Development of a carbon accounting model (FullCAM Vers. 1.0) for the Australian continent

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Summary

Continental-scale carbon accounting capable of the spatial and temporal distinctions demanded by the Kyoto Protocol requires a modelled approach which integrates over space and time the effects of changing land use, land management and climate variability.

To assist in the development of Australia's National Carbon Accounting System (NCAS), the Australian Greenhouse Office has developed and calibrated an integrated suite of models relevant to Australian conditions for which data were available or could be generated for their application. These point-based models were then made operational within a GIS environment to enable application at a fine spatial (25 m) and temporal (monthly) resolution for the Australian continent.

This paper focuses on the FullCAM 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 integrates information drawn from remotely-sensed land-cover change, modelled productivity surfaces, mapped resource inventories and other ancillary data to perform the various accounting procedures for Australia's NCAS.

This framework has been developed in parallel with a range of data collation, model calibration and verification activities across the continent. The framework provided by FullCAM has allowed highly specific and therefore targeted and cost-effective model calibration and verification activities. FullCAM, as the analytic model for Australia's NCAS, will continue to be refined within the established framework.

Keywords: carbon; carbon cycle; carbon sequestration; models; accounting; inventories; Australia

Introduction

A National Carbon Accounting System (NCAS) has been established by the Australian Government to provide a complete carbon accounting and projection capability 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 would have to rely on the collation and synthesis of resource information and the calibration and verification of a series of models. The vast and heterogenous land areas in Australia under extensive forest and agricultural management demand an approach founded on modelling. An approach based purely on measurements (inventory and monitoring) is not practical given these conditions and the spatial (maximum 1 ha land unit) and temporal (annual) carbon accounting requirements of both the United Nations Framework Convention on Climate Change, and the Kyoto Protocol to the Convention (Climate Change Secretariat 1997). Following the development of an Excel-based forest carbon accounting model (CAMFor), a linked model for forest and agricultural systems (known as FullCAM) has also been developed. It integrates the CAMFor and CAMAg-based routines into a single (C^{++} code) model capable of carbon accounting in transitional (afforestation, reforestation and deforestation) and mixed (e.g. agroforestry) systems. The fine spatial and temporal resolution modelling capability provided by FullCAM is fundamental to Australia's ability to respond to these accounting requirements at both national and project scales.

This paper is the first of a series of three in this issue of *Australian Forestry*. It provides a description of the first operational version (1.0) of the FullCAM carbon accounting model. The other papers in the series:

(i) provide a detailed overview of the site biomass-productivity-based method developed for continental biomass stock and stock change, and
(ii) apply the model to account for carbon in the post-1990 national plantation estate, using stem-volume-based inventory approaches.

An overall system framework (Richards 2001) was developed to guide the development of data gathering and analytic projects and programs which could then be integrated using spatial modelling approaches. Various models were selected, calibrated and verified through these projects and programs. A range of related projects was undertaken to identify, collate and synthesise the additional data needed to operate the models continent-wide at a fine resolution.

The models were integrated to provide an activity-driven carbon accounting model (FullCAM) capable of dealing with multiple carbon pools for the NCAS. FullCAM is an integrated compendium model and accounting tool. It has components that deal with the biological and management processes that affect carbon pools and the transfers for forest, agricultural, transitional (afforestation, reforestation) and mixed (e.g. agroforestry) systems. Multiple agricultural and forest species can be accounted for through time via a range of parameterised default species tables. Likewise, data describing the range of land-use practices and soils parameters are provided via default tables within the model. These default tables were constructed specifically for the NCAS development of FullCAM through a nationwide review program.

The models that comprise FullCAM are: the physiological growth model for forests, 3PG (Landsberg and Waring 1997; Coops *et al*. 1998, 2001; Landsberg *et al*. 2001); the carbon accounting model for forests (CAMFor) developed by the Australian Greenhouse Office (AGO), (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, 1991).

These models have been independently developed for the purposes of:

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

CAMFor and CAMAg are carbon accounting tools that are able to apply management effects resulting from fire, harvest, cropping and grazing to externally-generated growth and decomposition rates.

In preparing each model for integration into FullCAM, each (except for CAMAg, the only model which cannot be independently implemented as it is linked to the Roth C model) was translated to a common Microsoft Excel workbook 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 (Paul *et al.* 2003a,b) while providing for ease of later integration. The transparency of the development process also facilitates detailed review.

The integration of the models serves two primary goals. The first is to provide for complete carbon accounting for a particular area of land. This includes all carbon pools and transfers between pools to ensure that there is no double counting or omissions in accounting. Potentially, this could occur if any of the primary carbon pools (in soil, biomass or litter) were considered independently. The second is to provide the capacity to run the model continentally as a fine resolution, grid-based spatial, multi-temporal application. A single model is efficient for addressing the requisite large input data sets in a spatial context.

Model evaluation and selection

The need to develop an integrated model was highlighted during the International Review of the NCAS Implementation Plan for estimating carbon levels for the 1990 baseline (AGO 2000a,b). A key review recommendation was to take a holistic approach, with modelling and measurement considering all carbon pools and transfers between them.

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 tree 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 calibration of the Roth C soil carbon model for Australian conditions.

The initial selection and further development of the models for integration into 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. Detailed specifications were prepared to guide the fundamental data collection, research program and model calibration.

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) (Richards and Evans 2000b) performs similar functions to CAMFor, but unlike CAMFor it was developed with direct integration of the Roth C model.

Except for CAMAg, which was programmed directly in C-code computer language, 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. The translation process also allowed for the development of consistent naming conventions, methods and approaches which were transparent and readily reviewed. The replication of the models in their new format could be tested through comparison of results between original and derived models using identical model parameters.

Each component model within the FullCAM model is capable of being used independently, and linkages between component models are available in a variety of configurations (32 in all). This flexibility has encouraged wide use and application of FullCAM, providing further opportunity for independent model testing and development.

Model development

When there was confidence that the models were yielding the same results as the source code versions, the Excel models were fully documented and returned to the original authors or host organisations for checking and commentary. Modifications were subsequently made to improve code efficiency (improving computational speed and resource use), in recognition of the diverse biophysical conditions in Australia, and to provide spatially explicit, multi-temporal and multiple species implementation of the model. The integration to a single application of the various sub-models was initially undertaken in Excel. This provided a transparent test version of the proposed application.

The component models are being independently calibrated (Paul *et al.* 2003a,b; Skjemstad and Spouncer 2003) for the NCAS through a variety of programs, which are largely focussed on the development of the 1990 baseline (an estimate of the emissions of greenhouse gases in 1990) for the Land Use Change and Forestry activities under the Kyoto Protocol. This activity involves considerable investment in the calibration of each of the models for the range of conditions and management practices present throughout Australia. Over a 2–3 y period, the total investment in data collection and synthesis, and further development of understanding of biological processes required for model calibration was in the order of A$9M.

Model calibration includes collating a series of previous (quality audited) site measurements, and conducting additional field work and laboratory analyses. Independent data sets are maintained for model calibration and verification. The application of calibrated models in the spatial version of FullCAM will rely on interpolation across a range of spatially-continuous layers of input data. These include data such as those on climate and soil type.

Model description

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

3PG (physiological growth model)

The version of 3PG adopted is that described as Version 3-PGpjs 1.0 (Sands 2000) (http://www.ffp.csiro.au/fap/3pg/).

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 or other code) model. Subsequent changes were made to this model to enable spatially explicit application while still reflecting the development of the previous version by Coops and Waring (2000) and Landsberg and Kesteven (2002).

3PG is a monthly time-step model based on the calculation of net primary productivity (NPP) via estimation of the photosynthetically-active radiation absorbed by plant canopies (APAR). APAR is estimated using leaf area index (LAI) and incoming shortwave radiation. A conversion factor is used to convert APAR to NPP. Modifiers related to temperature, water availability, nutrition and atmospheric vapour pressure deficit are used to reflect non-optimum growth conditions. The principal task to implement this model spatially was to compile the fundamental spatial input data. This entailed:

- development of a slope- and aspect-corrected solar radiation (direct and diffuse) surface at a resolution of a 250 m grid, using the Digital Elevation Model (DEM) of AUSLIG – Geodata 9 second DEM (version 2);
- provision of access by CSIRO Land and Water to their Fertility and Soil Moisture Continental Surfaces (McKenzie *et al.* 2000);
- derivation of soil surfaces from the Atlas of Australian Soils (Northcote *et al*. 1960–1968);
- using the ANUCLIM software package (McMahon *et al*. 1995) to derive rainfall, temperature and evaporation surfaces;
- development of a frost (number of frost days per month) surface by the NCAS; and
- derivation of a Normalised Difference Vegetation Index (NDVI) 10-year average (1981–1990).

CAMFor (carbon accounting model for forests)

CAMFor has its origins in the 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 series of modifications was made to the original model including:

- the introduction of an inert soil carbon pool, in recognition of 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);
- the addition to the model of a fire simulation capacity to deal with stand-replacing and/or regenerating fires, being either low-intensity fires on the forest floor largely removing litter, or crown fires affecting the whole tree;
- the structures and lifecycles within the wood product pool were modified to reflect Australian data (Jaakko Pöyry 1999, 2000);
- greater resolution was added to the recognised components of standing trees, separating 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 use, as a primary data input, above-ground mass increment as an alternative to stem volume increment.

Within FullCAM, the CAMFor sub-component (see http://www.greenhouse.gov.au/ncas/publications/index.html) can take its growth information from any one of four sources:

- net primary productivity (NPP) derived from 3PG with feedback from management actions (thinnings, etc.) specified in CAMFor;
- information entered from external models;
- measures of either above-ground mass increment or stem volume increment; or
- a 3PG-derived forest productivity index applied to a simple growth formula.

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

A series of empirical defaults for plantation forests were developed for CAMFor using the growth rates and management descriptions drawn from the work of Turner and James (1997). Turner and James (2002) converted estimates of wood flow 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 are available from the work of Ilic *et al.* (2000), biomass carbon contents from Gifford (2000a,b) and decomposition rates from Mackensen and Bauhus (1999).

The information flowing from 3PG to CAMFor is the 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 total productivity) are specified within a CAMFor table.

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 (carbon accounting model for agriculture)

Within FullCAM, CAMAg (see http://www.greenhouse.gov.au/ncas/publications/index.html) serves the same role for cropping and grazing systems as CAMFor does for forests. The CAMAg model reflects the effects of management on carbon accumulation, and allocates masses to various product pools within plants and to decomposable and resistant organic residues. Yields may be entered in the model in a variety of ways including above-ground, total or product mass, along with turnover rates above and below ground.

With both CAMFor and CAMAg embedded within FullCAM, it is possible to represent transitional afforestation, reforestation and deforestation (change at one site) or a 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 for each of the woody (CAMFor) and non-woody (CAMAg) categories. This also provides capacity for modelling ongoing mixed systems such as agroforestry.

GENDEC (general decomposition model)

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

The effect 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 processes such as macroinvertebrate activity prior to material reaching a soil interface where decomposition is most active. 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 (soil carbon model)

The Rothamsted soil carbon (Roth C) model (http://www.rothamsted.bbsrc.ac.uk/aen/carbon/rothc.htm) accepts pre-determined masses of plant (above-ground litter) 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, and both have been incorporated in FullCAM. Version 26.3 is the recent 'release' version, while 26.5 is a developmental version yet to be fully tested.

It is recommended that, if calibration data are available, the Roth C model should be used in conjunction with CAMFor. It is a more widely calibrated and verified multiple-pool soil carbon model than simplistic soil carbon procedures implemented within CAMFor. As calibration data are 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

FullCAM was initially integrated 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 (Paul *et al.* 2001; Paul *et al.* 2003a,b). It formed a 10-Mb 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 the Excel 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 program the agricultural component of FullCAM

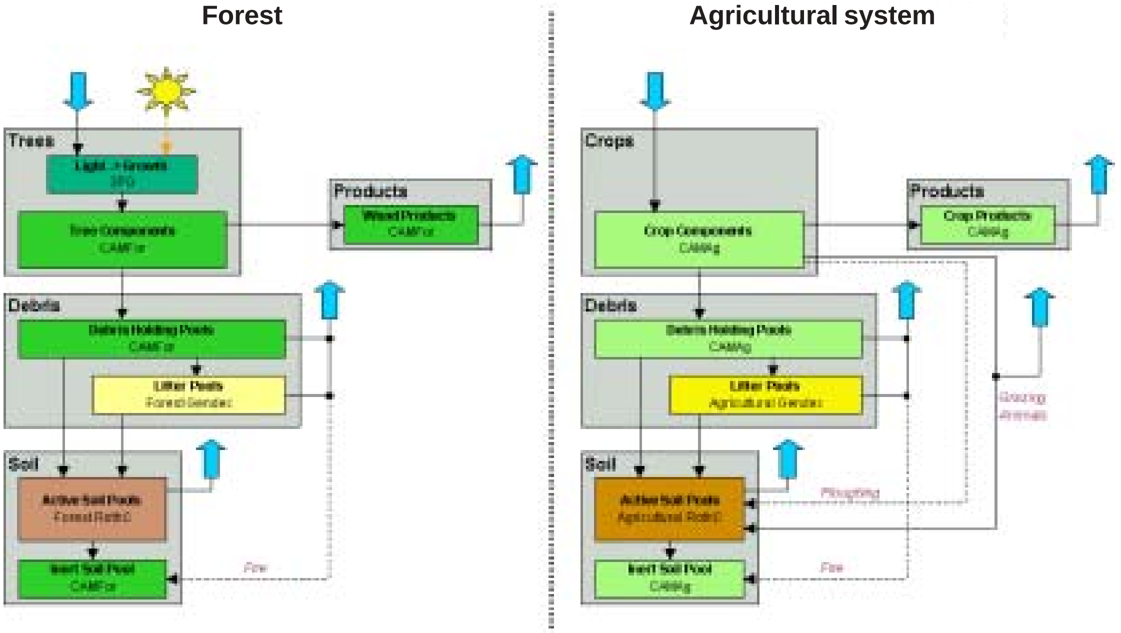

Figure 1. Overview of the FullCAM model

directly using the C++ computer language. This version is far more efficient and transportable (in size) than the Excel version, with run speeds capable of continental-scale application at fine spatial and temporal resolution.

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 linkage from 3PG to CAMFor is achieved by inputting the total biomass increment from the 3PG output to the CAMFor biomass table. This material is allocated to various tree components (above- and below-ground) through the CAMFor mass distribution species default table.

CAMFor links to GENDEC through a transfer of live material to the above-ground litter 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 with GENDEC, the CAMFor breakdown rates for input material are applied to act as a ‘flow’ mechanism to introduce material to the GENDEC model. The above-ground litter pools of CAMFor thus act as holding pools for material which can then flow to the GENDEC pools. Below-ground material is treated independently of GENDEC and is either transferred directly to the resistant and decomposable plant material pools (RPM and DPM) of Roth C from CAMFor, or, if Roth C is not being implemented, given an empirical decay rate within the CAMFor ‘Active’ soils pools.

If CAMFor and Roth C are used (without GENDEC), the ‘breakdown’ rates in CAMFor are used to decompose above-ground litter (unless it ploughed in) into the Roth C humified organic matter (HUM), RPM and DPM below-ground pools (minus losses to the atmosphere). Root material is transferred to the Roth C DPM and RPM pools.

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

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’) is dealt with in the DPM and RPM pools of Roth C.

Full descriptions of the sub-models that form the FullCAM model and of the process of standardising the programming (e.g. into a single program code version with consistent carbon pool structures and naming conventions) can be found in Richards (2001) at http://www.greenhouse.gov.au/ncas/publications/index.html.

Model calibration and testing

FullCAM is 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 trials, literature or third-party models. It is critical that appropriate empirical rates are used when applying the model.

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 climate. Each of the process components of the model (3PG, GENDEC and Roth C) is 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 choice of time step for any operation will largely depend on the temporal variability of the system being modelled and the temporal resolution of the available data.

The early testing of FullCAM was carried out on GRC3, the developmental Excel version, providing maximum transparency and therefore an ability to track iterations of the spreadsheet formula. Another advantage was an ability to attach the @Risk add-on (Palisade 1997). Among other things, @Risk provides a capacity for sensitivity analyses within the Excel model, given specified correlations between the various input variables. Each specified output is assessed for its sensitivity to each input variable. Correlations between input variables can be specified and Monte Carlo analyses run to enable uncertainty analyses given specified variability. @Risk can also interact with the FullCAM code version and is being implemented within developers' versions of the model.

A range of activities are underway within the NCAS that provide required calibrations for the various components of the FullCAM model. Much of this activity was initiated upon selection of the various component models for external model calibration and verification programs. Each of these programs also provides for ongoing model testing and verification.

Conclusions

The adoption of a modelling approach to Australia's national carbon accounting has been a technically and administratively complex task, despite the prior existence of component sub-models calibrated for a range of situations. This approach links together remotely sensed, natural resource inventory, climate and management data with a set of process and accounting system models.

The modelling framework has been developed around a number of existing models, with new models and links created where needed. The development of FullCAM has provided the needed integration of these models for national application. The linkages between models and multi-temporal spatial data within a geographic information system (GIS) provides an enormous analytic capacity which cannot be achieved through the application of point-based models to regionally 'averaged' data. It removes many of the problems of scaling by application at a fine spatial and temporal resolution, and is well suited to the 'land-based' accounting required under the Kyoto Protocol.

FullCAM provides the overall framework that integrates the component models, and therefore the various programs providing input to the NCAS. Rigorous model testing and verification initiatives are ongoing within the individual supporting programs. The principal focus of the testing of FullCAM has been, and continues to be, on the linkages between the models. Testing undertaken on the GRC3 Excel beta-version of FullCAM provided confidence in the structure of the model being able to robustly manage flows between model components, while providing enormous flexibility in the nature of input data and in selection of models in any implementation. The linking of the FullCAM model to the @Risk uncertainty and sensitivity capacity provides for good-practice application and analytic rigour in both model testing and implementation. It also provides a transparent and understandable analysis of the uncertainty in any input variable for the model.

FullCAM provides modular capacity whereby models can be taken in or out of operation, but this capacity is constrained by the necessity to maintain the appropriateness of pool transfers. It is recommended that any calibration or verification be done on a chosen configuration (of 32 options) of FullCAM to avoid any possibility that inconsistencies in pool transfers could occur through changing model structure after its calibration in original form.

A comprehensive approach to carbon modelling and accounting required consideration 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 of the FullCAM model. The independent data collection and model calibration can be easily transferred into the calibration and verification of the FullCAM model in both its plot and spatial versions. This was made possible (both technically and administratively) by the development of the NCAS being undertaken wholly within the Australian Greenhouse Office, the lead Australian Government agency on greenhouse matters.

The vast and diverse land mass of Australia, with its great complexity and variability of management and climate, often subjected to broadscale natural phenomena such as drought and fire, has demanded a relatively complex (yet highly efficient) model framework in order to satisfy the Kyoto Protocol accounting guidelines. These guidelines require that the developed nations develop accounting systems capable of fine spatial and temporal distinction in response to a variety of land management activities. Australia is well placed to meet these requirements through the development of the FullCAM model linked to a comprehensive natural resource management GIS system.

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