Brief Description Of Several Models For Simulating Net Ecosystem Exchange In Australia

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Introduction

This brief background paper has been compiled for the workshop on modelling net ecosystem exchange that was held in Canberra from 18-20 April 2001. It gives brief descriptions of the models that are currently available in Australia and that are of interest in modelling net ecosystem exchange for the Australian continent: APSIM, CENTURY, CenW, FullCAM, G'DAY, Gendec, GrazPlan, GRASP, Linkages, Promod, Roth-C, Socrates and 3-PG.

These models deal with the range of different ecosystems that together constitute the Australian biosphere. Some ecosystems or components of ecosystems are modelled by more than one model, but the different models approach their modelling tasks in different ways by providing more or less detail, and by including or omitting certain processes or plant or soil pools.

The workshop provided details of the treatment of various processes in each of these models which are described in other papers in this volume. This paper gives a brief description for each of these models to make it easier to better understand the overall modelling approach in the respective models and gain a better appreciation of the treatment of specific processes as they are dealt with in greater detail in the other papers of this volume.

APSIM

APSIM (**A**gricultural **P**roduction **S**ystem S**IM**ulator) is a software system that allows models of crops, pastures, trees, soil water, nutrients, and erosion to be flexibly configured to simulate diverse production systems (McCown *et al* 1996; see also web site (www.apsim-help.tag.csiro.au)).

The modelling framework has been developed over the last 10 years by the APSRU group (Agricultural Production Systems Research Unit), a collaborative effort between CSIRO Tropical Agriculture (now Sustainable Ecosystems) and Qld State agencies (DPI, DNR). APSRU is currently being renegotiated and it is likely that its core membership will be expanded to include CSIRO Land and Water and the Uni of Qld.

A key feature of APSIM, which distinguishes it from many vegetation specific models, is the central position of the soil rather than the vegetation. Changes in the status of the soil state variables are simulated continuously in response to weather and management. Crops, pastures or trees come and go, finding the soil in a particular state and leaving it in an altered state.

Another feature of APSIM is its "plug-in-pull-out" approach to design (Fig. 1). High order processes (for example growth of a crop, soil water balance, dynamics of soil organic matter) are represented as separate modules. This arrangement offers great flexibility for comparing alternative representations of different parts of the system without modification to the rest of the model. APSIM is well suited to modelling systems involving sequences of crops (rotations, phase farming) or mixtures of crops (intercropping, agroforestry).

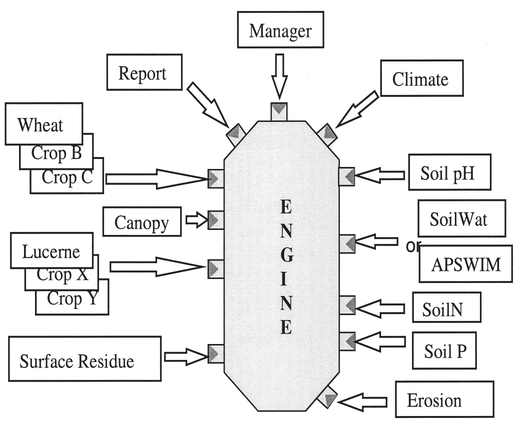


Figure 1: Diagrammatic representation of the modular structure of APSIM, illustrating the options of having alternative representations of certain processes (eg

SoilWat or APSWIM for the water balance) and multiple crops.

APSIM models are typically 1-dimensional, with the soil described as a multi-layered system. The recently released APSIM v 2.0 provides support for multi-point simulations for the first time. Most modules operate on a daily time-step. The minimum climatic data required to run APSIM are daily maximum and minimum temperature, radiation and rainfall.

The vegetation modules in APSIM use a simple framework to describe the daily capture and utilization of environmental resources such as solar radiation, soil water and nutrients. In response to environmental stimuli, plants develop through distinct phenological phases, a leaf canopy is produced, incident radiation is intercepted, absorbed energy is converted into assimilates which are partitioned between plant components, including yield.

The functions used in APSIM vegetation modules are outlined in greater detail on the APSIM web page, and in the document "Principles of simulating crop growth and development in APSIM" (Mike Robertson and others in APSRU, unpublished). APSIM vegetation modules generally include water and nitrogen as limiting factors; a phosphorus limitation is under development but at present is only operational for maize.

At the time of writing, modules exist for barley, canola, chickpea, cowpea, fababean, mungbean, navybean, hemp, wheat, lucerne, maize, millet, peanut, pigeonpea, sorghum, sunflower, sugarcane and cotton. A FOREST module provides a generalised vegetation treatment that has been used for *Eucalyptus*, *Pinus* and other natural plant communities.

The soil water dynamics are described by one of two modules, either SoilWat (a "cascading bucket" approach) or APSWIM (based on simultaneous solution of the Richards' equation for water flow and the advection-dispersion equation for solute transport). A comprehensive study comparing the two approaches found both to be capable of giving good descriptions of soil water content and solute movement (Verburg, 1996).

The turnover of organic matter is represented by the SoilN and Residue modules (Probert *et al* 1998). APSIM distinguishes between surface residues and residues in the soil. Within SoilN, organic materials are conceptualized as fresh organic matter (FOM), and two soil organic matter pools (BIOM and HUM) that differ in their rates of decomposition. The soil organic matter pools are considered to have non-varying C:N ratios. Decomposition rates are determined by soil water and temperature, and in the case of FOM its C:N ratio.

APSIM has pioneered very flexible specification of management regimes in farming systems modelling. The MANAGER module is controlled by a user defined script language which enables a diverse range of management operations to be specified in ways that are conditional on the state of the simulated system. Both the timing and nature of operations such as sowing, tillage, residue management, fertilisation, irrigation, crop management, harvesting etc are all controlled from this script specified by users. All these operations can be made responsive to the state of the weather, vegetation or soil system.

APSIM is distributed under a licence system. Currently approximately 200 licences exist and the model is in active use in farming systems research in all Australian States except Tasmania, and in project activities with International Agricultural Research Centre's and the National Agricultural Research System in a number of countries in Africa, in India, China and Indonesia. APSIM testing is on-going in this diverse range of situations. Details of specific module testing can be found within the science documentation on the APSIM web page (www.apsim-help.tag.csiro.au).

By far the most extensive testing has focused on the simulation of net primary productivity and economic yield and of simulation of the dynamics of soil water and soil carbon/nitrogen under different agricultural systems. The model's strengths are in cropping systems, with emerging capabilities in pasture and forest systems. At this point in time there is no livestock production capability in APSIM, although linkages are being explored with the GRAZPLAN / FARMWI$E effort from CSIRO Plant Industry.

CENTURY

The CENTURY version 5 agroecosystem model is the latest version of a soil organic model initially developed by Parton *et al.* (1987). This model simulates carbon, nitrogen, phosphorus, and sulphur dynamics on a monthly time step for an annual cycle over time scales of centuries and millennia and embodies the best understanding to date of the biogeochemistry of C, N, P, and S. Plant production can be simulated by using grassland/crop, forest or savanna system sub-models, with the flexibility of specifying potential primary production parameters representing site-specific plant communities. Land use change can be represented by changing the plant community type during model runs, i.e. beginning with forest, clearing to pasture then running a cropping system.

CENTURY was especially developed to deal with a wide range of cropping system rotations and tillage practices for system analysis of the effects of management, CO_2 fertilisation and climate change on productivity and sustainability of agroecosystems. Integrated in the model are the effects of climate, soil variables and agricultural management to simulate C, N, and water dynamics in the soil-plant system (Fig. 2). Simulation of complex agricultural management systems including crop rotations, tillage practices, fertilization, irrigation, grazing, and harvest methods are possible. The primary purposes of the model are to provide a tool for ecosystem analysis, to test the consistency of data and to evaluate the effect of changes in management and climate on ecosystems.

CENTURY simulates C,N,P,S dynamics in surface soils (0-20cm). The depth of analysis can be extended to 0-30cm by re-parameterisation. This allows analyses more aligned with the minimum default depth of 30cm proposed by the IPCC for national C inventory. Grassland/crop and forest systems have different plant production sub-models that are linked to a common soil organic matter sub-model. The savanna model uses the grassland/crop and forest subsystems and allows for the two subsystems to interact through shading effects and N competition. The soil organic matter sub-model simulates the flow of C, N, P, and S through plant litter and the different inorganic and organic pools in the soil. A range of variables are used to describe the system being simulated.

The major input variables for the model include:

- monthly average maximum and minimum air temperature,
- monthly precipitation,
- lignin content of plant material,
- plant maximum and minimum N, P, and S content,
- soil texture,
- atmospheric and symbiotic and non symbiotic N inputs,
- initial soil C, N, P, and S amounts, and
- disturbance events (cultivation, grazing, fire, harvest, irrigation, erosion).

Input variables are available for most natural and agricultural ecosystems and can generally be estimated from existing

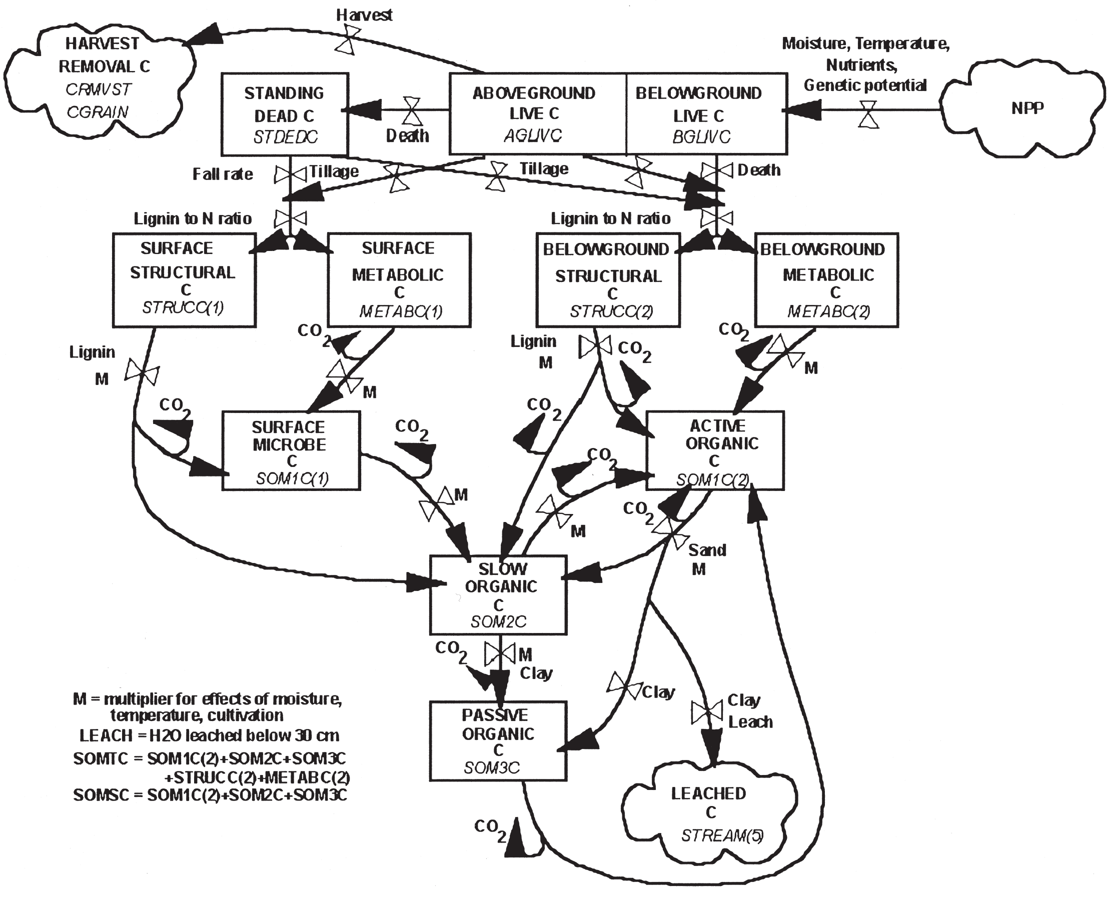


Figure 2: Basic outline of the carbon pools and flows in CENTURY.

literature or parameterised from field data. Most of the parameters controlling the flow of C in the system are in special file containing "fixed" parameters however these can be altered to simulate soils to a greater depth or control the C pool structure. The user can configure the model considering only C and N dynamics or a multiple array of elements namely, C, N, P and or C, N, P, and S. Initial soil carbon and nitrogen can be entered in parameter files or "spun up" using a long model run (> 1000 years) and or estimated within the model from simple regressions based on climate and soil texture. Climate inputs can be actual data, mean data or average climate with stochastic rainfall, this combination allows exploration of climate verses management impacts.

Simulation of carbon isotope concentrations for C_{14} and C_{13} within the soil matrix is possible within the model. This enables the user to better calibrate the model when isotope data from field studies are available. The model is most often used to simulate the C cycle at the plot or stand scale it has also been used at continental (VEMAP *et al.*, 1995) and global scales (Parton *et al.*, 1995) to simulate the carbon cycle under climate change. While the model has been developed to simulate real ecosystems at local to global scales, it can also simulate microcosm experiments where soils are incubated in the laboratory at known water content and temperature.

The strengths of the CENTURY model are: (1) its ability to model a diverse array of ecosystems. (2) Capability of simulating a wide range of disturbance events, especially those relevant to land use, land use change and forestry. (3) Its extensive use and testing around the world on a diverse array of systems.

On the other hand the model is largely empirical and the user is presented with what sometimes appears to be a bewildering array of parameters. In reality one can usually modify a small selection of these to give realistic simulations. Many of the parameters arise from the need to model a wide range of systems and disturbance events.

The plant production model sub components are probably less accurate than any number of specialist forest, crop and pasture growth models, although CENTURY seems to perform quite well in many situations. A number of other models e.g. CenW, G'DAY etc have taken elements the basic soil C/N dynamics from CENTURY and integrated them into their model structure.

The most recently released version of (CENTURY 5) (produce by a team of scientists at the Natural Resources Ecology Lab (NREL) Colorado State University) includes a layered soil physical structure, and new erosion and deposition sub-models. The model code has been rewritten in C++, reorganised, and modified to use platform-independent configuration and output files. Added to this version is a windows based graphical-user interface providing ease of configuration and running CENTURY simulations. Documentation and the model can be downloaded from the NREL web site, http://www.nrel.colostate.edu/projects/models.html. New versions of CENTURY that use daily rather than monthly water balance are under development. These developments allow the modelling of non-CO_2 greenhouse gasses and add to the already impressive capability of this model.

Evolution of the model will continue as the understanding of biogeochemical processes improves. The identification of problem areas where processes are not adequately quantified and demand for new applications in greenhouse inventory and climate change will drive further developments.

CenW

CenW (**C**arbon, **E**nergy, **N**utrients and **W**ater) is a generic forest growth model that simulates the fluxes of carbon and water, the interception of solar radiation and the dynamics of nutrient cycling through plant and soil organic matter pools. CenW contains all relevant carbon and nutrient pools and the various feed-backs that may be affected by changes in any of these pools or fluxes (Kirschbaum 1999a, 2000). The incorporation of a nutrient cycle was the particular research challenge that prompted the development of CenW. The model is currently available as version 1.0.7. Its basic outline is shown in Fig. 3.

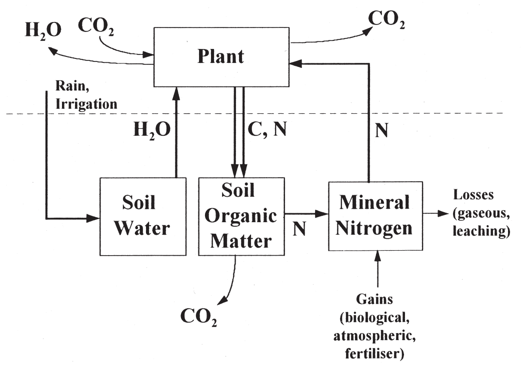


Figure 3: The basic modelling outline of CenW, showing the key pools and fluxes of carbon, nitrogen and water between these pools and the external environment (redrawn from Kirschbaum 1999a).

The model runs on a daily time step. Carbon gain is calculated in dependence on light absorption, temperature, soil water status, foliar nitrogen concentration and any foliage damage due to frost or scorching temperatures during preceding days. Some photosynthetically fixed carbon is assumed to be lost in respiration, with daily respiration rate calculated as a constant fraction of photosynthetic carbon gain or as a function of temperature and nutritional status.

Allocation to different plant organs is determined by plant nutrient status, tree height and species-specific allocation factors. Water use is calculated using the Penman-Monteith equation, with canopy resistance given by the inverse of stomatal conductance, which, in turn, is linked to calculated photosynthetic carbon gain. Water is lost by transpiration, soil evaporation and, under wet conditions, deep drainage.

Nitrogen can come from a constant rate of atmospheric deposition, fertiliser addition or mineralisation during the decomposition of soil organic matter. The model can be run with or without symbiotic nitrogen fixation. Decomposition rate is determined by temperature, soil water status and soil organic matter quality in a modified formulation based on the CENTURY model.

The nutrient cycle is closed through litter production by the shedding of plant parts, such as roots, bark, branches and, most importantly, foliage. Litter is assumed to be produced as a constant fraction of live biomass pools. In addition, foliage is shed during drought or when canopies become too dense. Litter is then added to the organic matter pools from where carbon is eventually lost and nitrogen becomes available as inorganic mineral nitrogen.

A fraction of mineral nitrogen is lost by volatilisation in the mineralisation of organic nitrogen. There can also be nitrogen losses by leaching or off-site removal of wood.

The model requires as minimum input daily minimum and maximum temperature and rainfall. Solar radiation is desirable, but can alternatively be calculated from empirical relationships of temperature and rainfall. There is also the requirement for a large number of soils and plant-physiological parameters. Where site- and species-specific information on these parameters is not available, parameters can be estimated from related species, and site-specific information can be based on typical soils values.

The model has been tested against data from the nutrient and irrigation experiments at the BFG site near Canberra (Kirschbaum 1999a) and has been used for simulations of net primary production and the effect of climate change for the whole Australian continent (Kirschbaum 1999b). Its primary application has been the investigation of the complex feed-back effects that determine ultimate system responses in climate change simulations (Kirschbaum 1999c).

FullCAM

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.

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 were undertaken to identify, collate and synthesise the additional data needed to operate the models continent-wide at a fine spatial and temporal resolution over a 30 year period.

To achieve this multiple pool, activity driven carbon modelling capacity the NCAS undertook the development of the *FullCAM* carbon model. *FullCAM* is an integrated compendium model and accounting tool 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) and mixed (e.g., 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, 2000a); the carbon accounting model for forests developed by NCAS, *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). *FullCAM* can run any of these models in a single coordinated simulation, including any model by itself.

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*);

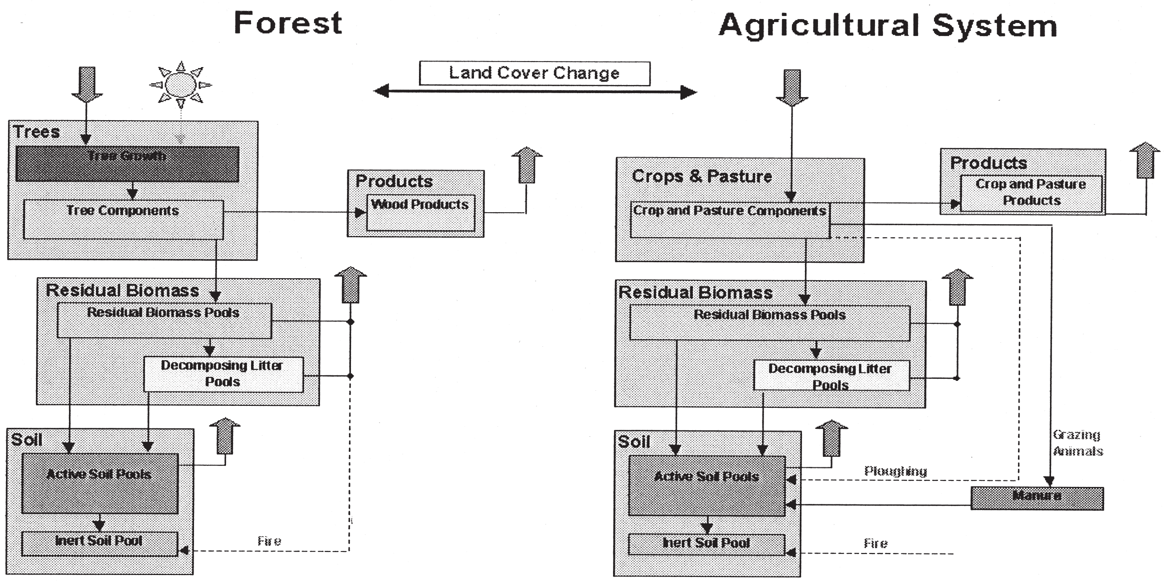


Figure 4: Diagrammatic representation of the use of the CamFor and CamAg models during land-use change.

- determination of rates of decomposition of litter (in the case of *GENDEC*); and
- prediction of growth in trees (in the case of *3PG*).

CAMFor and *CAMAg* are carbon accounting tools developed by the NCAS 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 (Fig. 4).

In preparing these models for integration into *FullCAM*, each model (except for *CAMAg*) 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 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 carbon pools and transfers (net of atmospheric uptake and emissions) between pools to ensure that there are no instances of double counting or omissions in accounting. Potentially, this could occur if any 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, multi-temporal application. A single efficient model is required to analyse the requisite large input data sets in a spatial context.

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 application of calibrated models in the 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.

The following describes the *CAMFor* and *CAMAg* models. The other model components of *FullCAM*, *3PG*, *Roth C* and *GENDEC* are individually described elsewhere in the report.

CAMFor

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 were made to the original model including:

- introduction of an inert soil carbon pool recognising the nature of 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;
- addition of a fire simulation capacity 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;
- modification of wood product pool structures and lifecycles to reflect those cited in Jaakko Pöyry (1999);
- improved resolution of component distinctions of the standing tree material, splitting coarse and fine roots, branch and leaf material;
- 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.

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 a total productivity change) 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*. For deforestation, the same applies, but with a large residual of decomposing woody material being the primary change remaining within *CAMFor*.

CAMAg

Within *FullCAM*, *CAMAg* serves the same roles for cropping and grazing systems as *CAMFor* does for forests. The *CAMAg* model reflects the impacts of management on carbon accumulation and allocates masses to various product pools within plants and to decomposable and resistant organic residues. Yields may be entered in the model in a variety of ways including above-ground, total or product mass, along with above- and belowground turnover rates. The principal human activities that drive transfers of material in CAMAg are ploughing, herbicide application, harvest, fire and grazing (with manure return).

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 for each of the woody (*CAMFor*) and non-woody (*CAMAg*) categories. This also provides capacity for modelling ongoing mixed systems such as agroforestry.

MODEL INTEGRATION

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

The C code based application of *FullCAM* is a far more efficient and transportable (e.g., Mac, PC or Unix environments) format, with run speeds capable of continental scale application at fine spatial (using ArcBinary file format) 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 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 belowground) will be as per the *CAMFor* mass distribution table.

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*. Belowground 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' (humified organic matter) belowground pool. 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*. Belowground material (and above-ground material 'ploughed in') is dealt with in the DPM and RPM pools of *Roth C*.

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 principal 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 to implement 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 will be implemented within developer's 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 independent programs. Each of these programs provides for ongoing model testing.

G'DAY

G'DAY, a **G**eneric **D**ecomposition **A**nd **Y**ield model, simulates the cycling of carbon (C), nitrogen (N) and water in plant and soil. The model's general structure is shown in Figure 5. The plant sub-model simulates the C and N contents of leaves, fine roots, and wood. The soil sub-model predicts C and N in plant litter and soil organic matter pools (as in the CENTURY model - see CENTURY in this volume) and water storage in the rooting zone. Processes represented include plant photosynthesis and respiration, plant water and N uptake, tissue growth and senescence, litter and soil decomposition, net soil N mineralisation, N input by atmospheric deposition and biological fixation, and N loss by leaching and gaseous emission (Fig. 5). Photosynthetic rates depend on [CO_2] and temperature, respiration depends on temperature and decomposition depends on soil temperature and moisture content. G'DAY has been used to investigate effects of altered climate and land use on forest ecosystems in tropical, temperate, mediterranean and boreal environments and on temperate grasses.

A time step of one day is used in the daily version of G'DAY. Carbon gain (denoted assimilation in Figure 5) is a function of absorbed light, leaf nitrogen, temperature, soil moisture and autotrophic respiration. The latter is a carbon loss that is usually represented as a constant fraction of gross primary productivity but can also be represented as a function that is proportional to plant non-structural N content (Ryan 1991) and temperature (Medlyn *et al.* 2000). Allocation of net primary produce (NPP) to foliage, fine roots and wood (stem, branches and coarse roots) is constant. The water balance is calculated using either the

Penman-Monteith equation or the RESCAP model as specified in Dewar (1997). Allowance is made for water intercepted by the canopy, runoff and drainage, and evaporation from a top soil layer to obtain effective rainfall (infiltration) before transpiration is calculated. Nitrogen inputs include atmospheric decomposition, biological fixation and fertilisation. Nitrogen losses represent N emissions and leaching as well as the removal of wood and other plant debris. Decomposition and mineralisation are represented by CENTURY and are based on functions of soil moisture, soil temperature, and litter quality (nitrogen and lignin contents). Daily inputs to G'DAY include total solar radiation (or PAR), maximum and minimum temperature, and precipitation. G'DAY also requires a range of site specific parameters, either sourced from empirical studies or estimations.

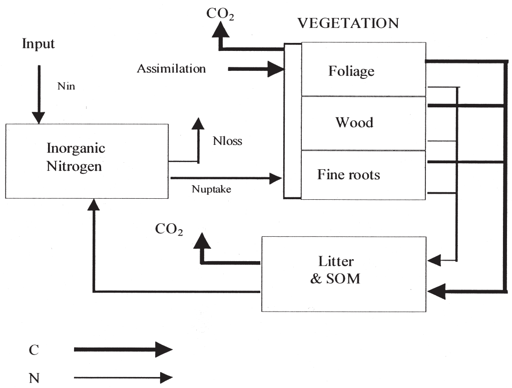


Figure 5: Pools and fluxes of C and N in G'DAY.

G'DAY is fully described in Comins and McMurtrie (1993) and modifications to the plant sub-model is fully described in Medlyn *et al.* (2000) and RESCAP in Dewar (1997). For the CENTURY decomposition sub-model see Parton *et al.* (1987) for a detailed description, and modifications are described in Parton *et al.* (1993).

GENDEC

GENDEC predicts litter mass loss during decomposition. It does this by combining elements of microbial physiology and population dynamics with empirical observations of C and N pool dynamics, litter mass loss and changing C:N ratios (Moorhead and Reynolds 1991).

Although GENDEC was originally developed to predict litter decomposition in the northern Chihuahuan Desert of southern New Mexico (Moorhead and Reynolds 1991), it has been more recently applied to decomposition of Artic tussock tundra (Moorhead and Reynolds 1993) and deciduous tree litter (Moorhead *et al.* 1999, Moorhead and Sinsabaugh 2000). The version of GENDEC shown in Figure 6 was derived from that used by Moorhead and Sinsabaugh (2000).

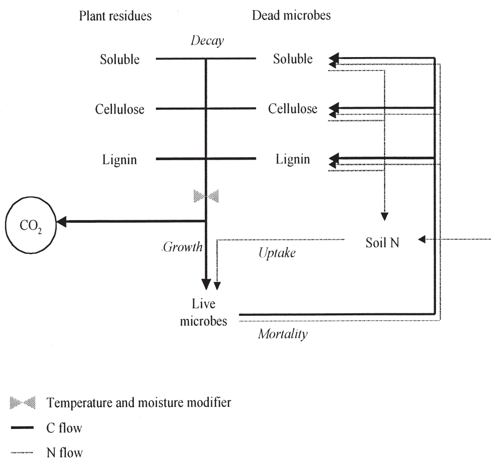


Figure 6: Basic structure and flows of carbon and nitrogen in GENDEC.

Various pools are used in GENDEC, representing dead organic matter (plant residues and dead microbes), living biomass and soil N (Figure 6). There are three pools of dead microbes and three pools of plant residues. Each of these six dead organic matter pools has a different decomposition rate. These rates are modified in accordance with moisture and temperature conditions and N limitation.

Flows between pools are driven by empirical relationships according to characteristics of the microbial community. Microbial growth and respiration are driven by total C losses from dead organic matter, assuming a microbial C assimilation efficiency. A microbial death rate is also inherent in the model. Nitrogen flows are assumed to balance calculated C flows, given assumed N:C ratios of live and dead microbial material. Nitrogen inputs to the soil can also be incorporated in the model.

Inputs required for GENDEC include:

- Microbial assimilation efficiency
- Microbial cell wall fraction
- Microbial cellulose fraction
- Microbial turnover rate
- Monthly limitations of temperature and water availability on decomposition (0 to 1)
- Initial C mass of the live microbes
- Initial C mass of the six dead organic matter (litter) pools

- Initial mass of available N and monthly input of N into the soil

When compared to CENTURY, GENDEC was found to be less sensitive to site conditions (i.e. temperature and moisture) but more sensitive to litter quality and soil nitrogen availability (Moorhead *et al.* 1999).

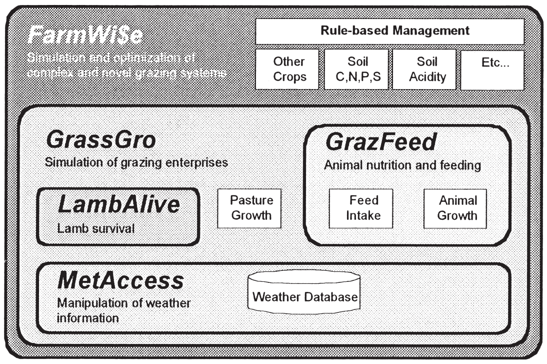
GRAZPLAN

The GRAZPLAN suite of models has been developed as part of a decision support project for temperate Australian grazing lands. The models are configured in different ways to meet particular purposes. For the purposes of the workshop, the key models are the ruminant biology model (Freer *et al.* 1997), the soil moisture budget and pasture growth model (Moore *et al.* 1997) and our unpublished soil nutrient cycling model. Together these models represent the cycling of C, N, P and S in the soil-plant-atmosphere-animal system. The models operate at a daily time step. They take precipitation, maximum and minimum air temperature, solar radiation, potential evapotranspiration and wind speed as driving variables (PET is usually estimated from pan evaporation).

The soil water budget is based on that of Williams *et al.* (1985). It includes a term for interception of water on herbage and its subsequent evaporation. Sub-daily time steps may be used in simulating percolation. Evaporation from bare soil and transpiration are modelled as parallel processes.

The pasture model distinguishes multiple species growing together, and within each species keeps track of tissue pools classified as seedling/established and leaf/stem/root/seed. For shoots live/dead/litter pools and five digestibility classes are also followed. Phenology of each species is followed, including dormant stages. Net assimilation is estimated as a function of radiation amount and intensity, temperature, soil moisture, PET and soil solution nutrient contents; it is computed as the product of radiation receipt and RUE, modified by growth-limiting factors.

The nutrient (N, P and S) economy of plants is modelled using a demand and supply approach. Uptake of nutrients is modelled using the approach of de Willigen and van Noordwijk (1994); biological N-fixation and internal recycling of nutrients are also modelled. Allocation of assimilate follows a functional equilibrium approach and depends on species, phenological stage and light regime. Tissue death, litter fall and changes in digestibility depend on phenological stage, soil moisture and temperature. Processes of seed dormancy, germination and seeding establishment are simulated.



The GRAZPLAN Suite of Models

The ruminant biology model is a development from the Australian feeding standard (SCA 1990). It may be applied to any breed of sheep or cattle. Potential intake of animals is a function of their size; their actual intake is estimated as a fraction of potential intake by considering the amount and quality of pasture available to the stock (animals select a diet of higher quality than that which is on offer). Intake may be influenced by the availability of supplementary feeds. Maintenance requirements for energy and protein are estimated from the breed and weight of the animal and its level of intake. Utilization of protein depends on the amount of digestible protein leaving the stomach, including bypass protein and microbial crude protein. Requirements for pregnancy, lactation and wool growth are estimated where appropriate. Once all other uses of energy and protein have been estimated, the balance is used to estimate the weight change of the stock. Faecal and urinary outputs of carbon and nutrients are predicted, as are methane emissions from livestock.

The soil nutrient cycling model has not yet reached a stable form. The current version has four SOM pools and follows profiles of inorganic nitrate, ammonium, urea, phosphates and sulphate. Separate "fixed" and "available" phosphate pools are simulated. Solution concentrations of the nutrients are estimated from available concentrations using a range of sorption functions. SOM decomposition is predicted using first-order equations for each pool, modified by soil temperature, moisture and pH; constant efficiencies of microbial synthesis and humification rates are assumed for each pool. The C:nutrient ratio of the biomass pool depends on external nutrient concentrations, while the C:nutrient ratio of humus is fixed. Transformations between N forms are simulated, as are inputs of excreta (taking spatial heterogeneity into account) and the application and breakdown of fertilizers. The model may be linked to a simple process model of soil acidification.

These models form the basis of the GRAZPLAN suite of decision support tools. In particular, the ruminant biology model underpins the successful GrazFeed decision support tool, which provides hundreds of users across southern Australia with tactical advice about livestock nutrition; and the pasture, soil water and ruminant models are distributed to users in the GrassGro decision support tool for analyzing grazing systems.

GRASP

GRASP is a 'pasture growth' model which combines a soil water model and a model of above-ground dry-matter flow. It has been built to meet specific objectives relating to grazing management of Australian rangelands:

- objective assessment of drought and degradation risk in near-real time (Carter *et al.* 2000);
- simulation of grazing management options including seasonal forecasting (Ash *et al.* 2000, McKeon *et al.* 2000, Stafford Smith *et al.* 2000);
- assessment of safe carrying capacity (Johnston *et al.* 1996, Hall *et al.* 1998);
- evaluation of impact of climate change and CO_2 increase (Hall *et al.* 1998, Howden *et al.* 1999);
- reconstruction of historical degradation episodes (Carter *et al.* 2000).

GRASP has been developed incrementally since 1978 in parallel with application studies and field trials. Thus the model has been under constant critique/review in terms of development, parameterisation, validation and usefulness to client needs. Currently GRASP is being developed to address issues of deep drainage, tree growth and death, and grazing land degradation. Each relationship in the model is described in Littleboy and McKeon (1997), and a critique of model limitations is given in Day *et al.* (1997).

Soil water balance

The soil water balance in GRASP simulates, on a daily time step, the processes of soil evaporation, pasture transpiration (Rickert and McKeon 1982), tree transpiration (Scanlan and McKeon 1993), run-off, and through drainage. Four soil layers are simulated on a daily time step (0-10cm, 10-50cm, 50-100cm, >100cm). Soil evaporation occurs from top 50cm, grass transpiration from top 100cm and tree transpiration from all four layers. Initially an empirical runoff model has been used (Scanlan *et al.* 1996) with run-off calculated as a function of surface cover, rainfall intensity and soil water deficit. A more standard hydrological approach (curve numbers linked to cover) has also been implemented (Yee Yet *et al.* 1999). Potential evaporative demand is input as Class A Pan or calculated from vapour pressure deficit (VPD) and solar radiation.

Dry matter flow

The above-ground pasture processes of growth, senescence of green tissue, detachment of standing dead, litter decomposition, animal trampling and consumption are modelled at a daily time step. Five pasture dry matter pools are represented: green leaf; green stem; standing dead leaf; standing dead stem; and surface pasture litter. Plant growth is calculated as a function of solar radiation interception, air temperature, VPD, soil moisture or grass transpiration, and available nitrogen. Growth parameters can be changed for different levels of CO_2. Senescence is a function of frost, soil water deficit and age. Detachment is a function of season and rainfall. Litter decomposition is a function of temperature and surface moisture. Trampling and consumption are functions of stocking rate (beasts/ha) and pasture availability. Pasture burning is also simulated by resetting dry matter pools. Daily climate data are used as inputs and surfaces of daily climate data (Jeffrey *et al.* 2000) have been developed to support application at a national level.

Nitrogen uptake is calculated as a function of transpiration accumulated from the start of the growing season in each year. Potential annual nitrogen uptake is a key parameter as nitrogen limits pasture growth in wetter years (Mott *et al.* 1985). Parameters have been derived from data collected in field studies (>100 sites) specifically designed to measure as many of the functional parameters (e.g. peak nitrogen yield) as possible (McKeon *et al.* 1990, Day *et al.* 1997). The project has been generously supported since 1986 by the goodwill of many pasture scientists in northern Australia. Calibration is usually restricted to a limited number of parameters (e.g. above-ground transpiration efficiency, nitrogen uptake per mm of transpiration, potential regrowth rate after defoliation or burning). Spatial versions of the model have allowed parameterisation using (1) extensive ground truthing measurements of above-ground standing dry matter (>200,000 observations in Queensland, Hassett *et al.* 2000); and (2) time series of remotely sensed green cover (NDVI, Carter *et al.* 2000). Animal production (annual steer live weight, wool cut) is calculated at an annual time step from simulated variables such as percent utilisation, number of green or growing days (Hall *et al.* 1998, McKeon *et al.* 2000).

Grazing effects

The various effects of grazing on pastures have been simulated with sub-models of:

- perennial grass basal cover which drives potential regrowth rate;
- pasture composition which changes species parameters (e.g. nitrogen use efficiency, detachment rates);
- effects of grazing on plant functioning (water and nitrogen uptake); and
- soil loss affecting available water range and nutrient availability.

Tree/shrub effects

The representation of tree/shrub effects has concentrated on the dominating competitive effect of trees/shrubs for water and nitrogen (e.g. Scanlan and McKeon 1993, Cafe *et al.* 1999). Sub-models of the effects of tree/shrub cover on pasture micro-climate, pasture species composition, and water, nitrogen and litter flow are now being developed. J.O. Carter (unpublished) is developing a tree growth model in GRASP for rangelands.

LINKAGES

LINKAGES is a simulation model of linked carbon and nutrient cycles developed to simulate forest growth and long term community dynamics in northeastern USA. The basic structure of the model consists of a set of three sub-models (TEMPE, MOIST, DECOMP) that determine site conditions and a set of three demographic sub-models (BIRTH, GROW, KILL) that calculate tree growth and population dynamics (Figure 7). These two set of sub-models are linked with GMULT sub-model that estimates growth multipliers.

LINKAGES represents effects of climate, soil N and water availability on growth of different tree species, and feedbacks between species chemistry, N availability, and forest production that may control species composition. It requires a relatively simple set of calibration data, and can simulate the development of both even-aged, single species, and mixed-age, mixed-species stands. It has been used in other forest types and conditions ; .

Production is simulated using the single-tree, non-spatial 'gap' model construct ; . Simulated plot size can vary depending on the stature of the forest. Individual trees of each species are established (with a dbh between 1 and 3 cm chosen stochastically) at a user-specified rate, if light and moisture conditions are suitable for the species. These established individuals increment in diameter on an annual time-step. Growth rate is a proportion of potential maximum diameter increment under optimal conditions (essentially a function of the maximum age and maximum diameter of each species), and modified according to the simulated availability of light, water and N, and varying species response to the availability of these different resources. Mortality is simulated in two ways: (i) exogenous mortality is simulated by killing a small proportion of trees each year, so that 1% of trees reach the potential maximum age for their species; and (ii) within stand competition is simulated by increasing the probability of death for trees that grow slowly due to lack of available resources.

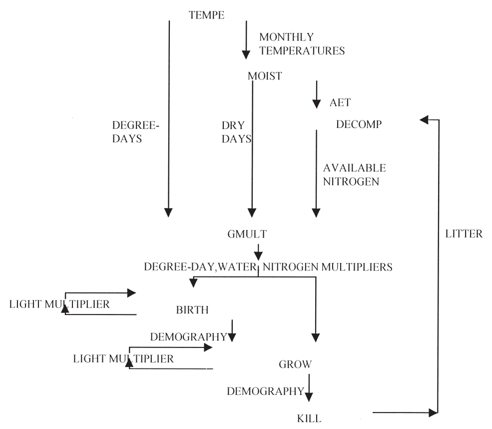


Figure 7: Schematic flow diagram of the Linkages.

Light at any level in the canopy is a function of the foliage biomass (determined from allometric relationships between diameter and foliar biomass) above that level, assuming all foliage for an individual is situated at the top of the tree, and spread across the entire plot. Available moisture is calculated from climate and soil texture. The mean and the standard deviation of monthly temperature and precipitation for the study area are input, and normally-distributed, random values are selected to simulate an annual climate. Thornthwaite and Mather's monthly actual evapotranspiration (AET) is calculated according to an approximation function (Pastor and Post, 1984), and combined with soil moisture-holding capacity (from soil texture) to determine the proportion of the growing season that soil moisture falls below field capacity. This value is used to reduce diameter growth. Foliar, root and twig litterfall are calculated for each year from foliar biomass and foliage retention time. Coarse woody litter is a function of mortality.

N is assumed to be limiting tree growth and N availability is calculated in the decomposition component. Litter mass loss is a function of litter quality (lignin:N) and AET. The model accounts for annual litter cohorts of each species and litter type (leaves, roots, twigs and logs). N dynamics is simulated for each cohort using a linear relationship between the mass remaining and the N concentration in the remaining material : The coefficients of this relationship are specified as input for each litter type. Woody litter cohorts lose mass at user-specified annual rates. Lignin dynamics are simulated in a similar way. Lignin:N ratio for each cohort is updated annually for each cohort, which affects mass loss for the following year. Depending on the slope of the relationship between %OM remaining and %N, and the proportion of mass remaining, the model simulates either nitrogen immobilisation or release. Some immobilisation is satisfied by N in throughfall, external inputs, and biological fixation, the remainder from N mobilised from other cohorts. When litter reaches a certain percent N remaining when it is transferred to the humus or well-decayed wood pools that lose mass, and N, at a constant rate (1-2% per year).

The model code is in FORTRAN (a C version has also been produced) and is structured to run over long time periods (50-1000 years or more). Up to 100 plot replications can be simulated to assess the variation associated with stochastic processes such as climate, regeneration and mortality. Outputs include above ground biomass and number of stems by species, NPP, litterfall, N mineralisation, and CO_2 evolution.

ProMod – A SITE PRODUCTIVITY MODEL

ProMod is intended primarily for screening prospective plantation sites. It focuses on the period following canopy closure, and provides a prediction of the closed-canopy leaf area index (LAI), annual net primary production (NPP), and water use by the stand, and available soil water (ASW). ProMod is calibrated to predict measures of site productivity of specific interest to forest managers, e.g. peak mean annual stem-volume increment of a plantation. It is used in combination with a conventional empirical model to predict stand development.

ProMod has its roots in a workshop ("FORMOD95: a Tree and Forest Growth Modelling Workshop", Sands 1995a) that brought together modellers and representatives from forest industries to assess if and how process-based models could provide tools for plantation management. Little specific interest was expressed in detailed predictions of biomass partitioning, so a pragmatic approach to the development of a model predicting site productivity was adopted: empirical expressions were developed for several key relationships that are other-wise difficult to model, and used in conjunction with a realistic, physiologically-based model for NPP.

A simple empirical submodel for the closed-canopy LAI was based on long-term climatic factors, drawing on the observation that LAI varies only slowly with long-term conditions following canopy closure. Daily canopy water-use

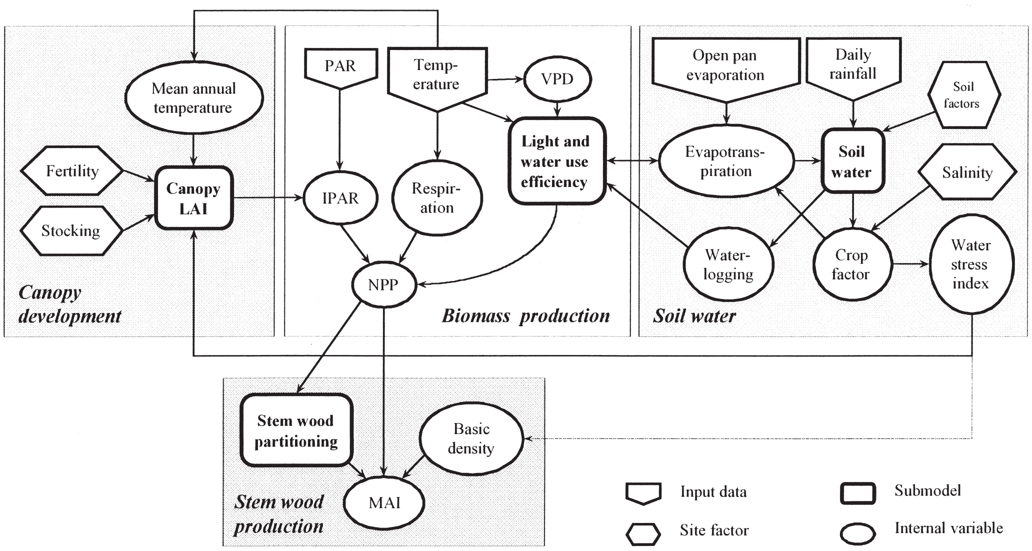


Figure 8: A simple representation of the structure of ProMod, and its input and output data.

efficiency is a function of vapour pressure deficit (VPD), and the crop factor, or ratio of actual transpiration to open-pan evaporation, depends only on relative ASW. However, development of ProMod was also physiologically realistic as ASW is modelled using a daily water-balance model (McAlpine 1970), and the heart of ProMod is a model of canopy photosynthesis (Sands 1995b, 1996) soundly based on physiological principles and parameterised from the results of physiological experiments. Production is calculated daily, taking limitations due to water stress or VPD into account, and summed to give annual NPP. Predicted NPP is converted to measures of site productivity through an empirical calibration based on a comparison of predicted NPP with observed measures of site productivity frequently used by forest managers.

ProMod was parameterised for *E. globulus* using data from 9 research plots in Tasmania and Western Australia, and validated against 19 *E. globulus* plots in N Tasmania. Full details of the development, structure, parameterisation and validation of ProMod are in Battaglia and Sands (1997), and its structure, input data and outputs are summarised in Figure 8. ProMod has since been parameterised for *E. nitens* and *Pinus radiata* and applied to various management-related problems (Sands 2000, Mummery and Battaglia 2001, Battaglia *et al.* 2001).

The input data required by ProMod are of a quality and quantity that forest managers can readily and cheaply obtain. The site factors are site latitude; measures of soil texture, stoniness, depth and drainage, including the presence or absence of a hard pan or other features that impede root growth; a measure of salinity; an index of the site's capacity to supply the nutrients necessary for growth; and the depth to any watertable. These can often be obtained from local knowledge and soil-data map sheets. The climatic factors are the monthly mean values of daily maximum & minimum temperatures, radiation, rainfall, pan evaporation and number of rain days. These can all be obtained from a bioclimatic package such as Esoclim, or from historical meteorological bureau data. ProMod can also be run using actual daily meteorological data.

The primary output from ProMod is NPP, an unequivocal measure of the productive potential of a site. However, as this is of little interest to a manager, NPP was calibrated against observed measures of stem volume production to provide practical measures of productivity. Other outputs include LAI, canopy water use, available soil water, and light use efficiency. ProMod can be used to infer the extent to which factors such as temperature, soil-water and site fertility are limiting production (Battaglia and Sands 1997). The measures of productivity predicted by ProMod can be used to drive conventional empirical stand development models, e.g. the hybrid of ProMod and NitGro predicts the age variation of mean dominant height, stand basal area, stem volume and MAI (Battaglia *et al.* 1999).

ProMod has been implemented as Visual Basic macros running behind Excel spreadsheets, and as a stand-alone package. The Excel version provides a convenient, flexible development tool, even though execution speeds are slow. The stand-alone program has a simple, user-friendly interface, and site and climatic data can be provided as a text file, or entered directly and edited using a data-entry form as part of the user interface. This implementation was subsequently included on a CD of software tools for use by farm foresters (Private Forests Tasmania 1999).

ROTH-C

The Rothamsted soil carbon turnover model (Jenkinson 1990) was initially developed for grassland, forest, pasture and crops under temperate European conditions. Figure 9 shows the model where plant material enters the soil environment and undergoes decomposition through the soil microbial biomass to form a number of well defined pools with the emission of CO_2. These pools have varying resistance to degradation, ranging from highly labile through to inert material.

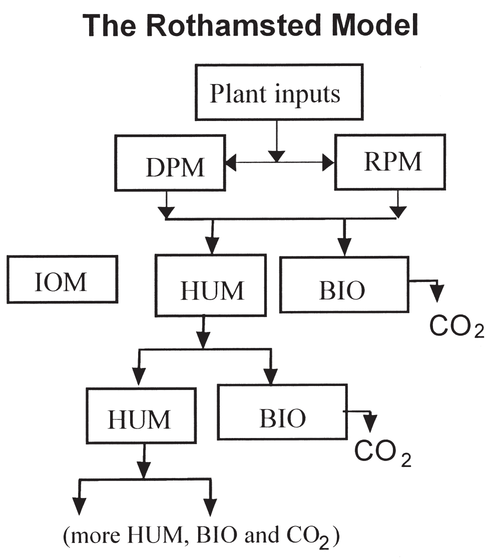


Figure 9: Schematic Diagram of Rothamsted Model. Carbon pools are indicated as IOM (inert), HUM (slow humic), RPM (intermediate resistant plant material), DPM (readily decomposable plant material) and BIO (biomass).

The model essentially consists of a five-compartment system with separate organic carbon pools:

- inert organic matter (IOM)
- easily decomposable plant material (DPM)
- resistant plant material (RPM)
- microbial biomass (BIO)
- humified organic matter (HUM)

Both DPM and RPM decompose to form CO_2, BIO and HUM, with subsequent further decomposition of the BIO and HUM to more CO_2, BIO and HUM. The amount and nature of plant material, clay content, rainfall, pan evaporation, soil temperature and the rate constant for each pool affect the rate of carbon decomposition and thus determine the carbon balance in the soil. Plant residue inputs are either measured directly or are estimated from crop yield data. Different qualities of plant input material (eg different N contents) are handled through varying the DPM/RPM ratio. The model runs on a monthly time step.

In Australia, the model has been calibrated and tested against a number of long-term field trials for depths between 10 and 30 cm using particulate organic carbon (POC) and charcoal-C as surrogates for the RPM and IOM pools respectively. The HUM pool is determined by difference. The model performs well under these conditions with a slowing of the RPM pool rate the only modification required.

SOCRATES

SOCRATES (**S**oil **O**rganic **C**arbon **R**ates **a**nd **T**ransformations in agro-**E**co**s**ystems) (version 3.00b) is a simulation model developed in Australia to estimate changes in SOC, as influenced by crop and pasture rotation, N fertilizer addition, disease, grazing intensity and climate. It was originally developed as a simple, less-data intensive alternative to the more complex CENTURY (Parton *et al.* 1987) and Rothamsted C models (Jenkinson 1990). The main considerations in the development of SOCRATES was that the input data could be easily and rapidly measured in the laboratory and the model was as widely applicable as both the CENTURY and Rothamsted C models. SOCRATES uses a weekly time step, however the driving variables include, annual or monthly precipitation (mm), mean annual temperature (°C), soil clay content (%) or CEC (mmol kg^{-1}) and initial soil organic C (%).

The carbon model consists of 5 components. Plant material entering the soil matrix is divided into decomposable (sugars and carbohydrate), and resistant material (lignin and cellulose) and the soil components consists of microbial biomass and humus. The microbial fraction is further divided into a transient unprotected fraction, which is involved in the initial stage of crop residue decomposition and a protected fraction that is actively involved in the decomposition of native humus and microbial metabolites (Ladd *et al.* 1995). When initialising the model, 2% of the measured SOC store is considered to be protected microbial biomass, with the remaining 98% being stable humus.

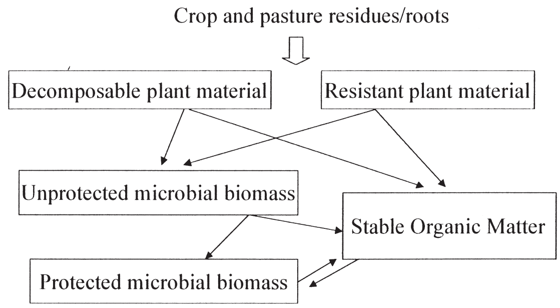


Figure 10: Compartmentalization of plant and soil components in the SOCRATES simulation model (v3.00b). Arrows indicate flow of organic C in the model structure.

The decomposition process in the model produces microbial material, humus and carbon dioxide (Fig. 10) in proportions which are dependent on soil texture, or more specifically the CEC of a soil (Amato and Ladd 1992).

The proportioning of C flows to the microbial biomass, humus and carbon dioxide, and the specific decay rates for each component of the model were initially calibrated using ^{14}C data of Ladd *et al.* (1995). The maximum first order decay rates currently used in the model are 0.84 w^{-1} for decomposable plant material, 0.06, 6.65, 0.055 and 0.0009 w^{-1} for resistant plant material, unprotected and protected microbial biomass and stable organic matter, respectively. The decay rate for the resistant plant fraction in SOCRATES is significantly faster than those specified in the CENTURY and Rothamsted C models, because by definition this material is considered to be recognizable light fraction which is capable of being removed prior to a SOC analyses being performed. The effect of temperature on decomposition is based on a Q_{10} relationship of 2. With respect to soil water calculations, the model has been simplified by considering them to be based on a consistent seasonal cycle. The decay rates are set at 26% of the optimal rate when growing cereal crops and 90% of the optimal rate for fallows (where water is plentiful). For pasture, because additional root production may extract more water, the value used to modify the rate (16%) is lower than the value used for cereals. A more detailed water balance model based on the potential evapotranspiration approach of Thornthwaite and Mather (1957) has been incorporated in later versions.

The model also contains a simple plant growth sub-model if required by the user. This sub-model is essentially a means of producing either leguminous or non-leguminous dry matter to be used in the SOC decomposition model. The user has the option to input actual yield data if available. Plant production is based on the relationship between growing season rainfall and stored soil water at sowing, and productivity, after adjustments are made for the water use efficiency of the system, which is similar to the approach used by French and Schultz (1984). A linear regression is specified for each crop or pasture for the potential yield in a certain environment and the yield is then adjusted using a water availability index (WAI) which also incorporates runoff and evaporation (Fig. 11).

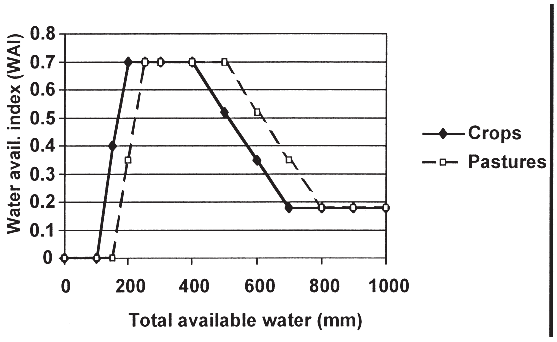


Figure 11: Relationship between total available water (seasonal rainfall and stored water) and the soil water availability index (WAI) for calculating aboveground plant production in SOCRATES v3.00b.

As a strong relationship exists between C accumulation, aggregate stability and infiltration (Tisdall and Oades, 1982), the WAI in the model will also change in response to fluctuations in annual C stores. The individual crops considered in the model are canola, barley, wheat, oats and grain legumes.

The model can also estimate grass and legume pasture productivity and is easily adapted for other crops (e.g. sorghum, millet, maize) through the generic plant growth sub-model. The plant production sub-model also responds to N fertilizer addition and the residual effect of N from grain and pasture legumes. Whilst the original version of SOCRATES does not explicitly simulate N mineralization, the partitioning of plant materials into decomposable and resistant fractions is based on their nitrogen content (i.e. cereals vs legumes). Mineralisation is explicitly outlined in later versions of SOCRATES with a linked soil C/N routine and modifications to simulate conservation tillage strategies. A complete array of plant materials across all biomes can also be simulated in later versions.

The original model was field calibrated using a selection of yield and SOC data from the Permanent Rotation Trial at the Waite Agricultural Research Institute (Grace *et al.*, 1995) and has been found to be accurate in a wide range of semi-arid systems in South Australia, Victoria and Western Australia (RIRDC, unpublished report).

SOCRATES has been recognised as a model of global significance. Izaurradle *et al.* (1996) selected SOCRATES after testing it against five other SOC models (CENTURY, ROTHC 26.3, DNDC version 4.3, EPIC 5125 and ECOSYS). They selected SOCRATES for an agroecosystem carbon aggregation experiment for cropped and grassland soils in Canada because it reproduced soil organic carbon dynamics best in a series of long-term studies and met both strict statistical and practical criteria (Post *et al*, 1999). Grace *et al.* (2001) also found it to be superior to the CENTURY model in simulating changes in SOC in semi-arid cropping systems in southern Australia and the model has been used in Ethiopia (Georgis *et al*, 2001) for C management and as a teaching tooling the Midwest USA (G.P. Robertson, pers. comm.). SOCRATES has also been used in a continental assessment of soil C stocks of Australia in response to a range of climate change scenarios (Grace *et al.*, 1996; 2001)

3-PG

3-PG is a generalised stand model (i.e. it is not site or species-specific, but needs to be parameterised for individual species) applicable to plantations or even-aged, relatively homogeneous forests, which was developed in a deliberate attempt to bridge the gap between conventional, mensuration-based growth and yield, and process-based carbon balance models (Landsberg and Waring 1997). The model consists, essentially, of two sets of calculations: those that lead to biomass values, and those that distribute biomass between various parts of the trees, and hence determine the growth pattern of the stand (Fig. 12). It includes water use and soil water balance calculations. Time step is a month and the state of the stand is updated each month.

The input data required by the model are monthly average values of solar radiation, atmospheric vapour pressure deficit (VPD), rainfall, frost days per month and average temperature, soil water holding capacity in the root zone (q, mm depth equivalent), initial stem number (n_{st}), initial total stem, foliage and root mass (w_s, w_f and w_r, Mg ha^{-1}), and an (index) value

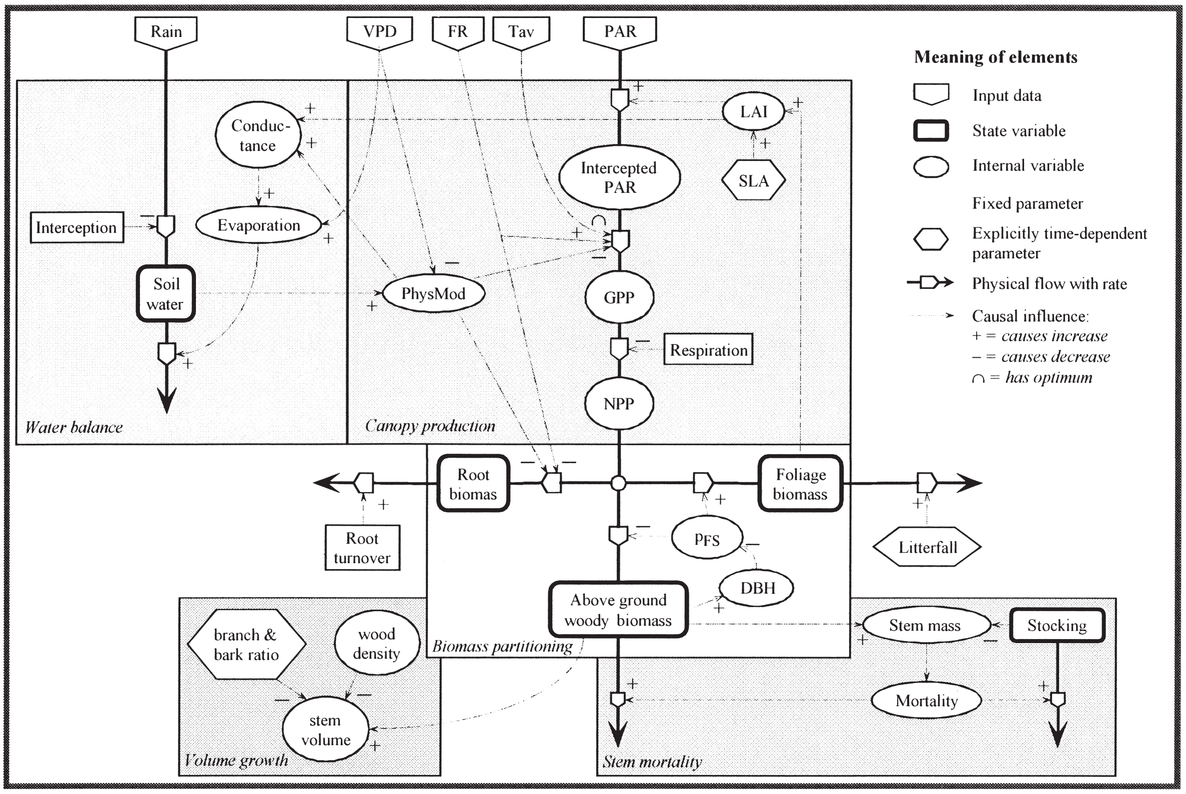


Figure 12: Flow diagram for 3-PG showing model structure, causal influences and interactions. (Diagram developed by Peter Sands)

for soil nutrient status (the fertility rating, FR). FR takes values between 0 (very poor nutrition) and 1 (optimum nutrition). Parameter values needed are the constants (a_i) and coefficients (n_i) of the allometric equations ($w_i = a_i B^{ni}$), specific leaf area (SLA), cardinal temperatures (see below), litterfall rate, maximum stomatal conductance and, the most important, canopy quantum efficiency (QE).

Output variables are those of interest to forest managers: monthly or annual values of Leaf Area Index (L*), stem mass and volume, stem growth rate, Mean Annual (volume) Increment (MAI), stem basal area and stem number. Litterfall (mass), and root turnover are calculated from input rates. Stand transpiration and evaporation of intercepted water are calculated producing monthly soil water balance values.

Gross Primary Production (GPP) is the product of Absorbed Photosynthetically Active Radiation (APAR) and QE, which is modified by correcting for the effects of soil drought, atmospheric vapour pressure deficits and temperature. Stomatal conductance is affected by VPD; it influences QE and the values are also used in the calculation of transpiration (Ewers *et al* 2001). QE (a_c) is also assumed to be linearly dependent on nutrition:

$$a_c = a_0(fN_0 + (1- fN_0)FR)$$

where a_0 is the maximum (unconstrained) value of QE. We originally used a default value of 0.03 mol C (mol quanta)$^{-1}$ (equivalent to 1.65 g C MJ^{-1} APAR, assuming 0.5 g C (g dry biomass)$^{-1}$). Values of 0.04 and 0.05 have been obtained from work in the USA (Law *et al.* 1999), and studies on fast-growing eucalypts indicate a maximum a_0 value of 0.07 mol C (mol quanta)$^{-1}$. We use a_0 = 0.05 for conifers and 0.065 for broadleaved species. fN_0 is usually taken as 0.6 or 0.55. Evidence for these values is not strong, but some exists.

The NPP:GPP ratio is assumed constant, eliminating the need to calculate respiration. Carbohydrates are allocated to roots first, the proportion of monthly NPP going to roots increases under poor nutritional conditions and is increased by water stress. Allocation to stems and foliage is on a single-tree basis and relies on the ratio of the derivatives ($p_{f.s}$) of the allometric equations describing leaf (w_f) and stem (w_s) mass in terms of stem (bole) diameter at 'breast' height (B). The procedure is dynamic and self-regulating. The equations are

$$p_{f.s} = (dw_f / dB)/(dw_s/dB) = a_f n_f B^{(n_f-1)} / a_s n_s B^{(n_s-1)} \int a_p B^{n_p} \qquad (1)$$

$p_{f.s}$ affects the carbon allocation coefficients for foliage (h_f), roots (h_r) and stems (h_s) - which must sum to unity – through the relations

$$h_s = (1- h_f)/(p_{f.s} + 1) \text{ and } h_f = 1- h_r - h_s. \qquad (2)$$

L* is calculated from SLA, foliage mass/stem and stem number.

Mass losses through litterfall and root turnover can be used as inputs to stand carbon balance calculations.

Stem size is calculated by inversion of the allometric equation; stand volume comes from stem mass, wood density and stocking (stem number per hectare).

Stem mortality is governed by the –3/2 power 'law'; the point where mortality starts is set by a stem mass value. This works well when natural mortality is the main mechanism, although the start of stem mortality tends to be too abrupt. 3-PG includes a thinning routine.

3-PG is being evaluated in many countries, including Australia (Coops *et al.* 1998; Tickle *et al.* 2000; Sands and Landsberg 2001), New Zealand (Coops *et al.* 1998a; White 2000; Whitehead *et al.* 2001), the USA (Coops *et al.* 2000b; Landsberg *et al.* 2000; Coops and Waring 2001a, b), South Africa (Dye 2001), Brazil, Chile, the UK (Waring 2000), Denmark, Sweden. It has been adopted as an operational tool by a major forestry company (Aracruz Celulose SA) in Brazil, where it will be implemented in a GIS, in association with calibration plots and fertilisation experiments. In that application stem number and volume outputs will be analysed using conventional forestry product models. It has also been combined with satellite measurements to give remotely sensed input information into important physiological driving variables in the model (Coops *et al* 1998b; Coops 1999).

EXCEL/Visual Basic software for the 3-PG model has been developed by Dr Peter Sands (CSIRO DFFP, Hobart) and another version of the code (produced by Dr Nicholas Coops and Andrew Loughhead, CSIRO DFFP) is available in C++. This allows spatial ARC/INFO coverages to be input and spatial estimates of parameters to be produced. Both of these versions of the code are available at www.landsberg.com.au and mirrored at CSIRO FFP WWW site (www.ffp.csiro.au). Peter Sands' software is accompanied by a Technical Report on the model (Sands 2001).

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