C content (0-30 cm, t C ha^{-1})	43.9	Lewis et al. (1981, 1987); Carlyle (2000) pers com.
Available soil water capacity (mm)	250	Carlyle (2000) pers com.
Clay content (%, 0-30 cm)	2.2	Carlyle (2000) pers com.
Average rotation length (yrs)	35	Carlyle (2000) pers com.
Initial stocking (stems ha^{-1})	1,352-1,600	Carlyle (1995, 1998)
Thinning operations		
1st thinning, age 10-15 years	50%	Carlyle (2000) pers com.
2nd thinning, age 20-25 years	25%	Carlyle (2000) pers com.
3rd thinning, age 25-30 years	10%	Carlyle (2000) pers com.

Table 7: Plantation experiments in the SA region and age (years) at which data was collected for MAI (mean annual increment), SV (stem volume), ABG (above ground biomass), BGB (below ground biomass, LAI (leaf area index), LF (litter fall), and LLM (litter layer mass).

Site	MAI	SV	AGB	BGB	LAI	LF	LLM	Reference
Mt. Gambiar[1]	~	~	~	1-3	~	~	~	Nambiar (1983)
Mt. Gambiar[1]	~	1-7	~	~	~	~	~	Nambiar et al. (1990)
Mt. Gambiar[1]	~	~	2-6	2, 6	6	~	~	Nambiar (1990)
Sphers-EM88	~	~	0-3	~	~	~	~	Smethurst and Nambiar (1995)
Caroline EM89	~	~	11	~	~	11,37	11,35[2]	Carlyle (1993); Smethurst and Nambiar (1990)
Caroline 366	~	~	~	~	24-28	~	~	Carlyle (1999) pers. com.
Sphers-6 EM99	~	10,11	~	~	12	~	10-11	Carlyle (1995)
Sphers-6	24-58	~	~	~	11-12	11-13	24-58	Carlyle (1998)
Mt. Gambiar[1]	24-58	~	~	~	~	~	~	Carlyle et al. (1998)
Tarpeena	~	~	3	~	~	~	~	Woods et al. (1992)
Mt. Gambiar[1]	30	16-29	~	~	16-29	16-19	16-29	May pers com. (2000)

[1] Numerous sites within the Mount Gambiar region

[2] 1-3 years after clear felling

E. grandis plantation, QLD region scenario

In the years 1999 and 2000, Queensland and New South Wales contained 3-5% and 7-8% of all the new plantations established in Australia, respectively. A substantial proportion of new hardwood plantations are likely to be established in coastal regions of southeastern Queensland and northeastern New South Wales (QLD region). *E. grandis* is commonly planted in north-eastern NSW and there are detailed growth studies of this species within the QLD region. General inputs are shown in Table 8. Table 9 details studies of plantation in the QLD region from which growth, biomass, litter fall, and litter layer accumulation data was collated for preliminary model calibration.

Table 8: General inputs used for simulation of the QLD region

	Value	Reference
Latitude (^{o})	26.18	
Soil type	Sandy loam	Ross and Thompson (1991)
Initial soil C content (0-30 cm, t C ha^{-1})	67.7	Ross and Thompson (1991); Bell et al. (1999); Noble et al. (1997); Turner and Lambert (2000)
Available soil water capacity (mm)	89	Thackway and Cresswell (1995)
Clay content (%, 0-30 cm)	11-17	Ross and Thompson (1991)
Average rotation length (yrs)	12-14	Cromer et al. (1991)
Initial stocking (stems ha^{-1})	756-1,110	Turner and Lambert (1983; 2000)
Thinning operations	None	Cromer pers. com. (2000)

Table 9: Plantation experiments in the QLD region and age (years) at which data was collected for MAI (mean annual increment), SV (stem volume), ABG (above ground biomass), BGB (below ground biomass, LAI (leaf area index), LF (litter fall), and LLM (litter layer mass).

Site	MAI	SV	AGB	BGB	LAI	LF	LLM	Reference
Conglomerate	~	~	27	~	~	27	27	Turner and Lambert (1983)
Coffs Harbor[1]	2-31	~	5-27	~	~	8-28	5-31	Turner (1986)
Coffs Harbor[1]	~	~	9-12	~	~	~	9, 12	Birk and Turner (1992)
Atherton	3	1-6	0-3	~	1-3	~	~	Cromer et al. (1990; 1991, 1995)
Coffs Harbor	3	1-6	0-6	~	1-6	7	~	Cromer et al. (1990; 1991, 1995)
Buladelah	~	3-6		~	~	~	~	Cromer et al. (1995)
Pomona	~	3-6		~	~	~	~	Cromer et al. (1995)
Coffs Harbor[1]	~	~	2-31	~	~	~	~	Byrne (1989)
Gympie	~	~	~	~	0-1	~	~	Leuning et al. (1991)
Toolara	~	~	~	1-2	~	1-3, 6	6	Stewart et al. (1990); Cromer et al. (1993); Raison et al. (1995)

[1] Sites near the Coffs Harbor region

P. radiata plantation, NSW region scenario

New South Wales contains 7-8% of all new plantations established in Australia in 1999 and 2000 (The National Plantation Inventory, Bureau of Rural Resources, March 2000). *Pinus radiata* is widely planted being established within the south-west slopes and southern highland regions. General inputs are shown in Table 10. Table 11 details studies of plantation in the NSW region from which growth, biomass, litter fall, and litter layer accumulation data was collated for preliminary model calibration.

Table 10: General inputs used for simulation of the NSW region

	Value	Reference
Latitude (^{o})	35.21	
Soil type	Loamy sand	Benson et al. (1992)
Initial soil C content (0-30 cm, t C ha^{-1})	46.8	Williams and Donald (1956); Gifford and Barrett (1999); Gifford (2000)
Available soil water capacity (mm)	250	Kirschbaum (1999)
Clay content (%, 0-30 cm)	5	Mike Connell (2000) pers. com.
Average rotation length (yrs)	37	Snowdon (2000) pers. comm.
Initial stocking (stems ha^{-1})	997-1,680	Benson et al. (1992); Woollons et al. (1995)
Thinning operations		
1st thinning, age 10 years	50%	Snowdon (2000) pers. comm.
2nd thinning, age 24 years	25%	
3rd thinning, age 27 years	10%	

Table 11: Plantation experiments in the NSW region and age (years) at which data was collected for MAI (mean annual increment), SV (stem volume), ABG (above ground biomass), BGB (below ground biomass, LAI (leaf area index), LF (litter fall), and LLM (litter layer mass).

Site	MAI	SV	AGB	BGB	LAI	LF	LLM	Reference
Pierces Crk	11-15	10-14	10-14	14	10-14	10-14	10-20	Snowdon and Benson (1992); Raison and Myers (1992); Khanna pers. com. (2000)
Buccleuch	~	14-28	~	~	~	~	~	Snowdon et al. (1995); Woollons et al. (1995)
Blue Range	~	~	5	~	~	~	~	Snowdon and Waring (1985)

E. globulus plantation, VIC region scenario

The National Plantation Inventory (Bureau of Rural Resources, March 2000) shoed that in 1999 and 2000, Victoria contained 20-28% of all new plantations established in Australia in 1999. A substantial proportion of the 25,326 ha of new harwood plantations in Victoria are *Eucalyptus globulus* in the south-east Gippsland region. General inputs are shown in Table 12. Table 13 details studies of plantation in the VIC region from which growth, biomass, litter fall, and litter layer accumulation data was collated for preliminary model calibration.

Table 12: General inputs used for simulation of the VIC region

	Value	Reference
Latitude (^{o})	38.10	
Soil type	Clay loam	Judd et al. (1996); Sargeant et al. (1997); Hooda (1998)
Initial soil C content (0-30 cm, t C ha^{-1})	103.1	Sargeant et al. (1997)
Available soil water capacity (mm)	340	Mike Battaglia (2000) pers. com.
Clay content (%, 0-30 cm)	23	Bennett et al. (1996)
Average rotation length (yrs)	15-20	Cromer (2000) pers com.
Initial stocking (stems ha^{-1})	900-1,015	Hooda (1998)
Thinning operations	None	Cromer (2000) pers com. (2000)

Table 13: Plantation experiments in the VIC region and age (years) at which data was collected for MAI (mean annual increment), SV (stem volume), ABG (above ground biomass), BGB (below ground biomass, LAI (leaf area index), LF (litter fall), and LLM (litter layer mass).

Site	MAI	SV	AGB	BGB	LAI	LF	LLM	Reference
Boola	2-9	2-6	2-10	~	6	2-6	6	Cromer and Williams (1982); Judd et al. (1996); Bennett et al. (1996; 1997); Hooda (1998)
Glrncoe	2-9	2-6	4-7	~	6	2-6	6	Cromer and Williams (1982); Judd et al. (1996); Bennett et al. (1996; 1997); Hooda (1998)
Maryvale	2-9	2-6	2,-7	~	6	2-6	6	Cromer et al. (1975); Cromer and Williams (1982); Judd et al. (1996); Bennett et al. (1996; 1997); Hooda (1998)

E. nitens plantation, TAS region scenario

In 1999-2000, 15-20% of new plantations in Australia were established in Tasmania (The National Plantation Inventory, Bureau of Rural Resources, March 2000). In 1999, 87% of all new plantations in Tasmanian were hardwood plantations. A substantial proportion of the 16,467 ha of new harwood plantations in Tasmania are *Eucalyptus nitens* planted in the frost prone, high rainfall regions. General inputs are shown in Table 14. Table 15 details studies of plantation in the TAS region from which growth, biomass, litter fall, and litter layer accumulation data was collated for preliminary model calibration.

Table 14: General inputs used for simulation of the TAS region

	Value	Reference
Latitude (^{o})	38.10	
Soil type	Clay loam	Wang et al. (1996); Bell et al. (1999); Sparrow et al. (1999)
Initial soil C content (0-30 cm, t C ha^{-1})	99.6	Sargeant et al. (1997)
Available soil water capacity (mm)	340	Mike Battagila (2000) pers. com.
Clay content (%, 0-30 cm)	23	Bennett et al. (1996)
Average rotation length (yrs)	15-20	Cromer pers com. (2000)
Initial stocking (stems ha^{-1})	900-1,015	Hooda (1998)
Thinning operations	None	Mike Battagila (2000) pers. com.

Table 15: Plantation experiments in the TAS region and age (years) at which data was collected for MAI (mean annual increment), SV (stem volume), ABG (above ground biomass), BGB (below ground biomass, LAI (leaf area index), LF (litter fall), and LLM (litter layer mass).

Site	MAI	SV	AGB	BGB	LAI	LF	LLM	Reference
Westfield	~	6-8	1-3, 8	1-3, 8	6-7	8	~	Misra et al. (1998); Baillie pers. comm. (2000)
Tasmania[1]	13	~	~	~	3, 7	~	~	Battaglia et al. (1998)

[1]Other Regions in Tasmania

RESULTS AND DISCUSSION

Figures 2 to 6 are examples of how allocation of NPP to various tree components was calibrated such that predicted growth, litter fall and litter layer accumulation matched that observed. The examples of calibrated model output given in Figures 2 to 5 are for the NSW case study.

Figure 2: Stem volume of *P. radiata* plantations at NSW. Solid circles represent observed data taken from Snowdon and Benson (1992), Woollons et al. (1995), and Snowdon et al. (1995).

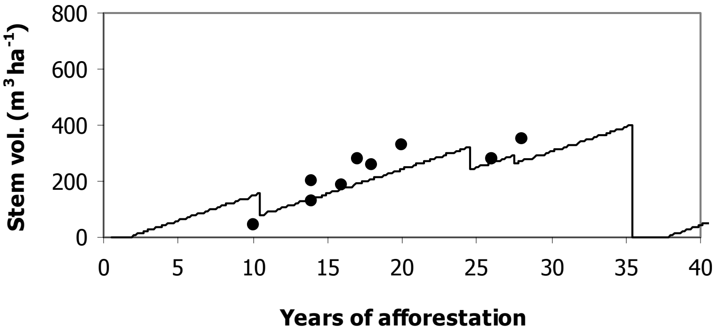


Figure 3: Above ground biomass of P. radiata plantations at NSW. Solid circles represent observed data taken from Snowdon and Waring (1985) and Snowdon and Benson (1992).

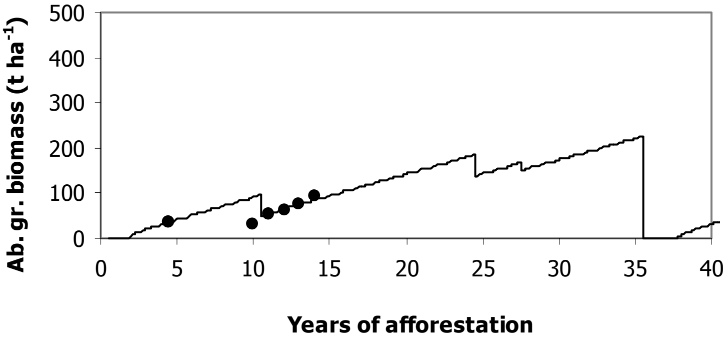


Figure 4: Leaf area index of *P. radiata* plantations at NSW. Solid circles represent observed data taken from Raison et al. (1992).

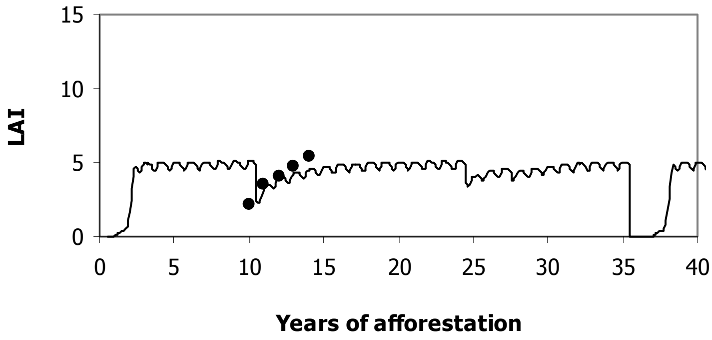


Figure 5: Total litter fall (minus C removed in products) under *P. radiata* plantations at NSW. Solid circles represent observed data taken from Raison et al. (1992).

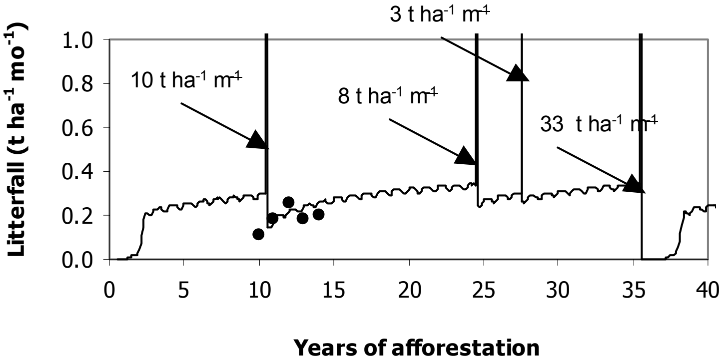
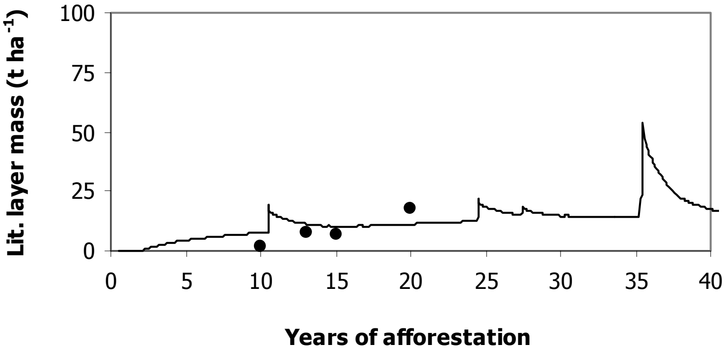


Figure 6: Litter layer mass under P. radiata plantations at NSW. Solid circles represent observed data taken from Khanna (2001) pers. com.



Changes in carbon within trees (both above- and below-ground), debris and soil for each case study are shown in Figures 7-13. After 40 years of afforestation it was predicted that between 373 and 810 t C ha^{-1} had been sequestered. It was predicted that 34-56% and 24-25% of this carbon entered the debris and soil, respectively. However due to the loss of carbon during debris and soil decomposition, up to only 5% of the net carbon sequestered accumulated in soil and debris, whereas 44-66% was in harvested products or in trees.

GRC3 has been calibrated to plantation growth, litter fall and accumulation of litter. However, simulations of the change in soil carbon remain unverified. Although the model was calibrated to litter accumulation by adjusting the allocation of NPP to the various tree components, the rate of carbon during litter decomposition and the rate of debris humification remains untested. The GENDEC and RothC models of decomposition need to be verified.

Figure 7: Net accumulation of carbon within tree biomass, debris, soil and total ecosystem over a 40 year period of forest establishment in the LRWA region.

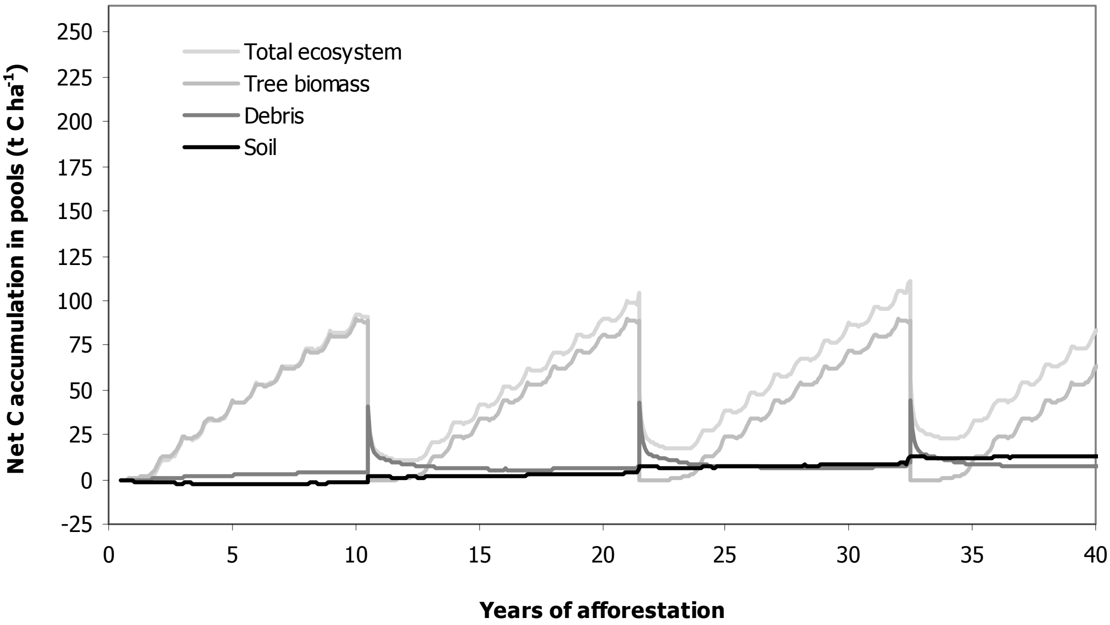


Figure 8: Net accumulation of carbon within tree biomass, debris, soil and total ecosystem over a 40 year period of forest establishment in the HRWA region.

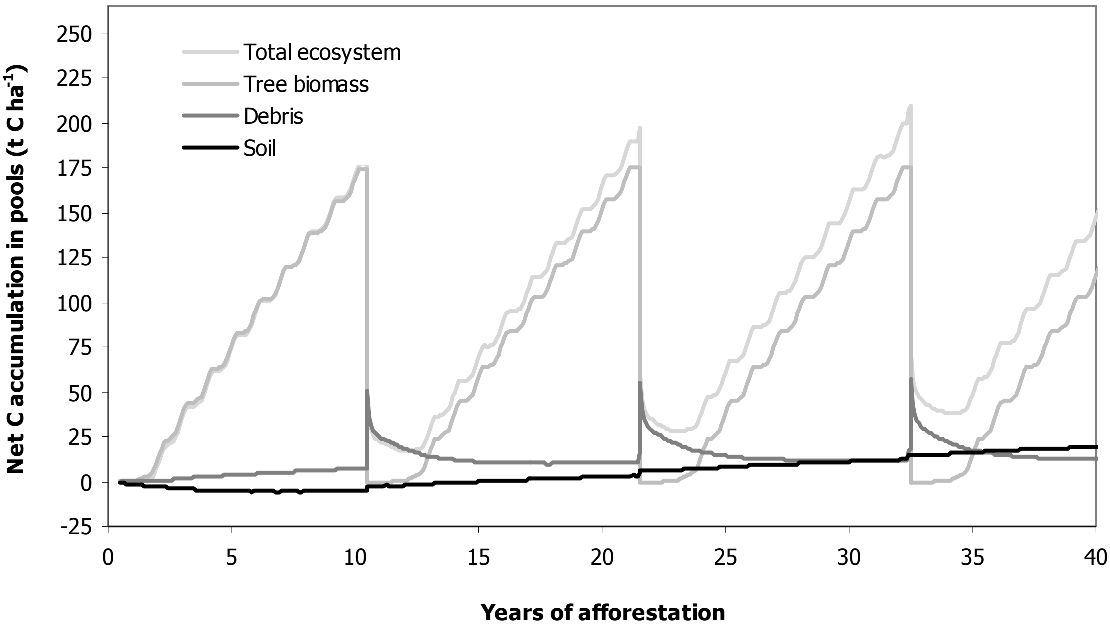


Figure 9: Net accumulation of carbon within tree biomass, debris, soil and total ecosystem over a 40 year period of forest establishment in the SA region.

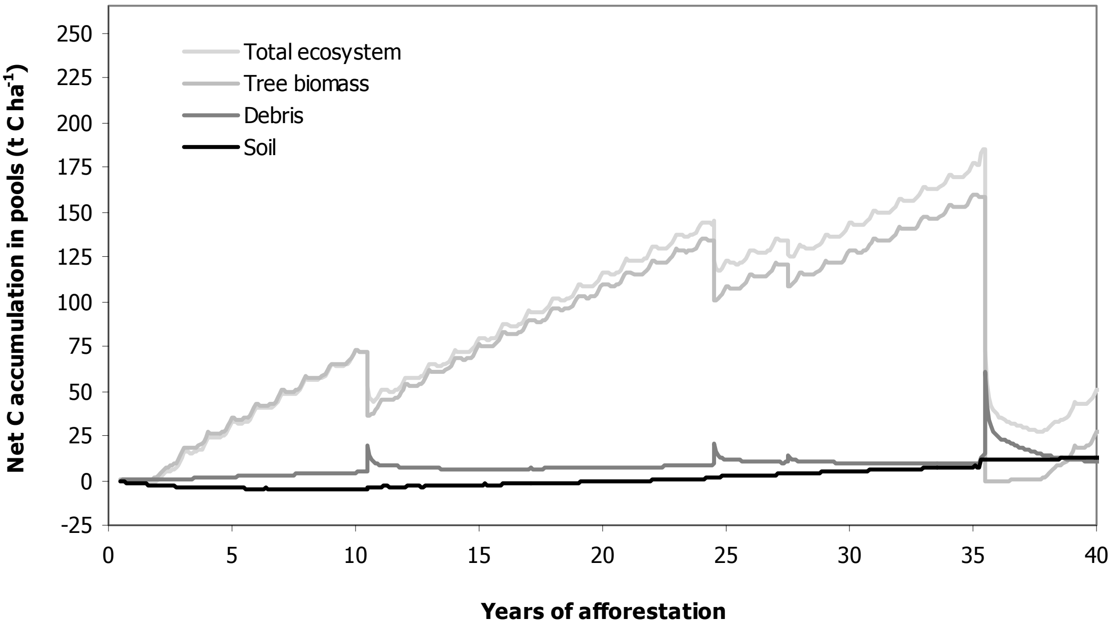


Figure 10: Net accumulation of carbon within tree biomass, debris, soil and total ecosystem over a 40 year period of forest establishment in the QLD region.

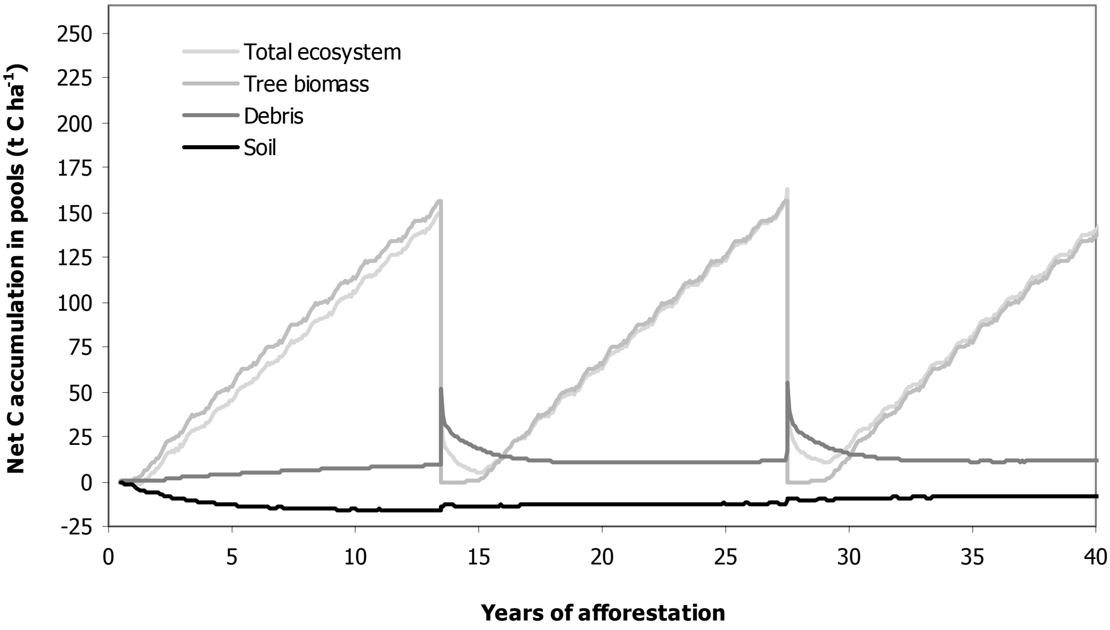


Figure 11: Net accumulation of carbon within tree biomass, debris, soil and total ecosystem over a 40 year period of forest establishment in the NSW region.

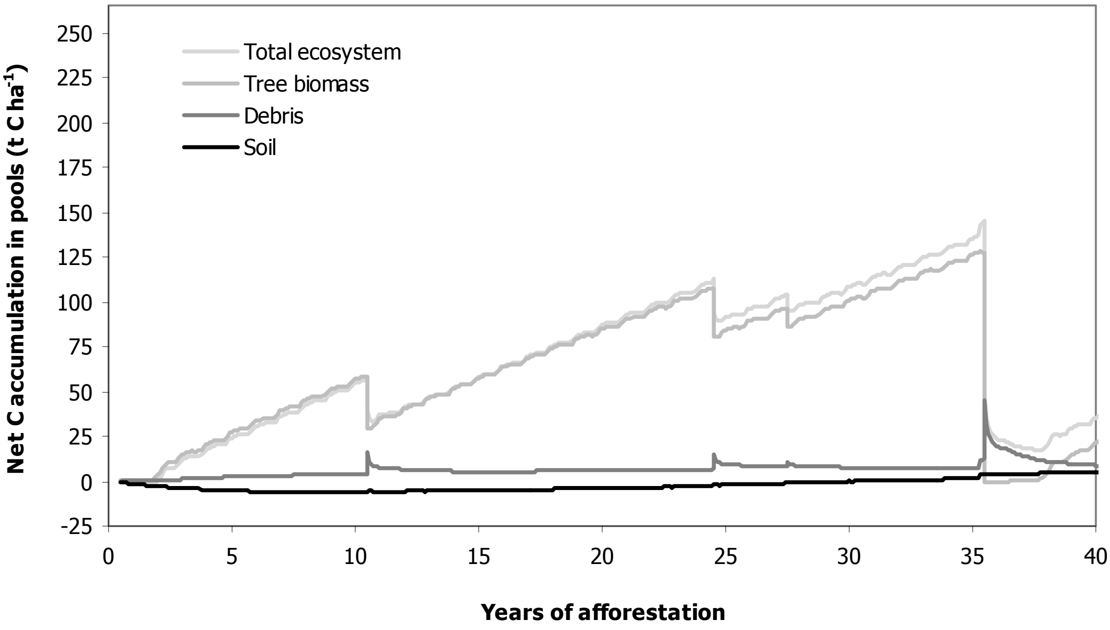


Figure 12: Net accumulation of carbon within tree biomass, debris, soil and total ecosystem over a 40 year period of forest establishment in the VIC region.

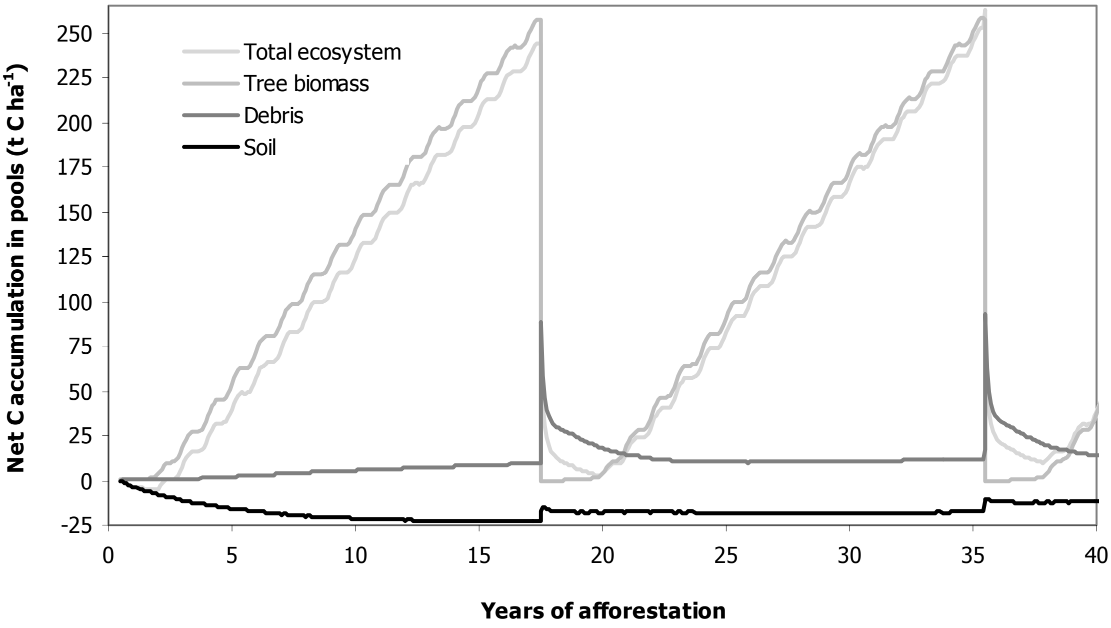
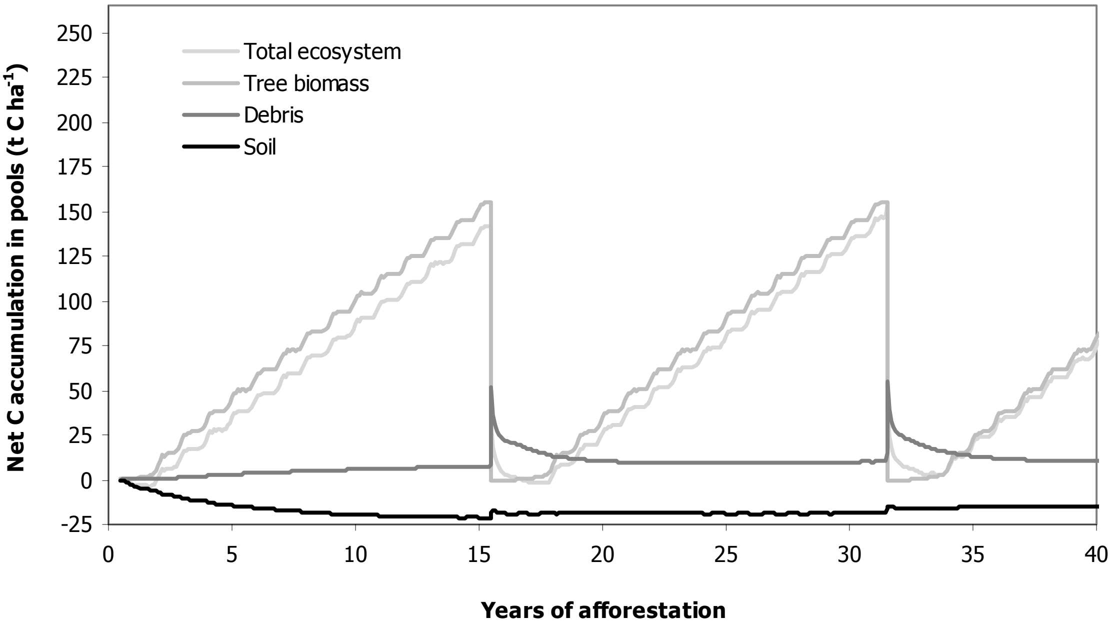


Figure 13: Net accumulation of carbon within tree biomass, debris, soil and total ecosystem over a 40 year period of forest establishment in the TAS region.



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