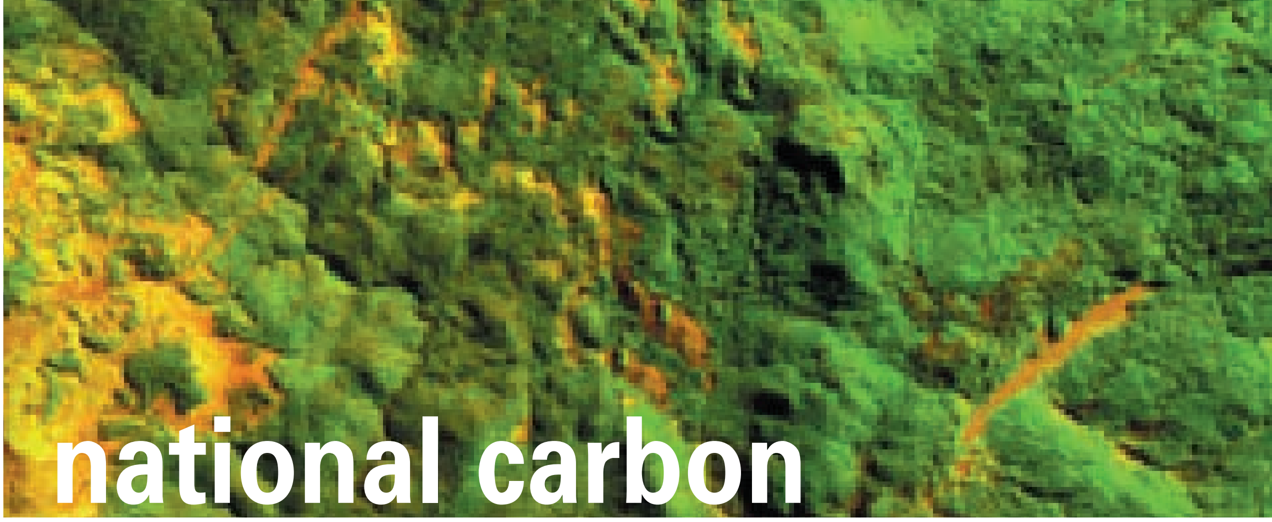

national carbon
accounting system

technical report no. 28

The *FullCAM* Carbon Accounting Model: Development, Calibration and Implementation for the National Carbon Accounting System

Gary P Richards

AUSTRALIAN
Greenhouse
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The lead Commonwealth
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EXECUTIVE SUMMARY

Subsequent to the development of the Excel based *CAMFor* model for the Australian Greenhouse Office, work commenced on the development of an integrated model which combined the *CAMFor* model with the *3PG* forest growth model, the *GENDEC* litter decomposition model and the Rothamsted soil carbon model (*Roth C*). A parallel version of the *CAMFor* model (*CAMAg*) was developed for agricultural systems and is also integrated with *GENDEC* and the *Roth C* model.

The model developed, known as *FullCAM*, integrates the *CAMFor* and *CAMAg* based routines to a single C code model capable of carbon accounting in transitional (afforestation, reforestation and deforestation) and mixed (e.g. agroforestry) systems.

The *FullCAM* model can be run in a spatial mode which will integrate information drawn from the remotely sensed land-cover-change program, productivity surfaces and other ancillary data to perform various accounting routines.

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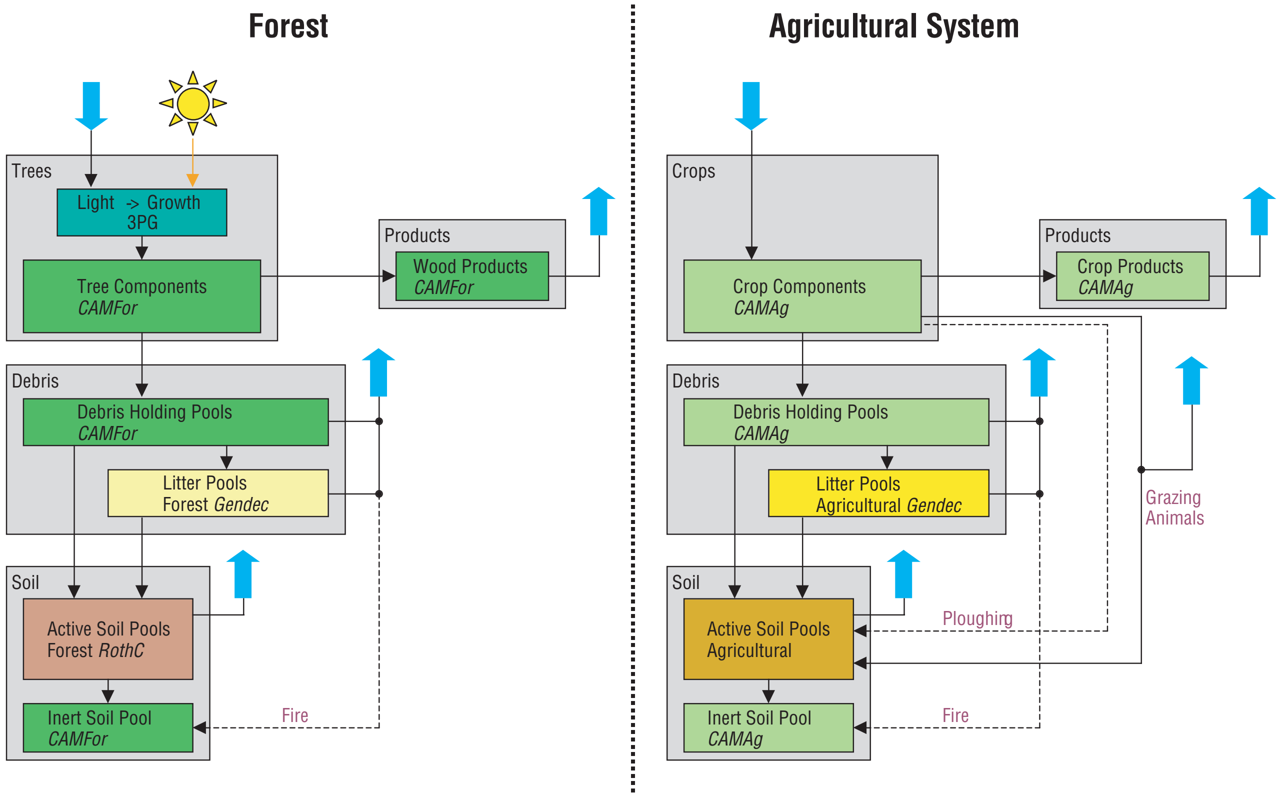


Figure 1. The *FullCAM* Model

1. 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 are not practical, particularly for project scale accounting.

An overall system framework (AGO, 2000c) was developed to guide 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 Waring, 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, decomposition, harvest, cropping, and grazing, to externally generated growth and decomposition rate inputs.

In further preparing 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. 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.

1.1 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, 2001b). 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 CO2 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

Except for *CAMAg* (which was developed directly in C code), models were translated from source code into a Microsoft Excel platform. The integrity of each of the original models was maintained during this initial translation. This allowed for the development of consistent naming conventions (Table 1), methodologies and approaches, which were also transparent and readily reviewed. Tests of the replication of the models in their new format could be undertaken through comparison of results between original and derived models using identical model parameters.

Table 1. Naming Conventions

Abbreviations used in names

Actv	=	Active soil carbon
Avg	=	Average
B	=	Microbes (dead) (see P, Micr)
Bkdn	=	Breakdown
C	=	Carbon Material whose every atom has six protons
C	=	Coarse (see Dcy, Root)
Cel	=	Cellulose (see Lig, Sol)
CM	=	Carbon mass of material Mass of carbon atoms in the material
Conp	=	Consumption (of fodder by animals, which emits methane)
Cons	=	Construction wood
Dcmp	=	Decomposition
De	=	Decomposable (see Re)
Debr	=	Debris
Dec	=	Decrease (due to)
Decomp	=	Decomposable
Dcy	=	Decay (sloughed off root), either CDcy (coarse decay)or FDcy (fine decay)
Dwd	=	Deadwood
Eff	=	Assimilation efficiency of microbes
Evap	=	Evaporation
F	=	Fine (see Dcy, Root)
Fibr	=	Fibreboard
Fodd	=	Fodder (inside animal stomachs)
Foli	=	Foliage Leaves and twigs of tree
Frac	=	Fraction of a specified part of a whole (a number from 0 to 1, inclusive)
Furn	=	Furniture
Grth	=	Growth (of trees or crops)
Humf	=	Humification
Inc	=	Increase (due to)
Inrt	=	Inert soil carbon
Lig	=	Lignin (see Cel, Sol)
Lit	=	Litter, either LLit (leaf litter) or BLit (bark litter)
M	=	Mass (dry weight)
Micr	=	Microbes (live) (see B, P)
Mod	=	Modifier
N, Nitro	=	(Available) nitrogen
NCRatio	=	Ratio of nitrogen mass to carbon mass
NM	=	Nitrogen Mass
Nutr	=	Nutrition
P	=	Plant matter (dead) (see B, Micr)
Pack	=	Packing wood
Papr	=	Pulp and paper
PB	=	Plant matter and microbial matter
Rel	=	Relative
Resi	=	Residue (from wood product mill)
Root	=	Root, either CRoot (coarse root) or FRoot (fine root)
RotAge	=	Rotation age (years since trees were planted)
Sol	=	Soluble litter (see Cel, Lig)
Tbl	=	Table
Temp	=	Temperture
Turn	=	Turnover
Wall	=	Microbe cell wall

Table 1. Naming Conventions (continued)

Abbreviated Quantities

ASW	=	Available soil water (in mm of rainfall or irrigation) (*3PG* only)
BIO	=	Microbial biomass = Fast and slow decomposing biomass combined (BIO-F + BIO-S) (*Roth C* only)
BIOF	=	BIO-F = Fast decomposing biomass (*Roth C* only)
BIOS	=	BIO-S = Slow decomposing biomass (*Roth C* only)
CO2	=	Carbon dioxide
DPM	=	Decomposable plant material (*Roth C* only)
GBF	=	Grain, buds, and fruit
GBFP	=	Grain, bud, and fruit products
GPP	=	Gross Primary Production = Overall production of tree or crop biomass in tonnes of carbon
HSS	=	Hay, straw, and silage
HUM	=	Humified organic matter (*Roth C* only)
NPP	=	Net Primary Productivity = GPP - carbon lost in respiration
PAR	=	Photosynthetically Active Radiation (*3PG* only)
RPM	=	Resistant plant material (resistant to decomposition) (*Roth C* only)
TSMD	=	Topsoil moisture deficit
VPD	=	Vapor Presure Deficit (in kPa) (*3PG* only)
XXX	=	DPM, RPM, BIO-F or BIO-S (all active soil carbon categories except HUM)

1.2 MODEL DEVELOPMENT

When there was confidence that the models were giving the same results as the source code versions, the Excel models were fully documented and returned for verification to the original authors or host organisations for checking and commentary. Modifications were only considered subsequent to this initial review. Recommended modifications were made for a variety of reasons including efficiency in code (computational speed and resources) and the recognition of the different biophysical conditions in Australia. The integration to a single compendium of the various sub-models was initially undertaken in Excel as a test version.

The component models are being independently calibrated for the NCAS through a variety of programs, which are largely focussed on the development of the 1990 Baseline for the Land Use Change and Forestry activities under the Kyoto Protocol. 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 and soil type.

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.

A brief description of each model, modifications made to the original models and supporting fundamental information bases follow.

2. THE COMPONENT MODELS

2.1 *3PG* (FIGURE 2)

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 Waring (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 250 m 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 (McKenzie *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) (Mc Mahon *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.

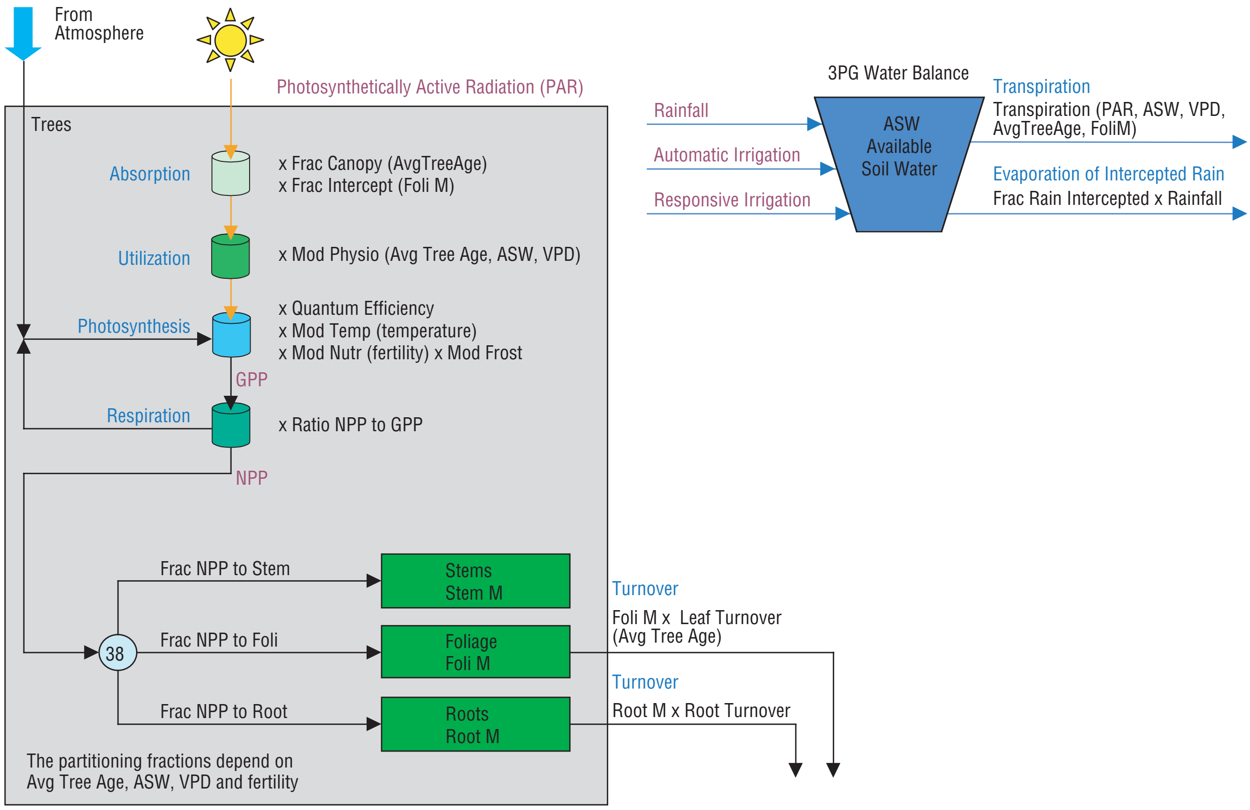


Figure 2. The *3PG* Model

2.2 *CAMFor* (FIGURE 3)

CAMFor has its origins in the 1990 *CO2 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*.

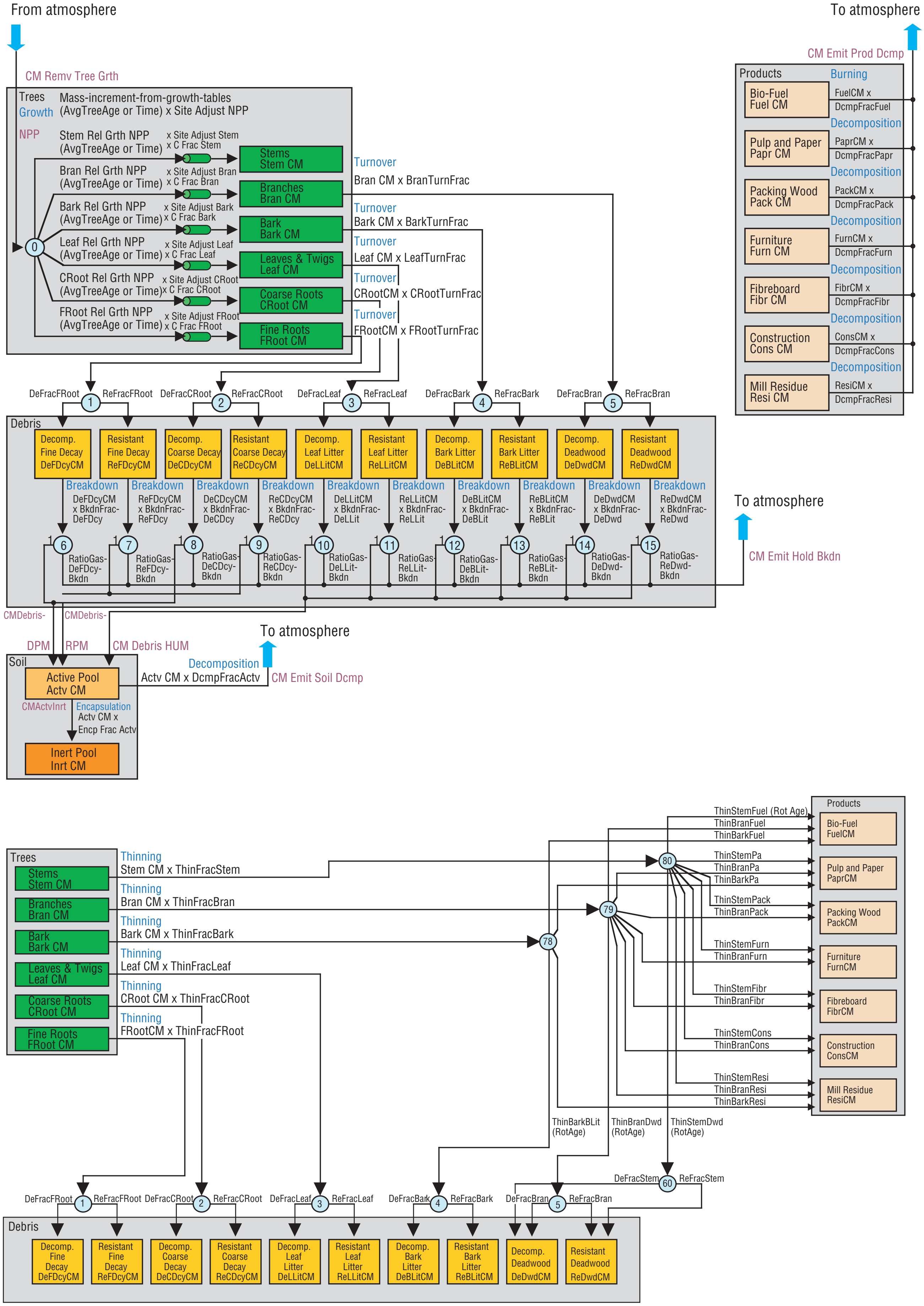


Figure 3. The *CAMFor* Model (a) Thinning

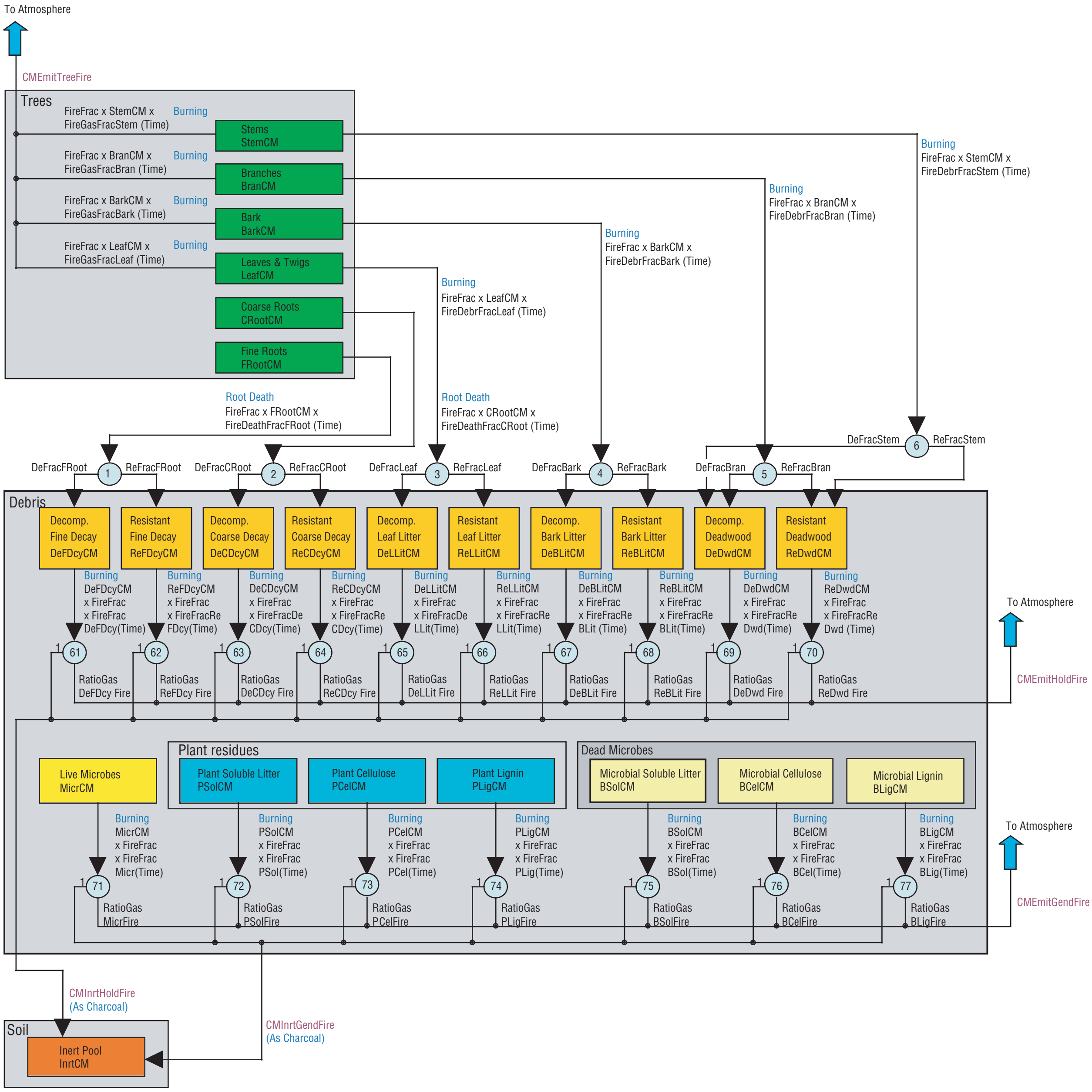


Figure 3. The *CAMFor* Model (b) Fire

2.3 *CAMAg* (FIGURE 4)

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.

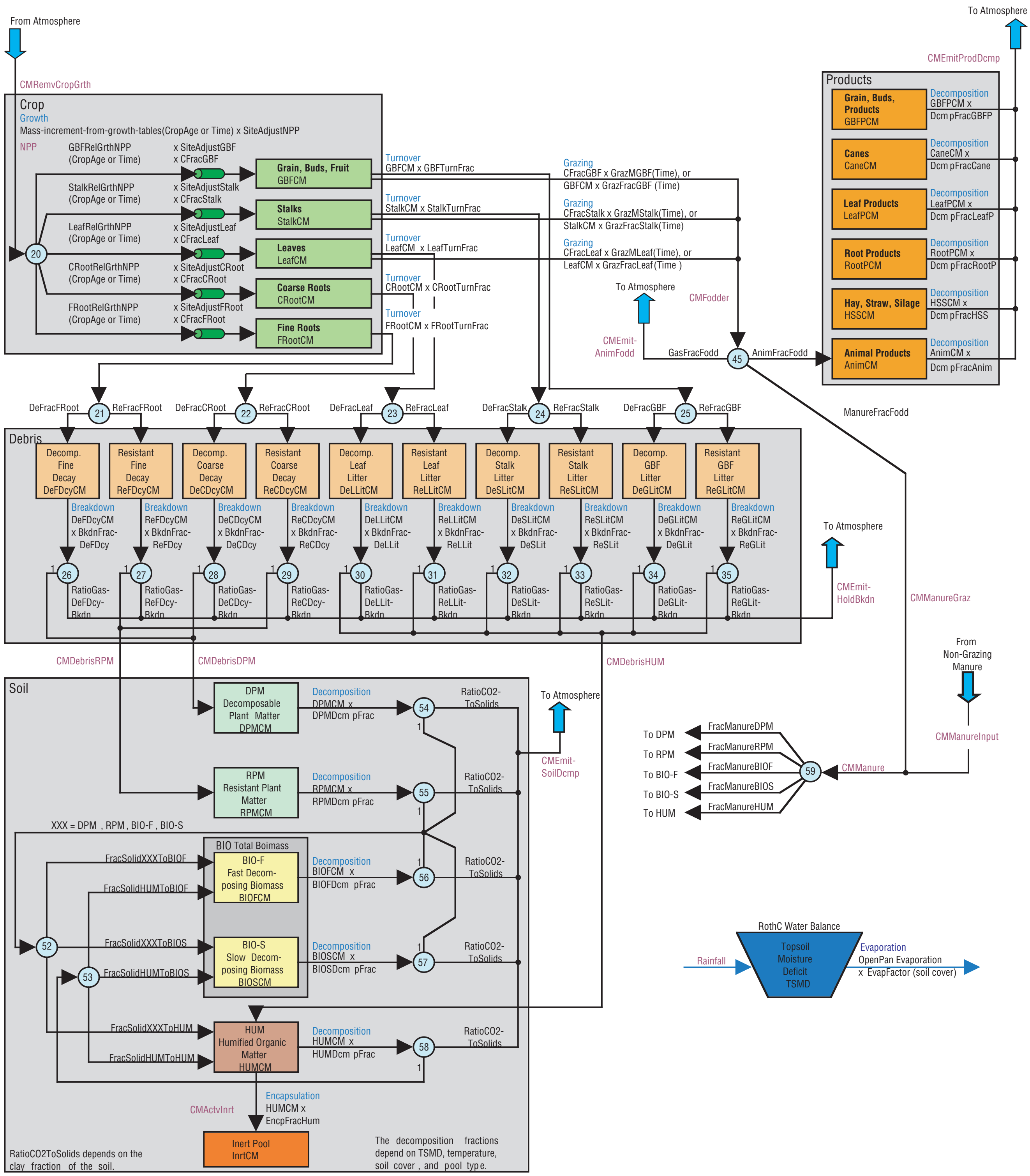


Figure 4. The *CAMAg* Model

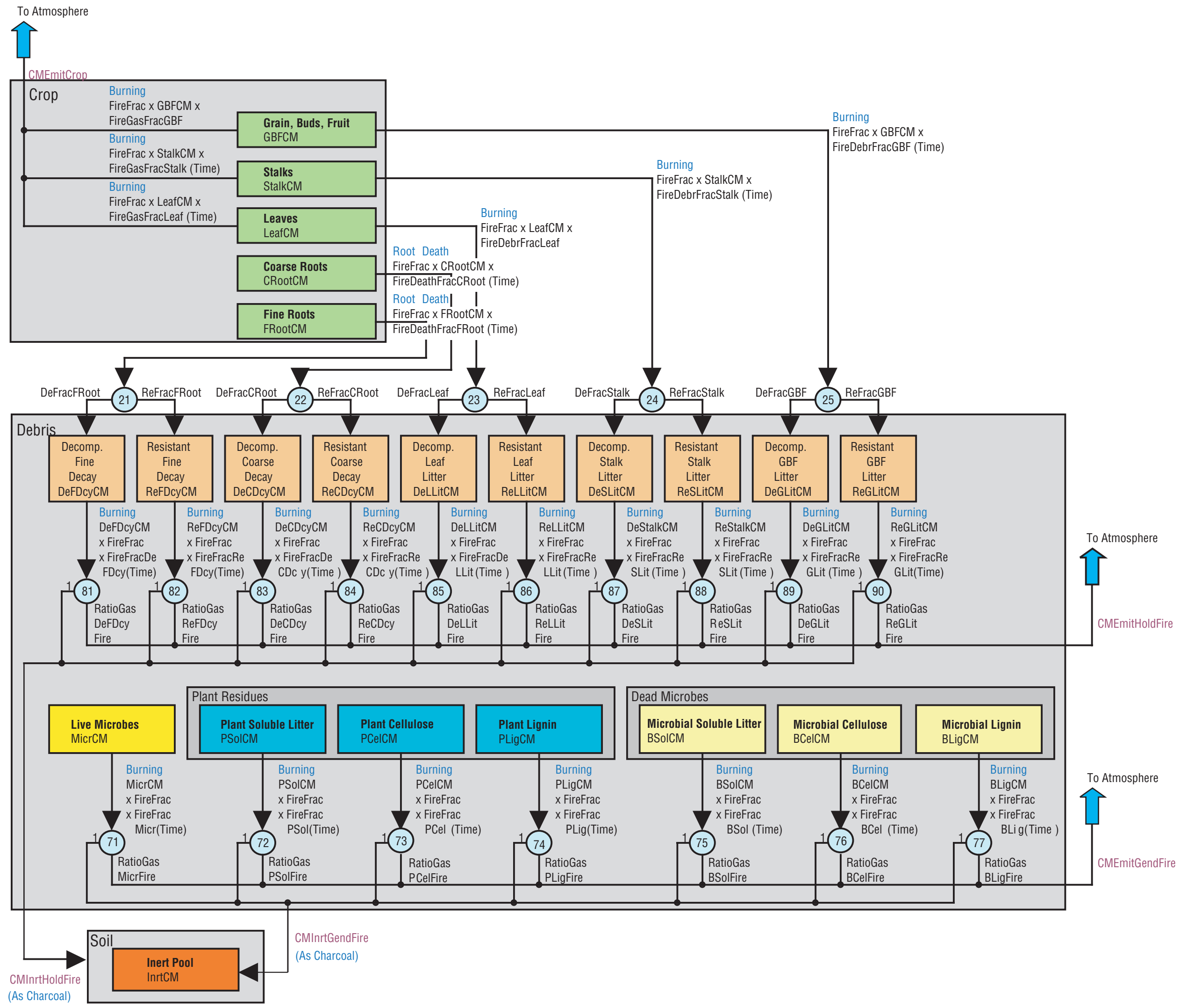


Figure 4.(a) Fire

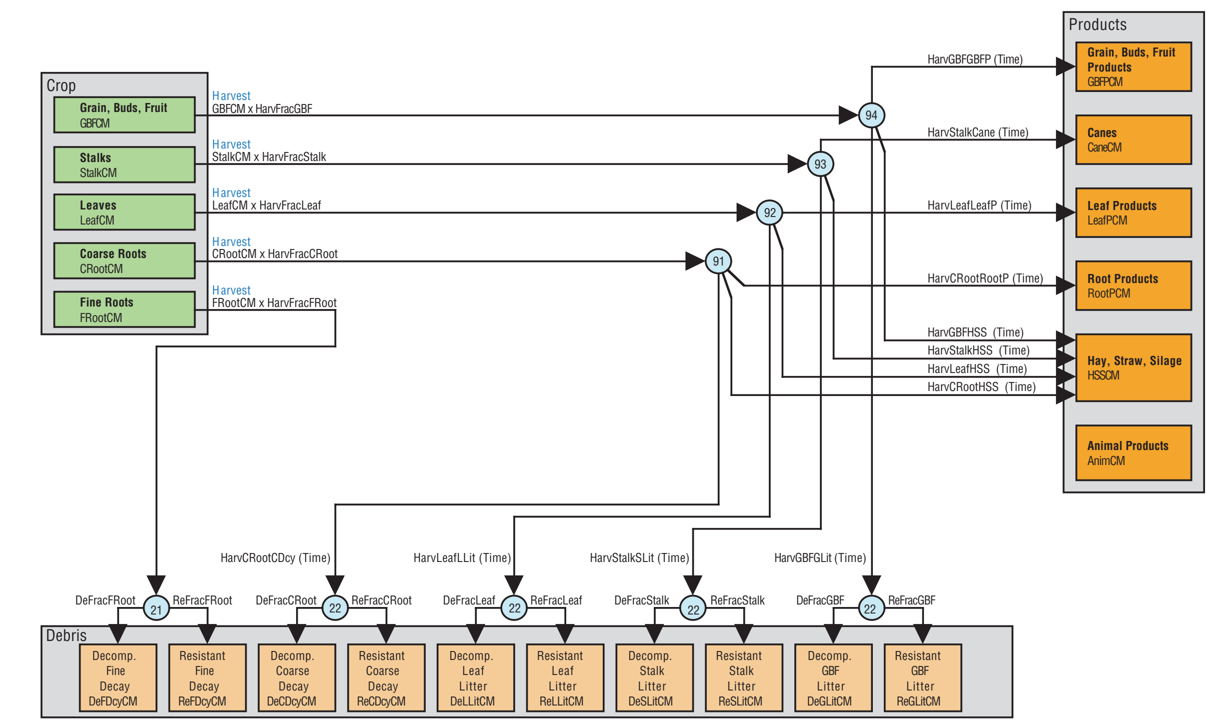


Figure 4.(b) Harvest

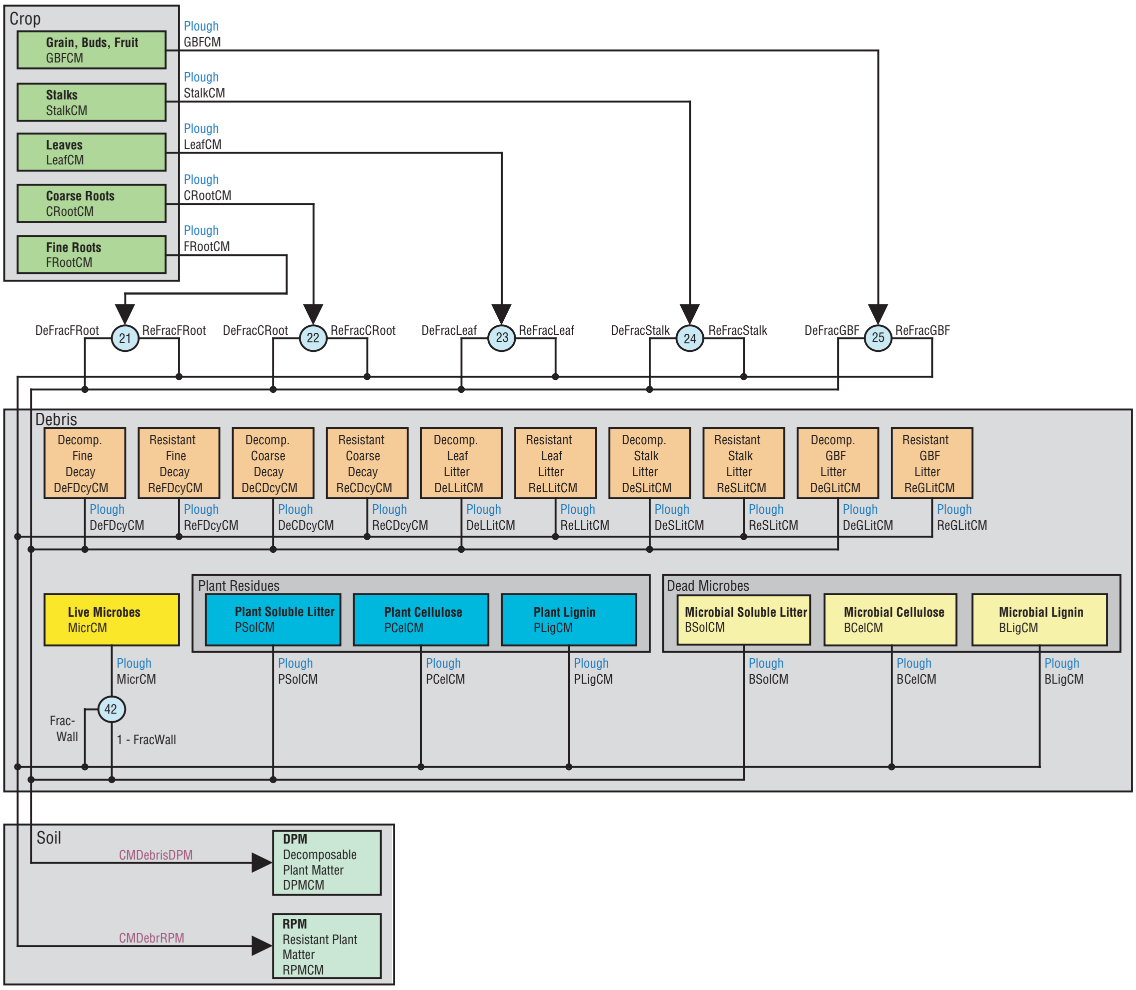


Figure 4.(c) Plough

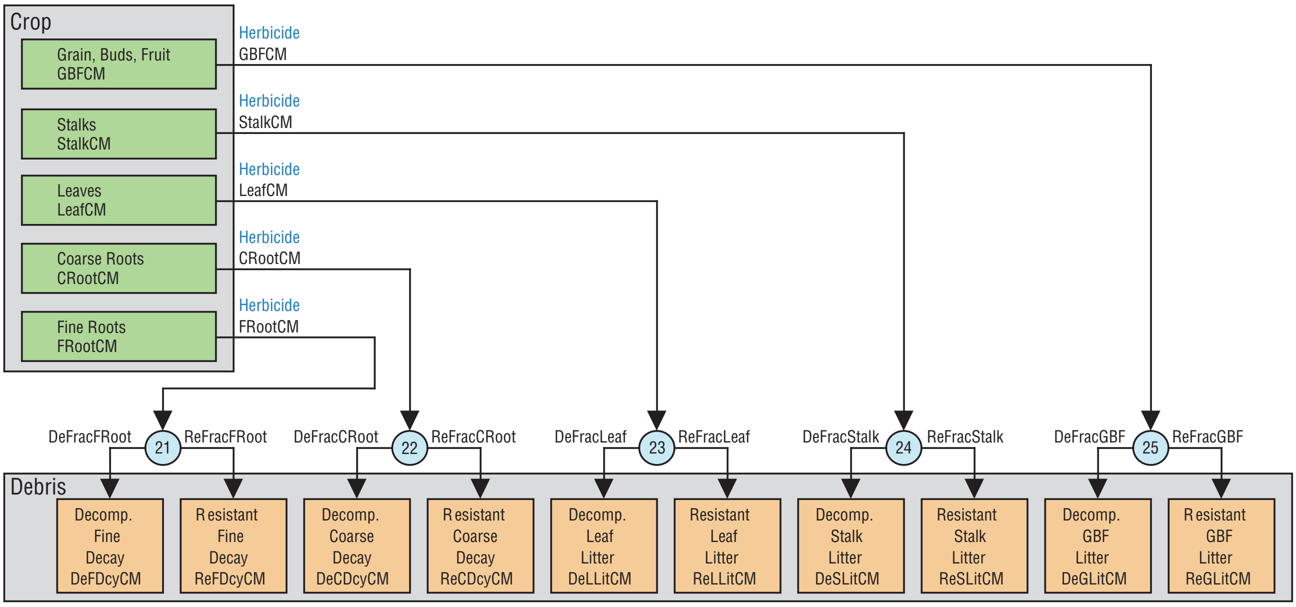


Figure 4. (d) Herbicide

2.4 *GENDEC* (FIGURE 5)

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.

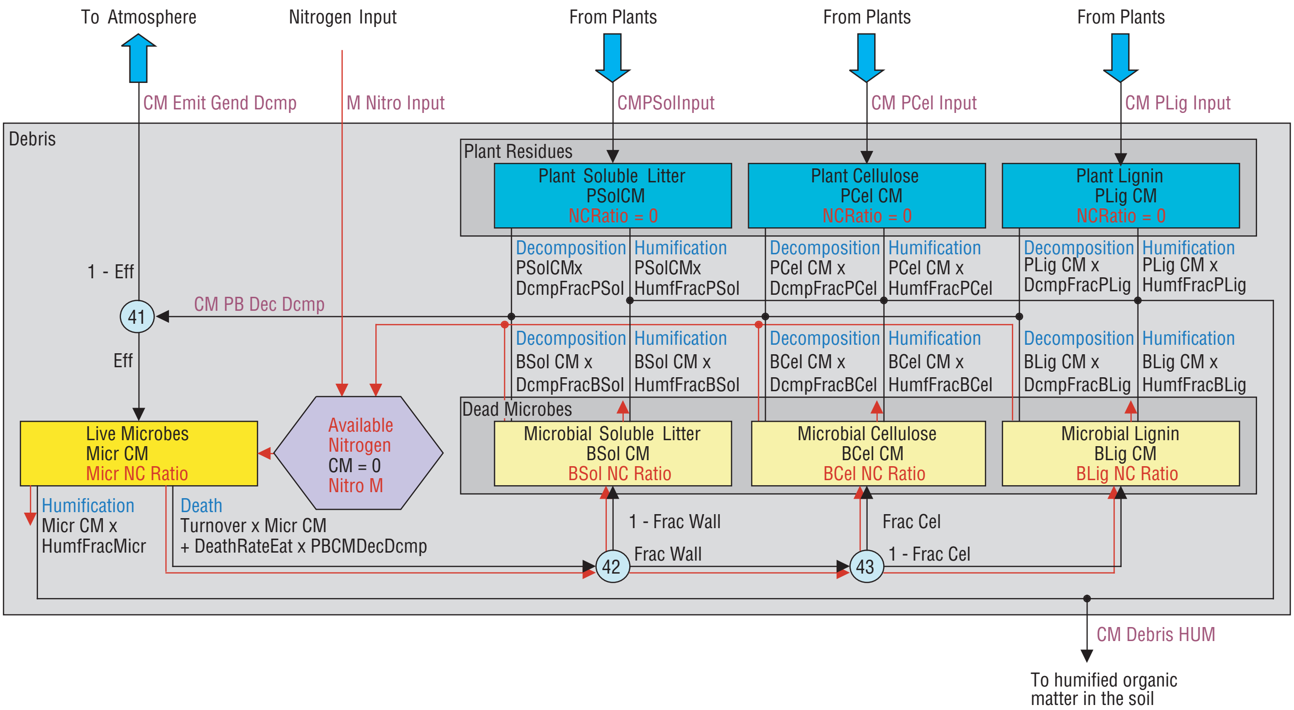


Figure 5. The *GENDEC* Model

2.5 *Roth C* (FIGURE 6)

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.

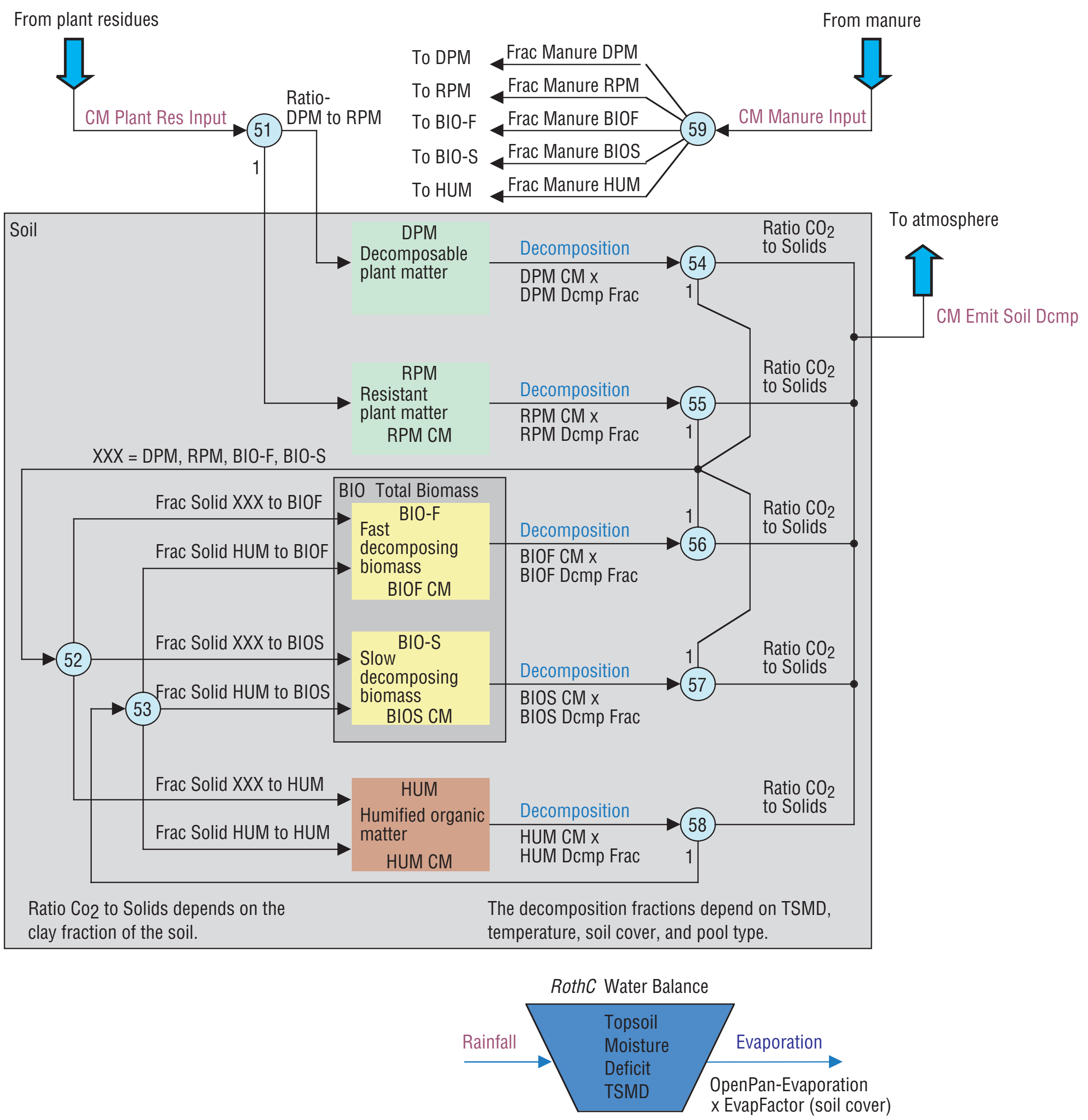


Figure 6. The *Roth C* Model

3. MODEL INTEGRATION (FIGURE 7)

The initial integration was performed on a Microsoft Excel developmental version of the forest component of *FullCAM* and linked 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 *Roth C* 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 application.

The linkages between models are sequential, from growth estimation (*3PG* for forests only) to management (*CAMFor* and *CAMAg*), decomposition (*GENDEC*) and soils (*Roth C*). The key linkages are as follows:

3PG to *CAMFor*: is achieved by inputting the total biomass increment from the *3PG* output to the *CAMFor* biomass table. Allocation of this material to various tree components (above- and below-ground) will be as per the *CAMFor* mass distribution table. This table can be filled manually or by using the formula embedded within *3PG*.

CAMFor to *GENDEC*: is a transfer of the above-ground debris pools, splitting the decomposable and resistant material described in *CAMFor* between the soluble, cellulose and lignin plant input pools of *GENDEC*. When operated in conjunction, the *CAMFor* breakdown rates for this material act as a 'flow' mechanism to introduce material to the *GENDEC* model. The above-ground debris pools of *CAMFor* thus become holding pools of material which can flow to *GENDEC*. Below-ground material is treated independently of *GENDEC* and is either transferred directly to the RPM and DPM pools of *Roth C* from *CAMFor*, or, if *Roth C* is not being implemented, given an empirical decay within the *CAMFor* 'Active' soils pools.

CAMFor to *Roth C* (direct): if *CAMFor* and *Roth C* are in use (without *GENDEC*) the function of the 'breakdown' rates in *CAMFor* is used to decompose above-ground litter (unless ploughed in) which is then (minus losses to the atmosphere) placed in the *Roth C* 'HUM' 'DPM' and 'RPM' (humified organic matter) below-ground pools. Root material is transferred to the *Roth C* DPM and RPM pools.

CAMAg to *GENDEC*: the interaction between *CAMAg* and *GENDEC* mirrors that of *CAMFor* and *GENDEC*. Again *GENDEC* only operates on the pool of above-ground litter.

CAMAg to *Roth C* (direct): the transfers of material when *CAMAg* and *Roth C* are run together (without *GENDEC*) are the same as for *CAMFor* to *Roth C*. Below-ground material (and above-ground material 'ploughed in') are dealt with in the DPM and RPM pools of *Roth C*.

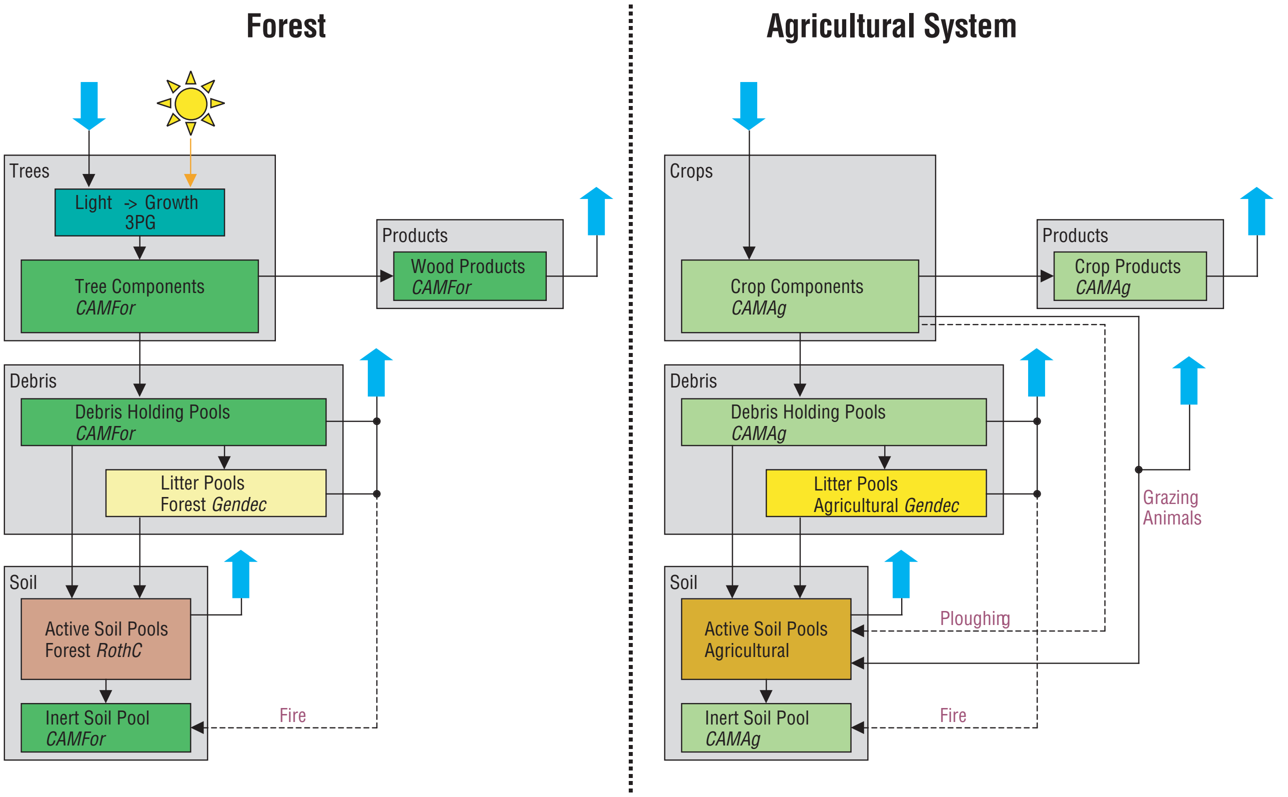


Figure 7. Overview of the *FullCAM* model

4. MODEL CALIBRATION

Any discussion on model calibration needs to recognise that *FullCAM* is a mix of accounting tools 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.

While the model is capable of being run at daily, weekly, monthly and annual time steps, the NCAS will generally operate the model at monthly time steps. The following sections describe the various calibration and data collection exercises that are underway to support the empirical and process elements of the model.

A range of activities are underway within the NCAS to provide required calibrations for the various components of the *FullCAM* model. Much of this activity preceded the development of the *FullCAM* model and was initiated upon selection of the various component models for independent parts of the overall program. The integration provided by *FullCAM* was not envisaged in the early development of the NCAS, and particularly not the operation of such a model in a fine resolution spatial form.

4.1 SOIL CARBON

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, 2000) 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. These include:

- Approximately 50 soils paired sites in Queensland;
- 10 soils paired sites in NSW; and
- 10 soils paired sites in WA.

These are sites in addition to those already available through previous studies. Details of the projects can be found on the NCAS website at http://www.greenhouse.gov.au/ncas.

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.

The *FullCAM* modules of *CAMAg* and *Roth C* will be used in conjunction to model carbon budgets at a 1 ha resolution, extracting information from the above-mentioned surfaces and tables relevant to each 1 ha grid within a model run.

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. *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.

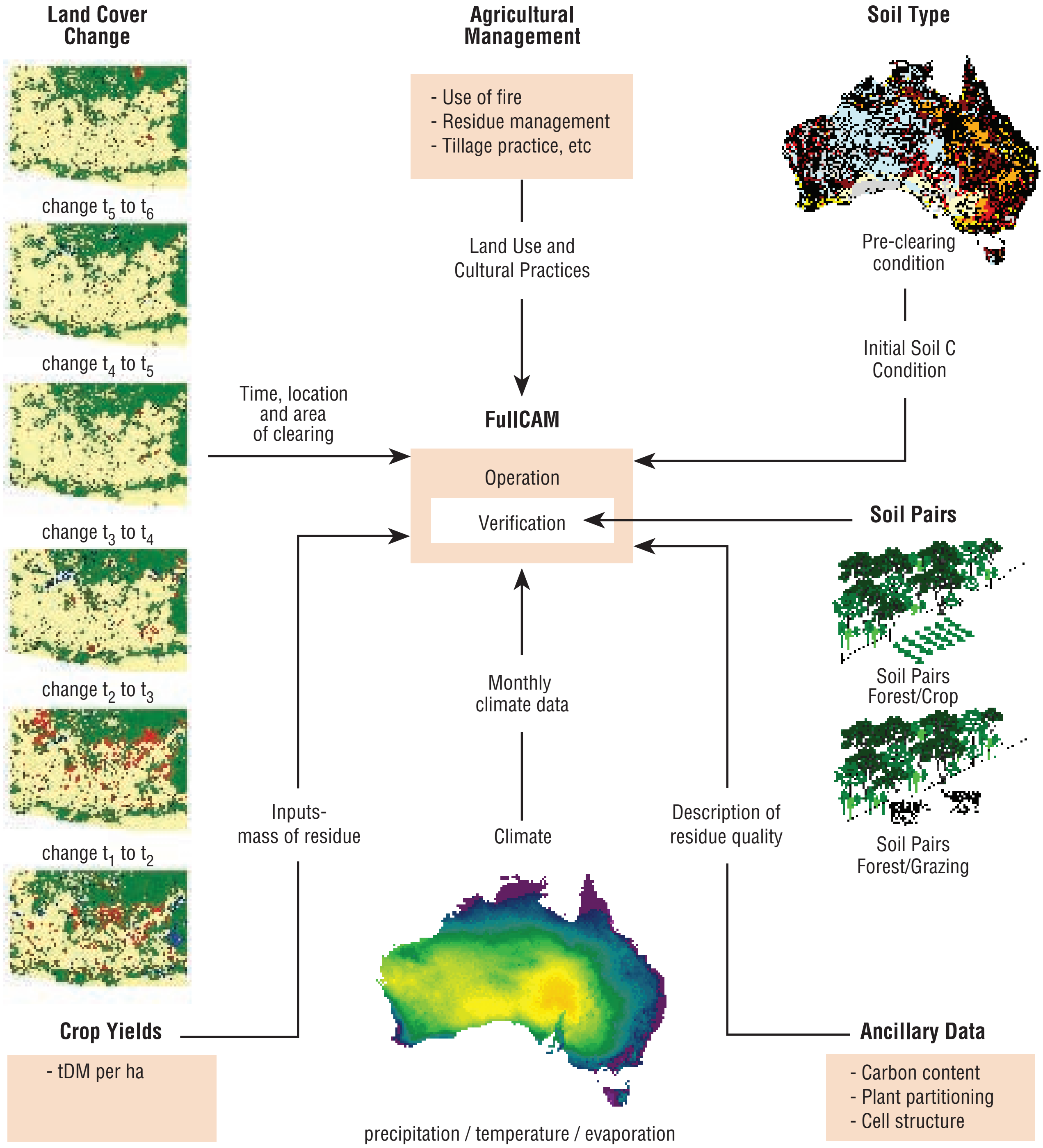


Figure 8. The Agricultural Soil Carbon Program

Figure 8

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 *CAMFor* and *Roth C* will be used in conjunction to model carbon budgets at a 1 ha resolution, extracting information from the above-mentioned surfaces and tables relevant to each 1 ha 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 (1 ha grids) to determine the timing of afforestation, reforestation and deforestation events.

4.2 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.

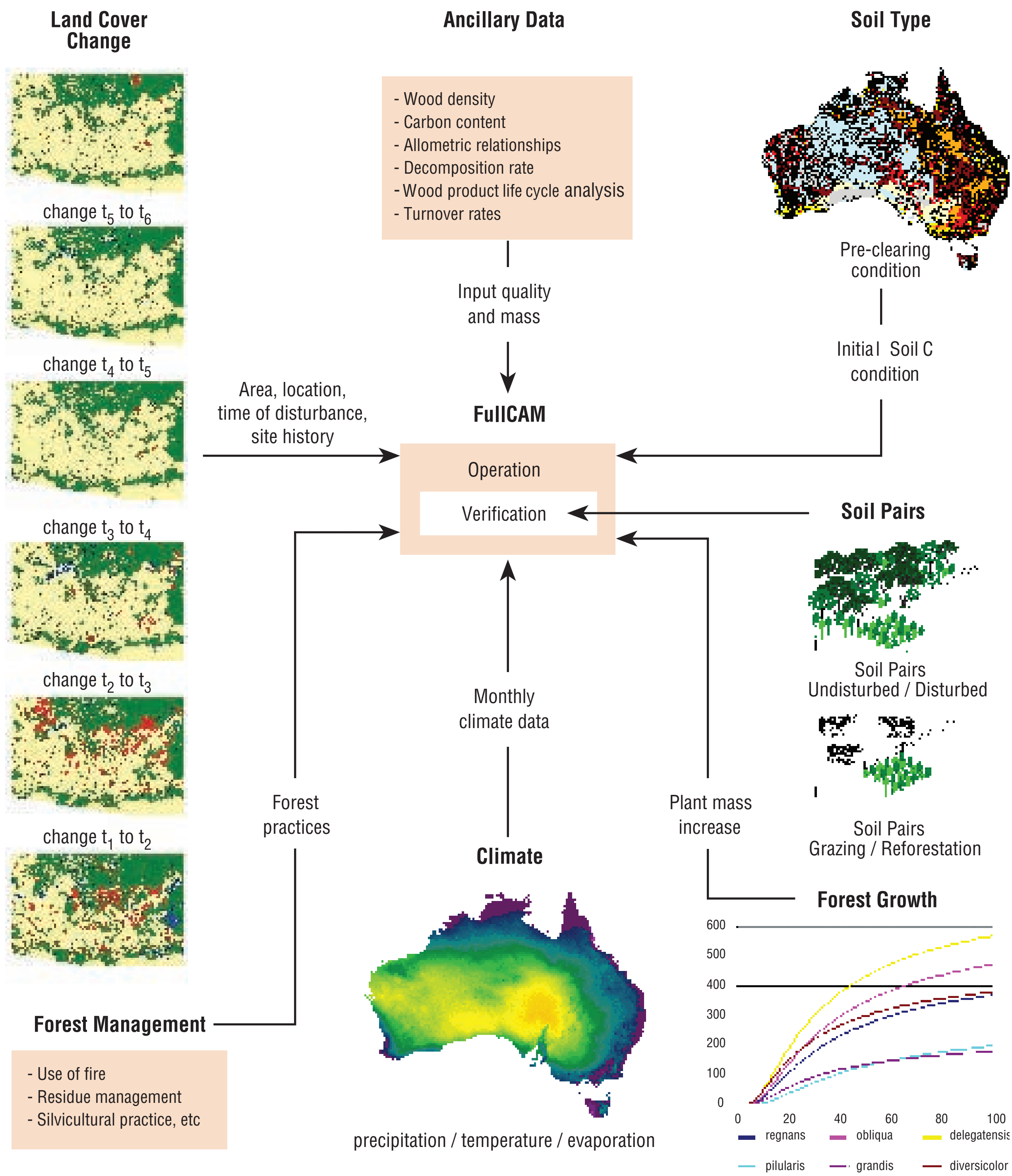


Figure 9. The Forest Soil Carbon Program

Figure 9

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.

4.2.1 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 1,000 ha. 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.

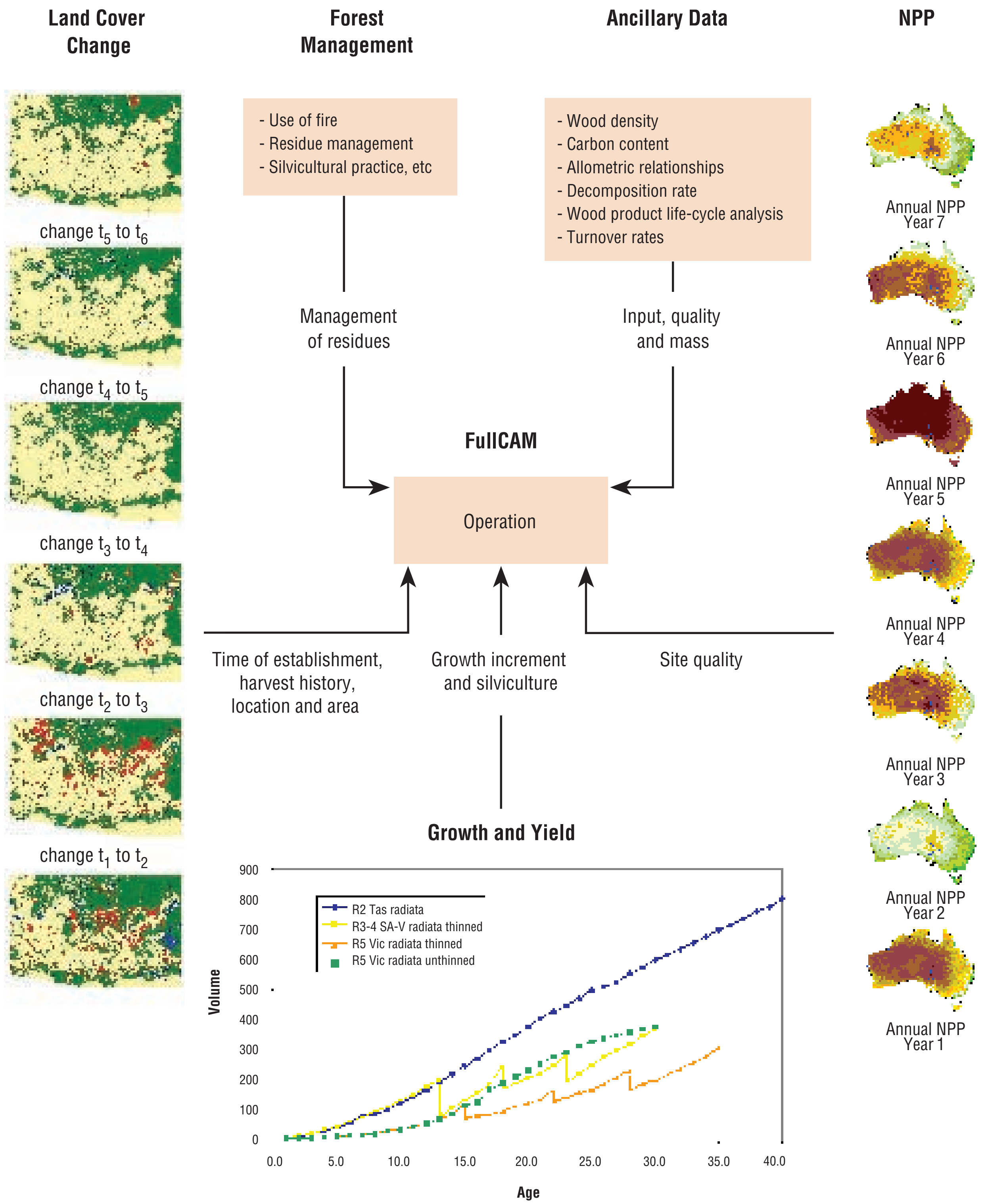


Figure 10. Plantations in 1990

Figure 10

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 (250 m) 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.

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 (2001).

4.2.2 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 in 1990 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.

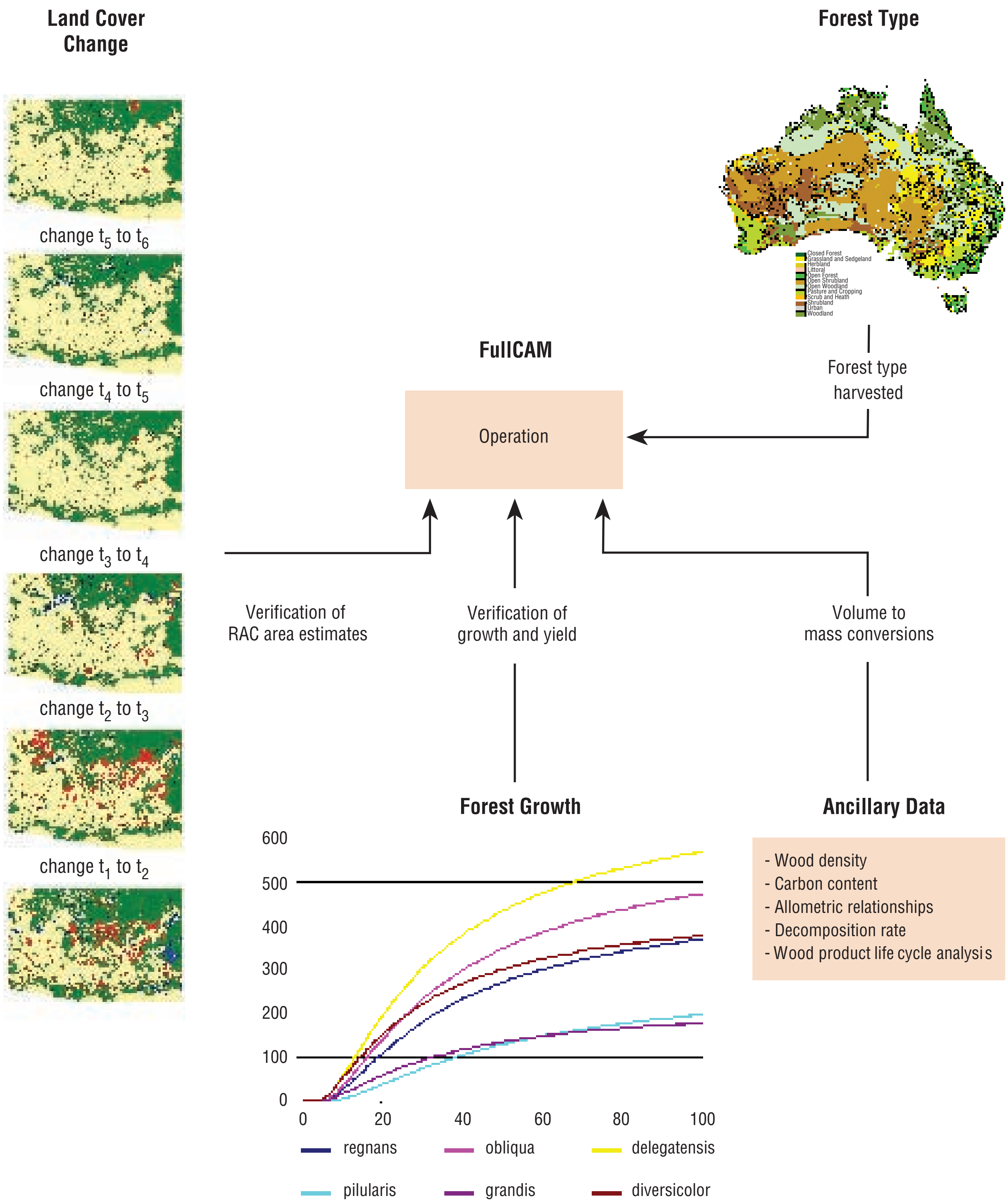


Figure 11. Managed Native Forests in 1990

Figure 11

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.

4.2.3 Wood Products

In 1999 the NCAS commissioned Jaakko Pöyry 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 in 1990 and beyond.

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.

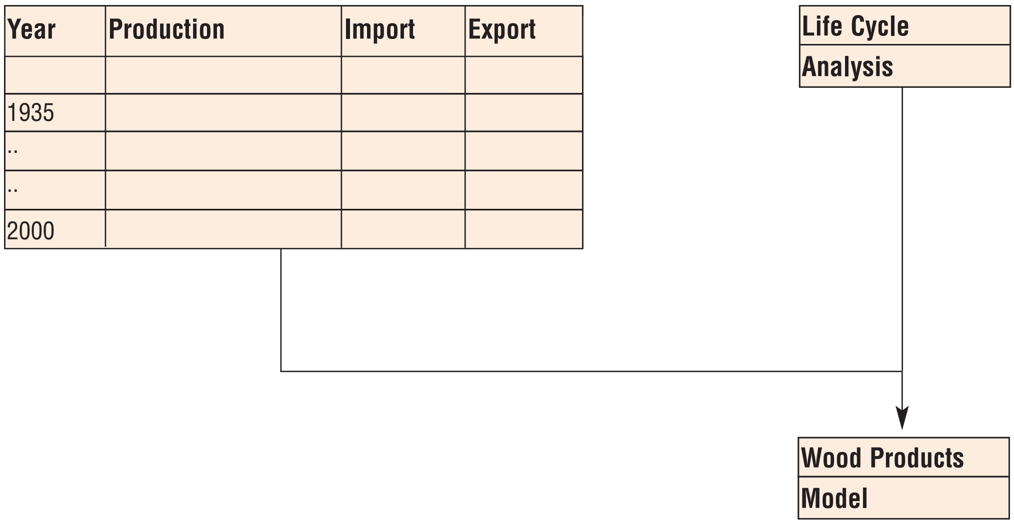


Figure 12. Wood Products in 1990

4.2.4 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 (250 m) 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 250 m 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).

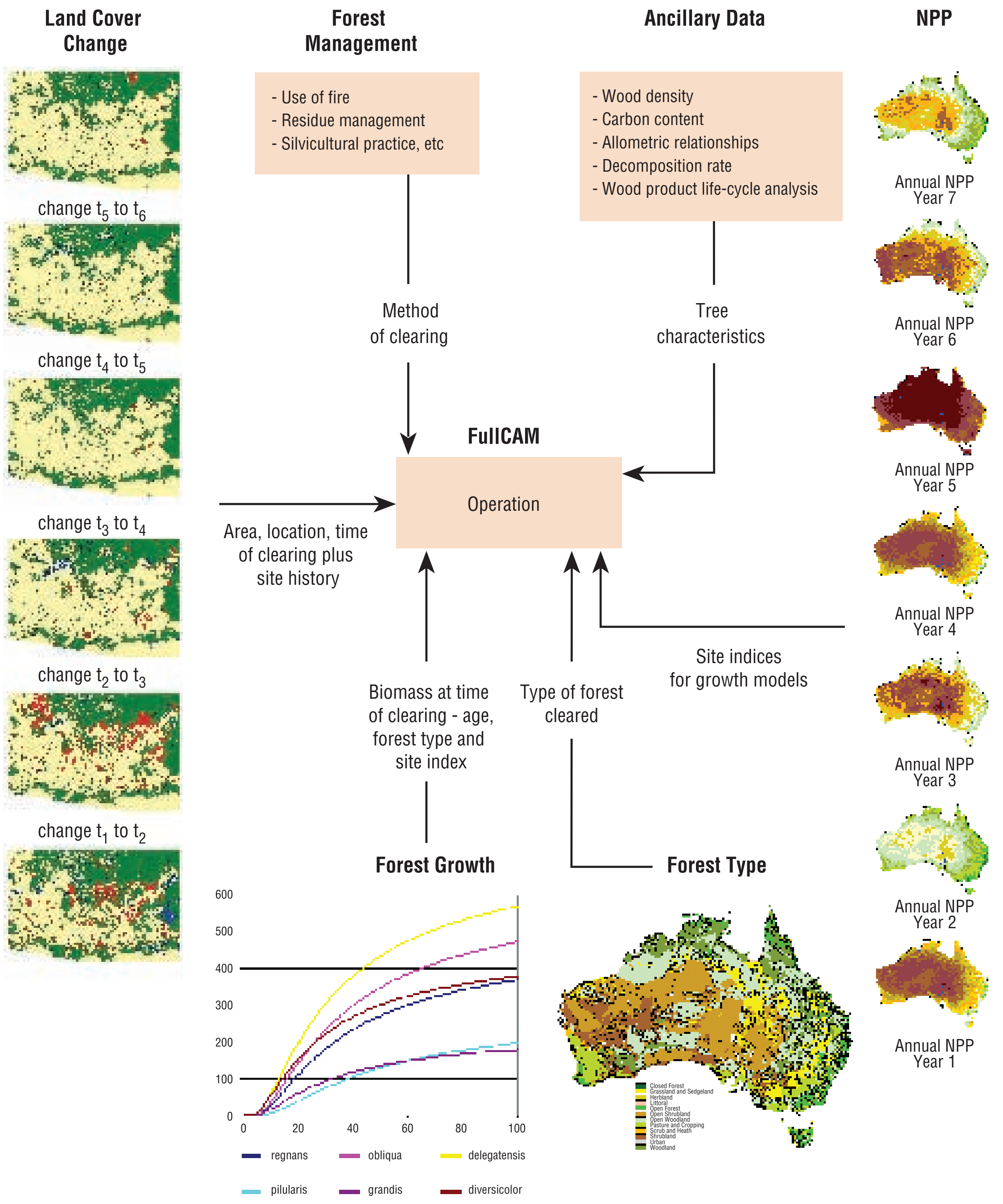


Figure 13. Land Clearing Biomass in 1990

Figure 13

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.

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.

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 (2001a) 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 (2001a) 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 in the 1990 Baseline 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 250 m 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.

4.2.5 Post-1990 Deforestation

The method used to estimate the biomass cleared in a location and at a time post-1990 will be the same as that used for the 1990 estimation. The spatially explicit 'activity' timing and area description will be extracted from the NCAS multi-temporal land-cover-change analyses. The age class determination in 1990 is limited to up to 18 years (commencing in 1972) with older ages considered to carry mature biomass as a default until a further span of time (age) is obtained in later reporting periods. The span of potential ages, and therefore range of the mass estimates, can obviously be increased over time as the span of time since the first continental remotely-sensed imagery increases.

Biomass estimation will be able to use the same multi-phase sampling (for mature biomass) results that were used for the 1990 Baseline. This can be continually improved as additional total biomass data becomes available. If it is identified that the vegetation has not reached an age suggesting maturity, then age-based 'site index' growth models can be applied, taking age from the land-cover-change analysis and site index from the annual 1 km productivity surfaces.

4.2.6 Post-1990 Afforestation and Reforestation

Unlike the regional estimates used in the *CAMFor* modelling of the national account for the 1990 Baseline approach (Brack and Richards, 2001) the post-1990 afforestation and reforestation needs to be accounted for on an activity basis, project by project, which explicitly records geospatial and temporal features including the time of establishment. This activity approach is consistent, in fact symmetrical in method, with the approach used for deforestation accounting for the 1990 Baseline and for post-1990 accounting.

The move to a spatially explicit accounting approach after 1990 places significant additional demands on data inputs. However, the fundamental tools and ancillary data (allometry, carbon content, and wood density) are still relevant. The *FullCAM* model, although previously used for regional level accounting, can be modified to operate at a project by project scale.

The multi-temporal land-cover-change analysis of the NCAS has been designed to detect change in both directions, that is, loss and emergence of woody vegetation. It is therefore possible to detect the area and age of establishment of woody vegetation for post-1990 plantings as was done for the pre-1990 plantation estate. The change in canopy cover can be monitored so that it is feasible to make initial assumptions about site stocking and productivity. Consideration of the prior site history, size, geometry, canopy cover and spatial relationship to other similar areas enables determination of the allocation to plantation and management type.

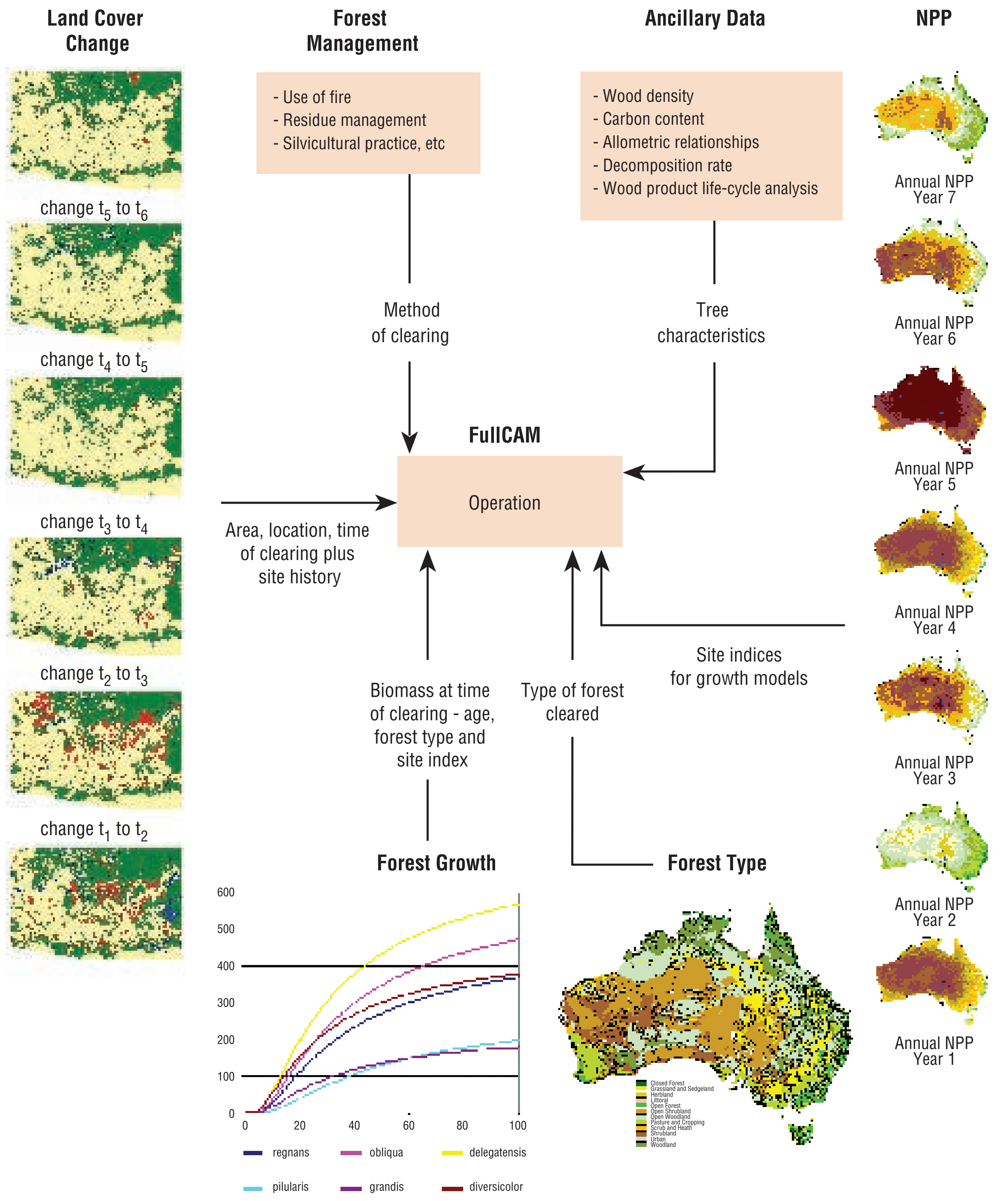


Figure 14. Post-1990 Deforestation

Figure 14

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 major determinant of the additional information that may be available to the NCAS is the development of registers to facilitate carbon trading. Access to registers, be they private or public, or maintenance of a central government register, would provide a high quality information source on post-1990 plantation location, area, growth and management.

Random sub-sampling of identified projects could also be used to verify growth against predictive growth models adjusted for annual productivity. Annual growth could be estimated using the technique previously described, linking site index dependent models such as those of West and Mattay (1993) to age and disturbance histories from the land-cover-change analyses. However, outside of a carbon trading environment, and even within that environment, accurate reporting of carbon stock change will be required only over the period 2008 to 2012. This allows time for a phased approach to the development of this accounting capacity.

Over time it will be possible to refine growth estimates through improved growth models, particularly as the fine scale productivity surface approach can be annualised using up-to-date climate data.

Changes such as management intensity and thinning should be detectable through the remote-sensing land-cover-change program, allowing for the modelling of growth response to disturbance. Harvesting will also be clearly identifiable through the multi-temporal land-cover-change program. The current life cycle analysis for wood products will be a solid base on which to determine the impact of wood product storage and decomposition with the life cycle analyses applied at a stand, rather than national scale. Further work on life cycle determination will refine the models.

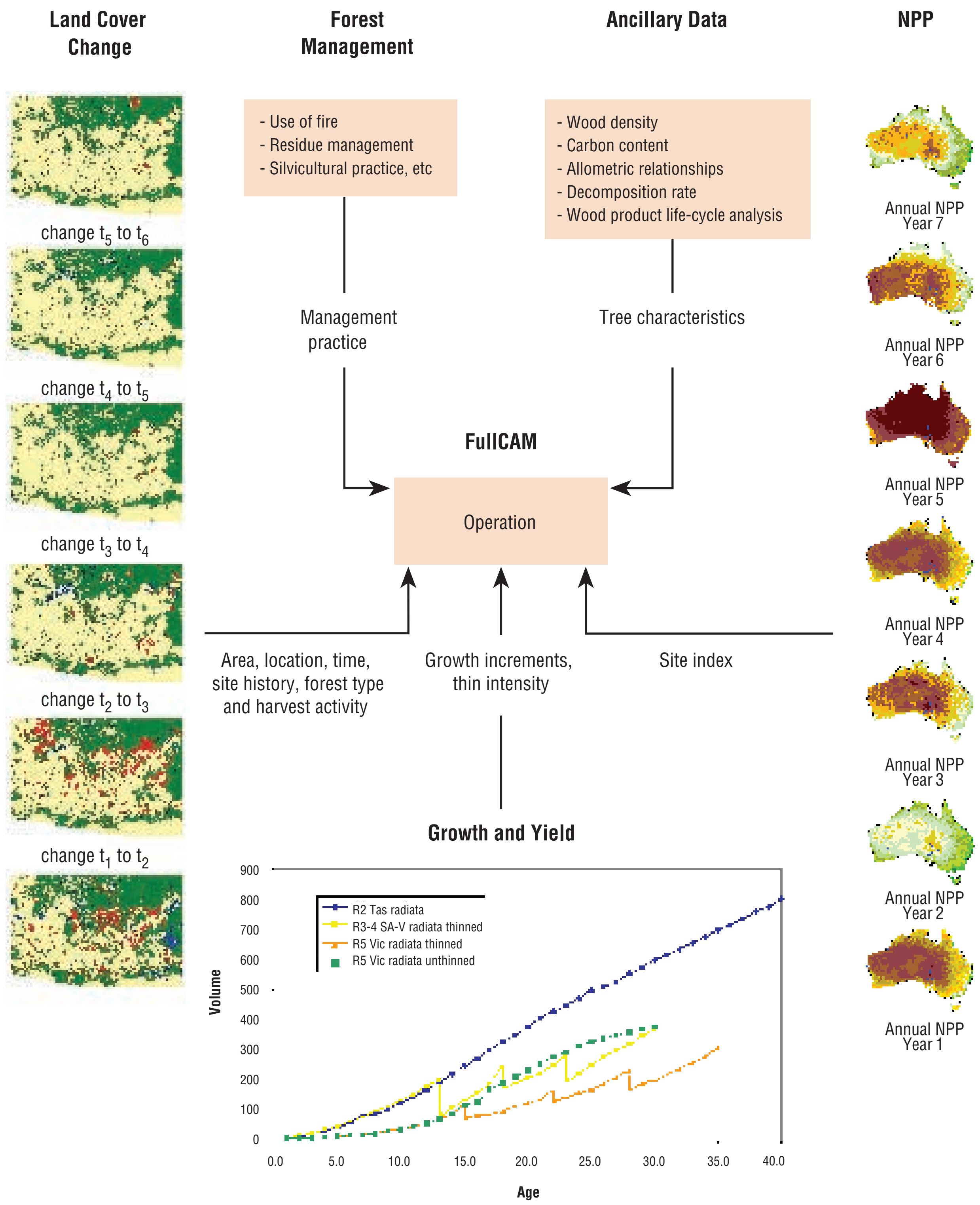


Figure 15. Post-1990 Afforestation and Reforestation

Figure 15

The Land-Cover-Change results can be used to identify the area, location, time, site history and forest type (conifer / broadleaf), and harvest activity. The annual NPP can be used for determining site quality. Growth and Yield can be taken from Turner and James (2000) and Forest Management from the NCAS survey. Ancillary Data, such as carbon content, can be taken from a variety of sources.

4.2.7 Forest Management (Article 3.4)

Forest management can be taken to include those forests under human management that are not otherwise included under Article 3.3 as post-1990 afforestation and reforestation. Particular categories of forests that will come into this account are the pre-1990 plantation estate, regrowth (clearfall) native forests and selectively harvested native forests. Grazed woodlands and rangelands are considered in the Grazing Lands component of accounting under Article 3.4.

There are two potential approaches to Article 3.4. The first is a broad approach that brings all relevant lands into the accounting framework. The second is to establish an ‘activity’ on a relevant parcel of lands which brings only that physical area of land into the accounting framework.

Whichever approach is followed, the implications for carbon accounting have several data and methodological elements in common. Many are also shared with the accounting procedures for the forest sector accounting under the 1990 Baseline and for post-1990 plantations.

The approaches to each of the forest components of Article 3.4, under both broad- and activity-based accounting, are considered in the following sections.

4.2.8 Post-1990 Plantations

For the 1990 Baseline these plantations can initially be described on a regional basis by type – broadleaf or conifer. These areas, in 10-year age classes, can then be allocated to one of the indicative yield patterns of Turner and James (2001). This approach imposes strict rules for thinning and harvest timing, with ages evenly distributed across the broad 10-year age classes. Refining these estimates by identification of plantation areas using the multi-temporal land-cover-change analyses will move the accounting from a regional scale, with 10-year age classes, to a spatially explicit approach, with a maximum of five-year age classes. This will also allow for the tracking of changes in canopy cover on those sites and therefore determination of the impact and timing of thinning and harvest events. Such analysis will also be vital in making allocations to post- and pre-1990 plantations.

From the location, and therefore the likely markets for wood products, wood product type allocations can be made. Accounts using the *FullCAM* model could be derived in much the same way, using largely the same ancillary data, as used in the 1990 Baseline estimation.

Activity-based accounting brings with it an additional demand, the need to be able to identify the timing and implementation of a relevant ‘activity’. Accounting may also be called upon to identify the resultant carbon stock change directly attributable to a particular activity. This demands more detailed modelling than even the annual productivity-adjusted growth modelling proposed within the current NCAS. The segregation of effects such as those of CO2 fertilisation has not been considered because neither the data nor model approaches currently available could support routine implementation. It is proposed that, should such capacity be required, model approaches will be explored rather than the extremely expensive approach of maintaining a series of relevant measured control plots as a baseline which can only account for ‘managed’ effects.

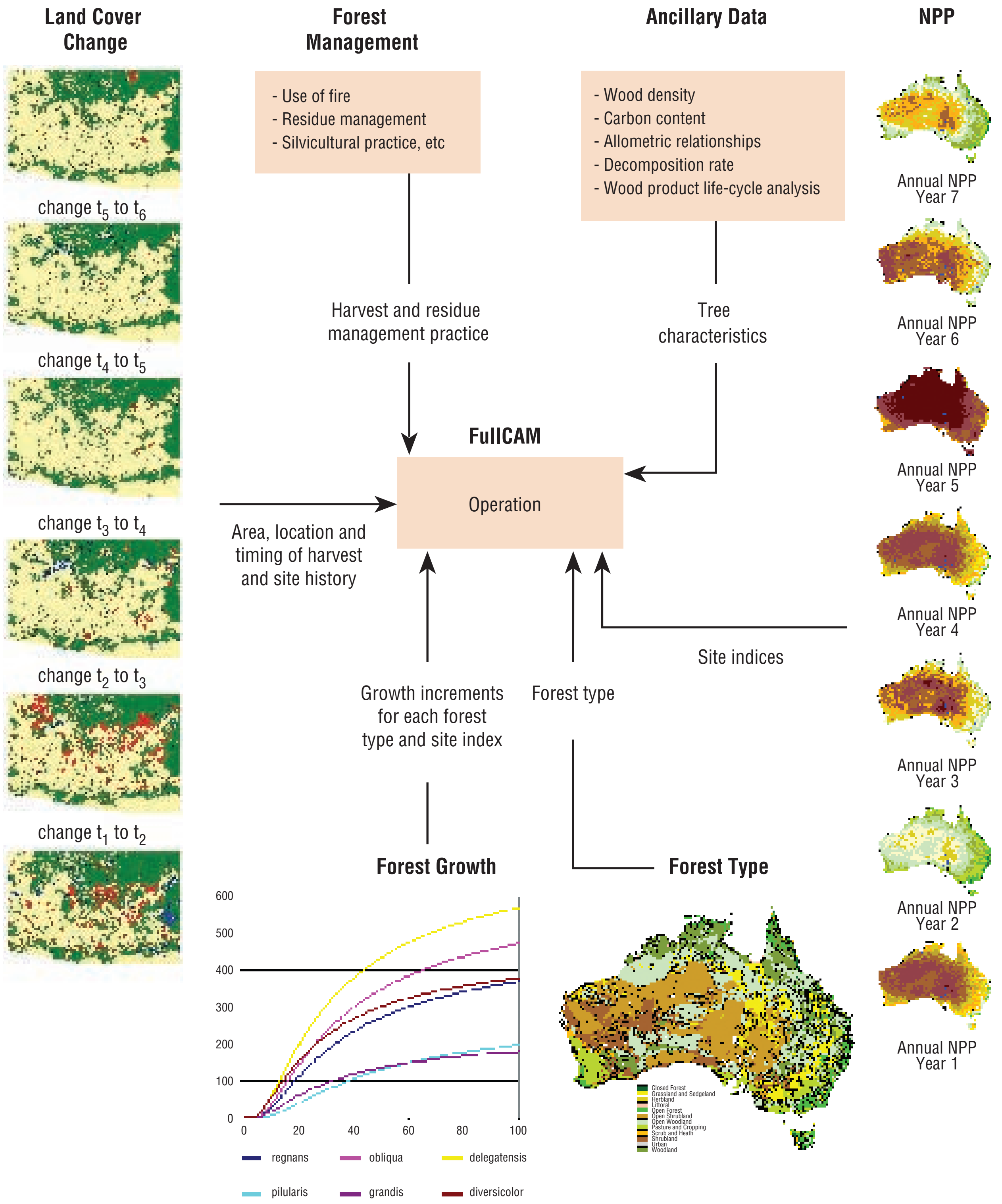


Figure 16. Forest Management: Regrowth Forests

Figure 16

The area, timing, location of forest harvest, and site history can be taken from the Land-Cover-Change results. This can be matched to the relevant Forest Type and the NPP value as a site index. The biomass at the harvest and subsequent growth increments can be drawn for Forest Growth models using Forest Type, site index (NPP) and age (Land-Cover-Change). Forest Management information can be drawn from the NCAS survey, and Ancillary Data from a variety of sources.

4.2.9 'Regrowth' Forests

Regrowth forests as described here are the regeneration of commercial forests following a clearfall operation. This intensive form of harvest occurs across approximately one percent of managed forests and is generally practiced on the more productive forest types. Some clearfall on sites of moderate productivity does occur, particularly where harvesting includes pulpwood.

The timing of harvest in these forests will be readily detectable using the land-cover-change analyses. Both clearfall harvests and canopy change due to thinning should be identifiable through changes in canopy cover. Manual checking of charge analyses for fire will largely isolate disturbances due to harvest.

Density changes can be matched to multi-temporal productivity surfaces to provide both the age and 'site index' as they influence growth. Drawing on ancillary data to describe forest type or floristics, it will be possible to fit growth functions, such as those provided by West and Mattay 1993, to enable time based and productivity adjusted annual growth estimates. The productivity index will provide the 'site index' constant for these models. The models will define the trajectory of change, with the eventual mass at maturity being defined through the multi-phase sampling. The use of time-based models acknowledges that, while the effects of climate variability tend to average out over time, to give relatively consistent growth over a long period, the short term predictions needed to report under the Kyoto Protocol (2008–2012) will require sensitivity to growth at the relevant time.

Verification of growth increments by field sampling will be required and should be completed on a selection of permanent plots. These are likely to be available as part of existing inventories. Obviously care needs to be taken that data from plots used for verification are clearly segregated from any used for model calibration.

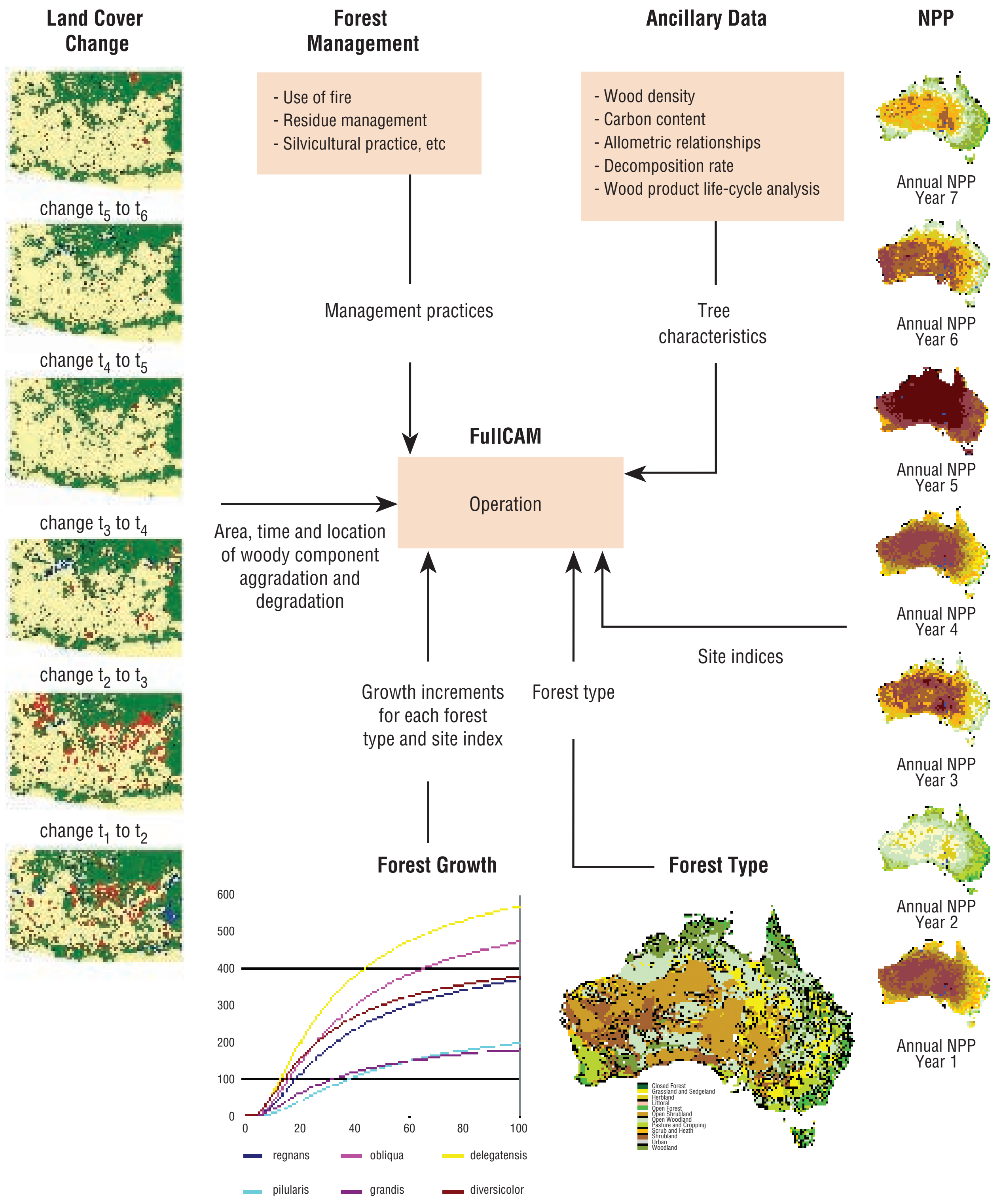


Figure 17. Forest Management: Selectively Harvested Forests

Figure 17

The area, timing, location of forest disturbance, site history and intensity of disturbances can be taken from the Land-Cover-Change results. This can be matched to the relevant Forest Type and the NPP value as a site index. The biomass at harvest and subsequent growth increments can be drawn from Forest Growth models using Forest Type, site index (NPP) and age (Land-Cover-Change). Forest Management information can be drawn from the NCAS survey, and Ancillary Data from a variety of sources.

4.2.10 Selectively Harvested Forests

Selectively harvested forests represent the most complex, widespread and variable of the forest management systems. To assist in defining these management systems, the NCAS has commenced a compilation of material to describe the management of various forest types and for various products over time. This work will be the parallel of the NCAS Technical Report No. 13 (Swift and Skjemstad, 2000), which considered agricultural management.

One of the initial considerations in adopting these approaches to this task was to determine the impact of tenure on carbon increments and carbon storage capacity. Reports, particularly the results of the Resource Assessment Commission (1991), show that, in terms of merchantable timber volume, significant differences can be expected with tenure. Far lower mean annual increments (MAIs) for merchantable volumes are reported in the private than in the public estate. A critical element in using the preferred multi-phase inventory technique is that this difference does not hold for total biomass as it appears to for merchantable volume (Brack, 2001a).

Brack (2001a) tested the assumption total stem volume would not vary by tenure, and could therefore be used as a reliable basis for the determination of total biomass across all tenures. He used forest inventory data for private and public estates covered by the Tasmanian PI forest typing (Stone, 1998) and found that tenure was not a significant factor in determining total biomass, whereas it was for merchantable volume. This result is particularly significant to the NCAS because it confirmed the appropriateness of using the same multi-phase approach to total biomass estimation for forest activity as can be used for the estimation of biomass lost due to land clearing.

4.2.11 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.

Attribution of either form of change to a ‘cause’ requires the identification of both the cause of change and the relative contribution of multiple causes which may be acting in concert, only some of which are relevant activities under the Kyoto Protocol.

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 be readily identified, it will be possible to segregate this ‘natural’ cause of change from land clearing events. Regrowth post-clearing

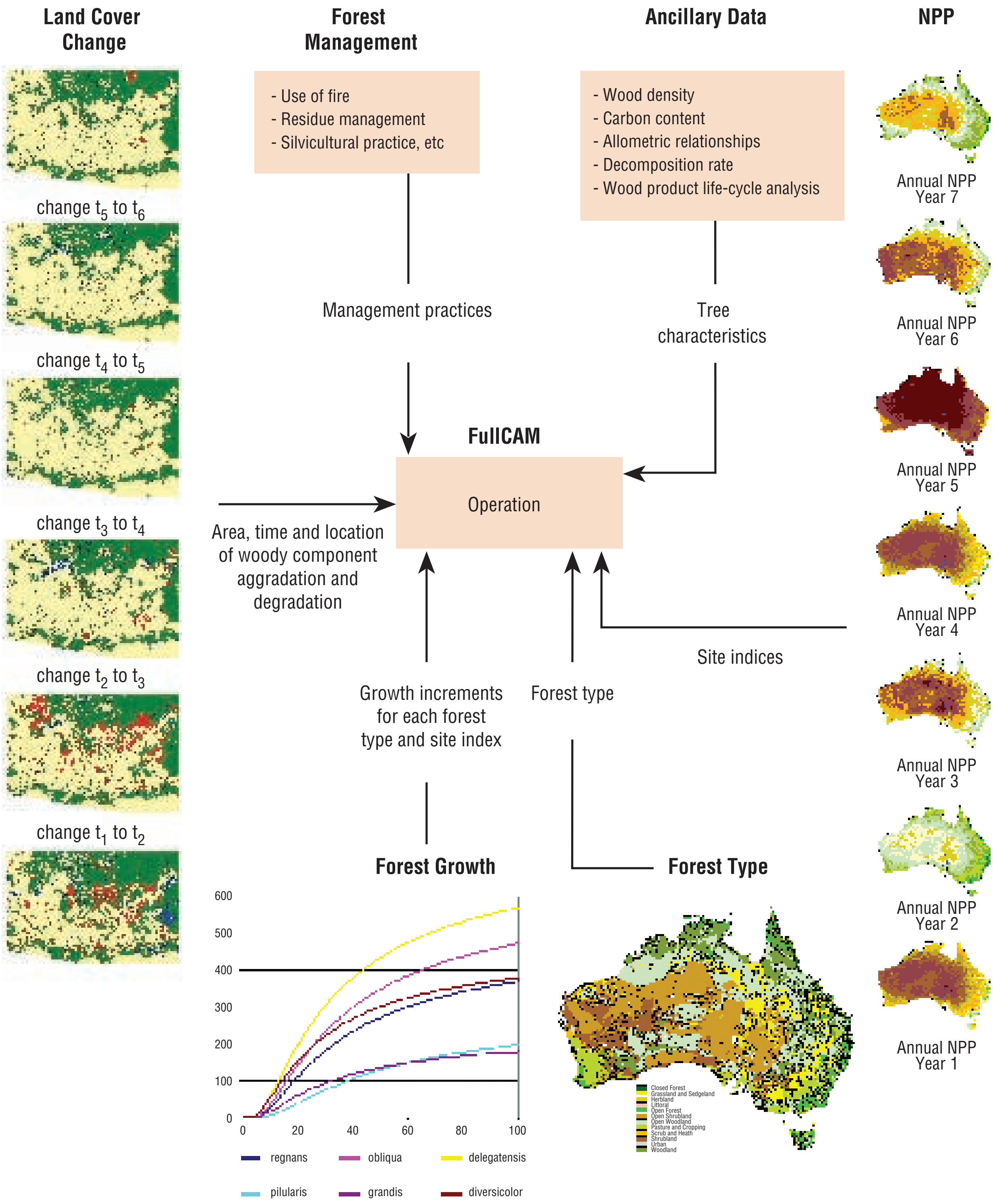


Figure 18. Grazing Lands

Figure 18

The area, location and timing of aggregation and degradation of the woody components of grazing lands can be taken from the Land-Cover-Change results. Forest Management information can be used to identify likely causes and impacts of degradation. The Forest Type and Site Index (NPP) information can be applied to the appropriate Forest Growth models to determine the growth increment in biomass. Ancillary Data can be drawn from a variety of sources to define carbon contents, allocation of growth to various tree components, etc.

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 the canopy based method is only appropriate for detection in early years in dense systems.

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'.

5. MODEL VERIFICATION (FIGURE 18)

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 otherhand, 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.

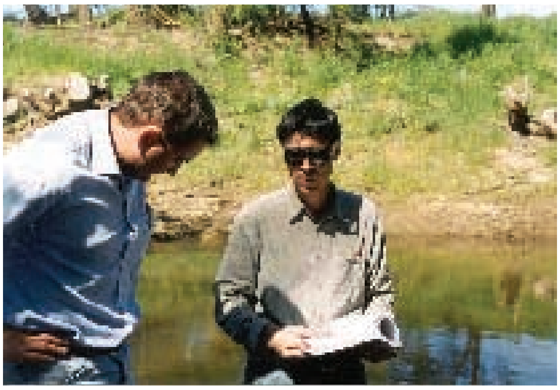
The various verification activities include permanent plot, long-term trials with internal measurement, landholder survey, ongoing chronosequence pairs activity, and comparison with other reliable, independent methods and models.

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.

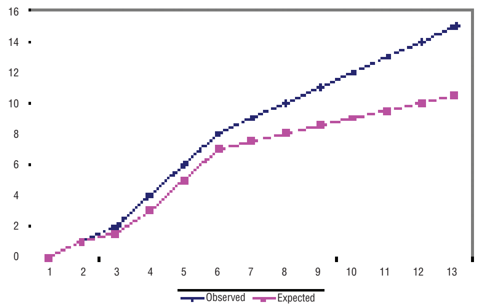
Chronosequence Set
Pairs as model targets

Long term measurement to validate
growth model results

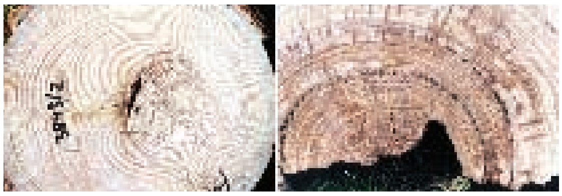
Ongoing survey of management activity



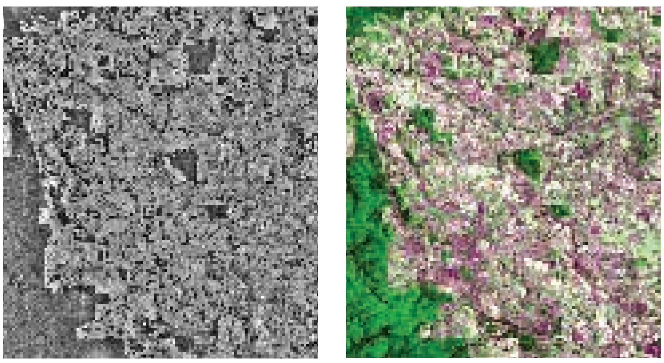
Verification of models
against measured data



Chronosequence decomposition studies



Air photographs used to verify
satellite interpretation



air photograph

satellite image

Figure 19. Verification Activities

6. 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 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, AGO 2000c).

The development of the integrated *FullCAM* model has furthered this synthesis by providing an ability to operate a singular intergrated model framework. 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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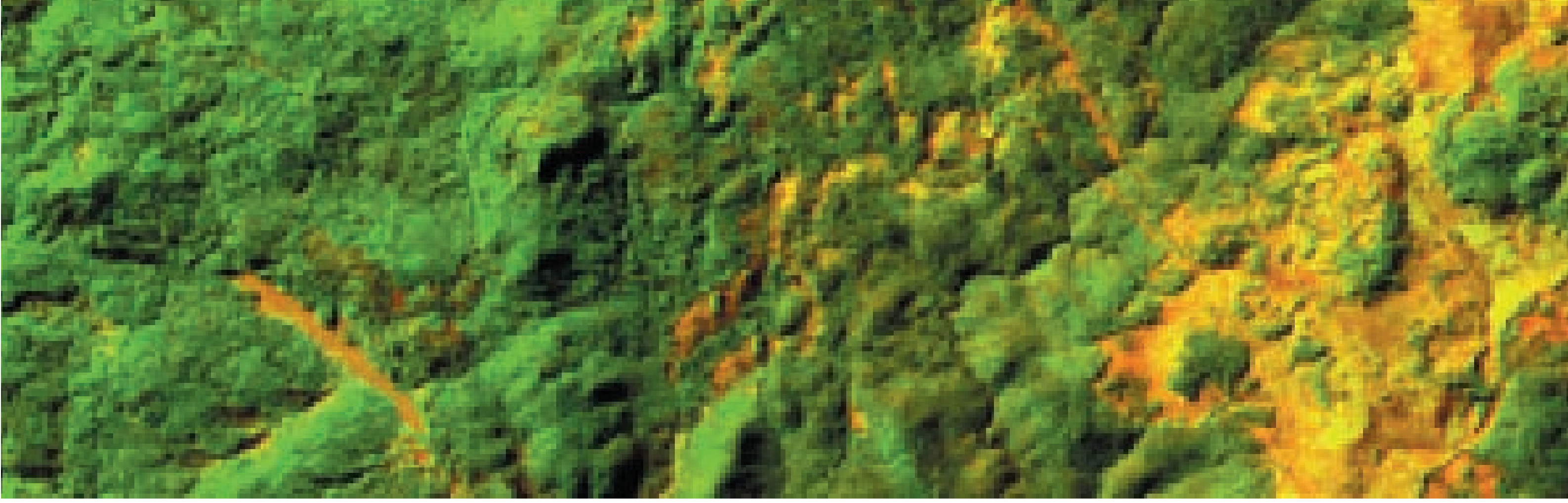

The National Carbon Accounting System provides a complete accounting and forecasting capability for human-induced sources and sinks of greenhouse gas emissions from Australian land based systems. It will provide a basis for assessing Australia's progress towards meeting its international emissions commitments.

The *FullCAM* Carbon Accounting Model: Development, Calibration and Implementation for the National Carbon Accounting System

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