

# A modelled carbon account for Australia's post-1990 plantation estate

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## Summary

Australia's national carbon account for afforestation and reforestation activities qualifying under Article 3.3 of the Kyoto Protocol between 2008 and 2012 can be estimated using a carbon accounting model supported by a range of forest-related data. Using inventories of current plantation areas and projected expansion of the plantation estate, it is possible to project carbon sequestration in 36 known plantation management regimes to give an annual national account of net (sequestration minus emissions) carbon stock change.

Data for the modelling were provided through a range of studies undertaken for the development of the National Carbon Accounting System (NCAS). These included compendiums of available information on management regimes, plantation growth and yield, wood density, carbon contents and allocations to non-stem components of trees.

Future refinements of the modelling will include the extraction of a 'mask' of relevant afforestation and reforestation activities from the continental multi-temporal Landsat satellite coverages of Australia developed for the NCAS. Other improvements will include the use of the NCAS national annual 1 km grid productivity mapping to determine variability in growth associated with variability in climate and soil characteristics. Soil carbon modelling capability using the Roth C model will also be possible when the spatial mapping is complete and details of plantation areas can be merged with the relevant maps of soils and climate.

*Keywords:* carbon; carbon sequestration; models; accounting; inventories; remote sensing; forest plantations; forest management; area; projections; productivity; growth rate; increment; thinning; Australia

## Introduction

The Kyoto Protocol to the United Nations Framework Convention on Climate Change introduces, via Article 3.3, a requirement to account for carbon stock change due to afforestation (establishment of forest on land that has not been forested for at least 50 y), reforestation (establishment of forest on land that was not forested in 1990) and deforestation (removal of forest, except for temporary destocking, since 1990). This paper is the third in a series of three in this issue of *Australian Forestry*. It provides for a description of methods used in the FullCAM model to estimate continental carbon stocks for the NCAS. The other two papers in the series:

- (i) describe the development of the integrated carbon accounting model FullCAM, and
- (ii) provide a detailed overview of the site biomass productivity-based method developed for estimating continental biomass stock and stock change.

Australia's national account for afforestation and reforestation will be largely delivered from the expanding commercial plantation estate, while the account for deforestation will be largely due to emissions from agricultural land clearing.

The Australian Government's capacity for current accounting and account projections has been developed in the initial phase of Australia's National Carbon Accounting System (NCAS). This initial phase included four principal sectors: remote sensing of land cover change, biomass estimation, soil carbon estimation, and system development. A brief synopsis of each of these programs follows.

## Land cover change

Twelve continental coverages of Landsat MSS (50 m resolution, 1972–1988), Landsat TM (25 m, 1988–1998) and Landsat ETM+ (25 m, 2000–2002) were geographically co-registered and spectrally calibrated to provide a history of change in land cover at a fine resolution from 1972 to 2002 (Furby 2001a,b). Change was identified via an objective and automated thresholding procedure on a pixel-by-pixel (25 m) basis. These satellite 'change' data were then merged with the vegetation mapping contained in the National Vegetation Information System and other climate and resource maps (e.g. soils, rainfall). The analysis can also identify areas of afforestation and reforestation capable of being detected as change; that is, providing sufficient change in signal, within each 25 m pixel.

## Biomass

Several data synthesis activities were performed for this program, including collation of published and unpublished literature on biomass estimation, partitioning of biomass into various tree elements, carbon contents of tree types and components, and wood density. Plantation growth (yield) data were calculated from the published wood yield estimates of the National Forest Inventory (NFI 1997a) by Turner and James (2001).

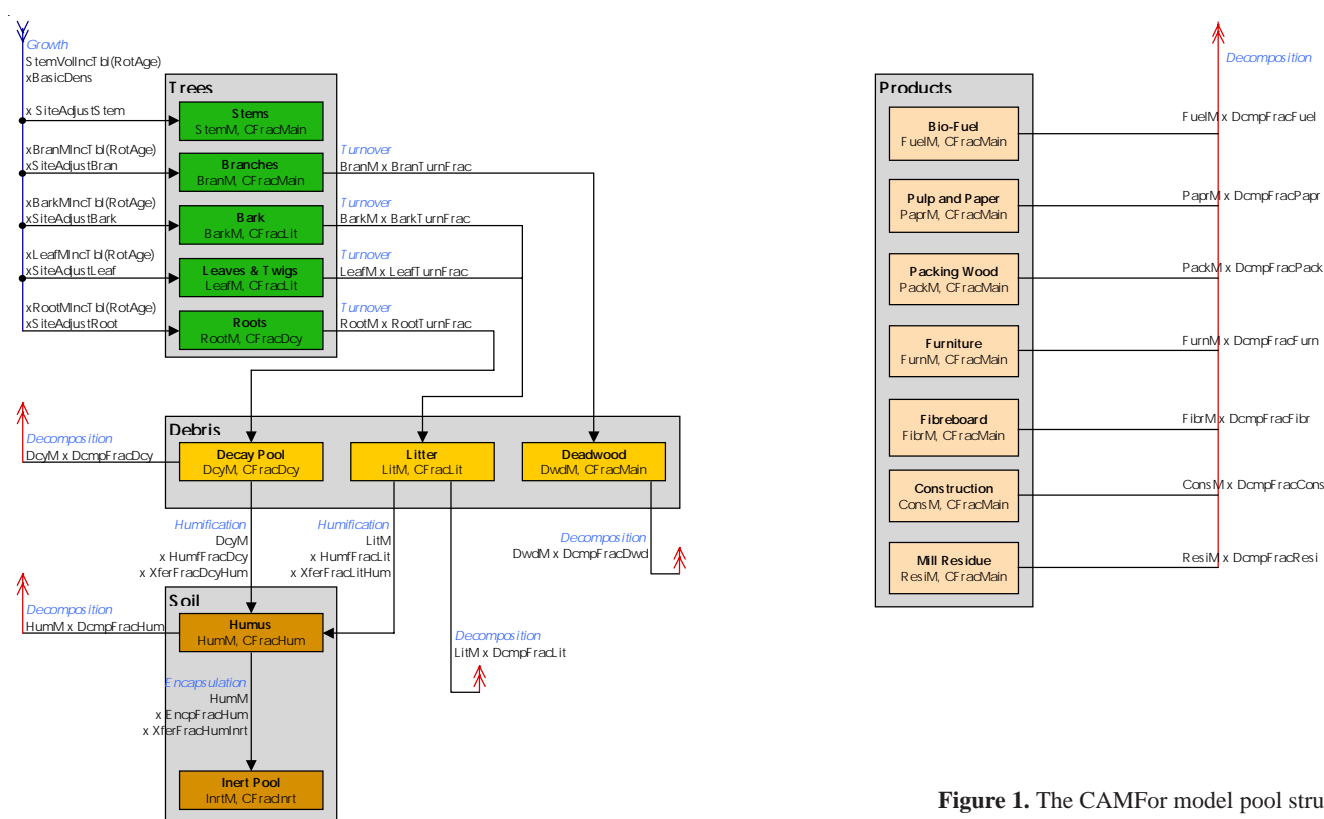


Figure 1. The CAMFor model pool structure

For native forests a modified version of 3PG (Landsberg and Waring 1997; Coops *et al.* 1998; Coops *et al.* 2001; Landsberg and Kesteven 2001; Landsberg *et al.* 2001) was applied spatially to provide relative indices of productivity (1970–2000 and long-term average) at 1 km resolution. A 250 m slope-and-aspect-corrected productivity surface was also produced. Regressions with productivity developed around known measures of mass in native forests were subsequently fitted to generalised yield curves. The spatially and temporally variable productivity indices provide a moderator to achieve ‘real time’ estimates of biomass accumulation which vary by age as derived from the Land Cover Change program. The productivity mapping will be used to estimate growth when spatial modelling is implemented.

### Estimation of soil carbon

The agricultural soils program considered several elements including calibration of the Roth C model (Jenkinson *et al.* 1987, 1991), development of a national land use and management database (Swift and Skjemstad 2001), preparation of a pre-disturbance soil carbon map of Australia (Webb 2002), standardisation of analytic (laboratory) methods and correction of historic results (Skjemstad *et al.* 2000), yield estimation for different crop types by region over time, and extensive field verification of modelled results (Skjemstad and Spouncer 2003).

Forest soils have been treated independently, albeit drawing relevant information from the agricultural soils program and following technically and conceptually similar processes. State-of-knowledge and model development have been reported (Polglase *et al.* 2000; Paul *et al.* 2001). Development of model calibration programs has progressed (Paul *et al.* 2003a,b) and will be applied when the spatial modelling is implemented.

### System development

The system development for the NCAS started with the point-based and spatial ‘estate’ Excel versions of the CAMFor model (Richards and Evans 2000). CAMFor (Fig. 1) was then integrated with the RothC soil carbon model which is independently calibrated and verified in the soils program, the 3PG forest growth model and the GENDEC litter decomposition model (Moorhead and Reynolds 1991; Moorhead *et al.* 1999) in an Excel application (GRC3). The individual models can be applied independently or in various combinations within the model framework. For example, CAMFor can take data inputs from user-entered data tables, from 3PG or from a generalised, productivity-driven growth formula.

Once testing of the GRC3 model was complete, an equivalent agricultural model was developed around a new model CAMAg (Richards 2002), which replicated the role of CAMFor. The forest and agricultural applications were then integrated in the FullCAM model (Richards 2001, 2002), providing the capacity for spatial (GIS) application, with transitions between agricultural and forest systems, or mixed systems such as agroforestry and grazed woodlands. The ability to change agricultural and forest species over time was also introduced into FullCAM (Fig. 2). The FullCAM model provides the framework for integrating the model calibration and verification activities, data on land use and management systems, remotely-sensed information on land cover change, and collated (tabular) data such as crop yield and wood density.

### The approach to post-1990 plantations

The approach to estimating carbon accumulation in plantations established after 1990 will evolve and be refined as the NCAS

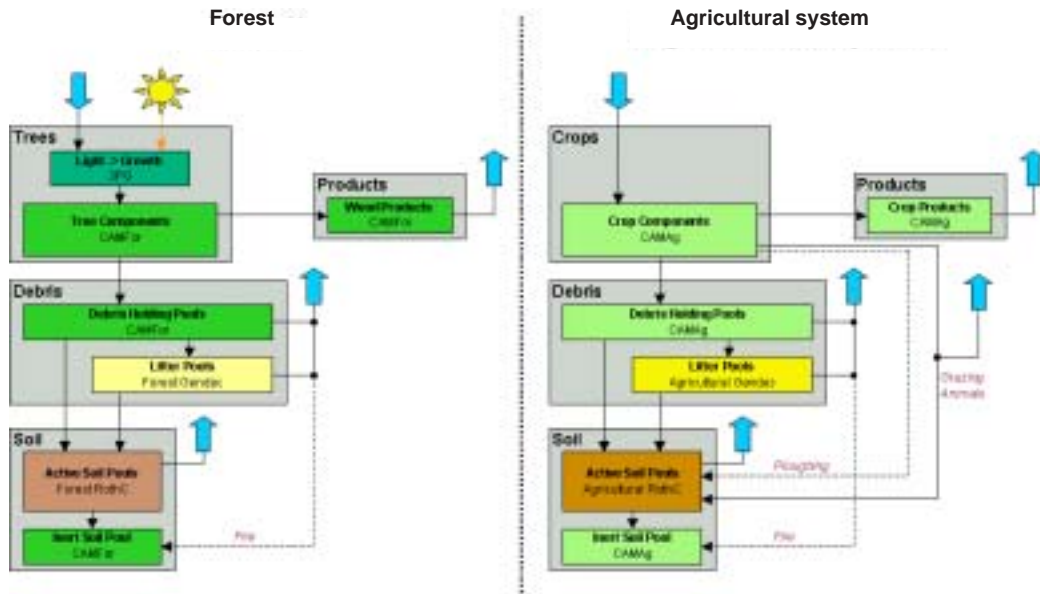


Figure 2. The FullCAM model principal pool structure

develops. In this initial implementation, growth increment tables based on the work of Turner and James (2001) as developed from the National Forest Inventory (NFI 1997a) estimates of wood flow, are used as a basis for growth modelling (Brack 2001; Brack and Richards 2001). Areas of relevant (to the Kyoto Protocol) plantation types have been derived by Spencer (2001) from the National Plantation Inventory establishment estimates (NFI 1997b, 2000). Overall estimates were discounted by the estimated areas of establishment subsequent to the clearing of native forests and second-rotation plantations, neither of which are compliant with the afforestation and reforestation definitions of Article 3.3 of the Kyoto Protocol. Spencer (2001) also provides estimates for the projected expansion of the plantation estate to 2019. These estimates and the growth tables of Turner and James (2001) underpin the current approach as reported in this paper.

The next significant stage of model development will be the use of the multi-temporal remote sensing program to spatially define the expansion of the plantation estate. Such an approach will allow for the linking of areas of establishment to the productivity mapping previously described. This will allow the generation of growth tables according to variable productivity (over both space and time) and for informed allocation of management regimes as affected by site productivity.

While soil carbon contents for most plantations do not change in the medium to long term (Polglase *et al.* 2000), there are frequently short-term losses (later recovered in most situations) and some instances of long-term losses (Paul *et al.* 2002). Work is underway to develop capacity for soil carbon accounting for the range of plantation situations. Initial work (Paul *et al.* 2003a,b) shows the potential to develop this capacity.

The model capability for the NCAS is also being extended to include the non-CO<sub>2</sub> gases which may arise from activities, such as fertiliser application and decomposition, producing nitrous oxide and methane under moist conditions. These gases and their potential impact have not been considered in the current analyses.

**Model implementation**

The data provided by Spencer (2001) are reported on the basis of the 14 National Plantation Inventory regions (Fig. 3). Three classes of forest are defined: short rotation hardwood (SRH), long rotation hardwood (LRH) and softwood (SW). Projected areas of establishment (beyond 2000) are a medium (mid-range) expectation (Table 1) for projected establishment rates. Data are generally presented as an average over five-year areas of establishment.

These data were subsequently annualised (cumulative area divided by number of years) within the blocks of years reported by Spencer



Figure 3. The National Plantation Inventory regions: 1 Western Australia; 2 Tasmania; 3 Green Triangle; 4 South Australia Lofty Block; 5 Central Victoria; 6 Murray Valley; 7 Central Gippsland; 8 East Gippsland/Bombala; 9 Southern Tablelands; 10 Central Tablelands; 11 Northern Tablelands; 12 North Coast; 13 South-east Queensland; 14 Northern Queensland; 15 Northern Territory

**Table 1.** Estimated plantation areas (ha) post-1990 (after Spencer *et al.* 2001)

Region	1990–1994			1995–1999			2000–2004			2005–2009			2010–2014			2015–2019		
	SRH	LRH	SW	SRH	LRH	SW	SRH	LRH	SW	SRH	LRH	SW	SRH	LRH	SW	SRH	LRH	SW
Western Australia	33814	37	6389	106722	364	12470	73700	700	5900	37900	3800	11400	31000	5200	25900	20700	5200	5900
Tasmania	2385	666	2247	9674	2100	5273	14700	7400	7400	11400	7600	7600	10300	10300	10300	10300	5200	0300
Green Triangle	2786	154	4766	22842	504	6772	88500	6300	8300	37900	9500	9500	10300	10300	10300	5100	8300	5100
Central Victoria	392	177	1234	5537	400	1782	25100	3200	900	7600	1900	1900	10300	2100	2600	5200	2100	2600
Murray Valley	7	136	7123	2018	773	12142	4800	4800	4800	2900	2900	2900	3800	3800	3800	3900	3800	3800
Central Gippsland	4971	1279	2957	7420	224	4286	8100	2000	900	5100	1700	1900	6900	2300	2600	6900	2300	2600
East Gippsland	411	82	639	1157	255	5387	2600	0	3700	2700	0	3800	2100	0	2100	2100	0	2100
Southern/Central Tablelands	0	6	5006	0	69	8397	0	1900	23600	0	1900	24200	0	2000	16600	0	1500	6600
Northern Tablelands	51	491	1257	569	16198	2918	3700	22100	2900	3800	17000	3000	5200	18600	2000	5200	14000	2000
Queensland	0	674	2357	0	4807	7539	7300	14700	7300	7500	22700	7500	5200	20700	8200	5200	20700	8200
TOTAL	44817	3702	33975	155939	25694	66966	228500	63100	65700	116800	69000	73700	85100	75300	84400	64600	63100	79200

SRH: Short-rotation hardwood; LRH: Long-rotation hardwood; SW: Softwood

**Table 2.** Typical plantation management regimes in each National Plantation Inventory (NPI) region

Species	NPI region	Regime
<i>Pinus pinaster</i>	Western Australia	Average sites — 65% thin @ 18 y, 37% @ 25 y and clearfall @ 40 y
<i>Pinus radiata</i>	Western Australia	Average sites — 51% thin @ 12 y, 39% @ 18 y, 32% @ 24 y, clearfall @ 35 y
<i>Pinus radiata</i>	Victoria, New South Wales	Poor sites — clearfall @ 30 y
<i>Eucalyptus globulus</i>	Western Australia	Clearfall @ 10 y
<i>Pinus radiata</i>	Victoria, New South Wales	Average sites — 65% thin @ 16 y, 57% @ 24 y, 27% @ 30 y, clearfall @ 35 y
<i>Pinus radiata</i>	Victoria, New South Wales	Poor sites — 26% thin @ 18 y, 32% @ 24 y, clearfall @ 30 y
<i>Pinus radiata</i>	Victoria, New South Wales	Average sites — 65% thin @ 16 y, clearfall @ 30 y
<i>Pinus radiata</i>	Victoria, New South Wales	Average sites — 65% thin @ 16 y, 57% @ 24 y, clearfall @ 30 y
<i>Pinus radiata</i>	Murray Valley	Very good sites — 44% thin @ 14 y, 31% @ 18 y, 27% @ 23 y, clearfall @ 30 y
<i>Pinus radiata</i>	Victoria, New South Wales	Average sites — clearfall @ 30 y
<i>Pinus radiata</i>	Murray Valley	Average sites — 47% thin @ 14 y, 35% @ 22 y, 29% @ 29 y, clearfall @ 30 y
<i>Pinus radiata</i>	Murray Valley	Average sites — 47% thin @ 14 y, 35% @ 22 y, clearfall @ 30 y
<i>Eucalyptus</i> spp.	Vic (Central Gippsland)	All sites — clearfall @ 35 y
<i>Pinus radiata</i>	Vic (Central Gippsland)	Average sites — 33% thin @ 15 y, 37% @ 20 y, clearfall @ 30 y
<i>Eucalyptus</i> spp.	Vic (Central Gippsland)	All sites — clearfall @ 20 y
<i>Eucalyptus</i> spp.	Vic (Central Gippsland)	All sites — clearfall @ 30 y
<i>Pinus radiata</i>	Victoria (Central)	Average sites — clearfall @ 30 y
<i>Eucalyptus</i> spp.	Victoria (Central)	All sites — clearfall @ 25 y
<i>Pinus</i> spp. (not <i>P. radiata</i> )	Tasmania	All sites — clearfall @ 35 y
<i>Pinus radiata</i>	Victoria (Central)	Average sites — 34% thin @ 15 y, 18% @ 22 y, 24% @ 28 y, clearfall @ 35 y
<i>Eucalyptus nitens</i>	Tasmania	All sites — clearfall @ 25 y
<i>Pinus radiata</i>	Tasmania	Average sites — clearfall @ 35 y
<i>Eucalyptus nitens</i>	Tasmania	All sites — clearfall @ 30 y
<i>Eucalyptus nitens</i>	Tasmania	All sites — clearfall @ 15 y
<i>Eucalyptus</i> spp.	South Australia	All sites — clearfall @ 25 y
<i>Pinus</i> spp. (not <i>P. radiata</i> )	South Australia	Average sites — 54% thin @ 13 y, 25% @ 18 y, 28% @ 23 y, clearfall @ 30 y
<i>Eucalyptus</i> spp.	South Australia	All sites — clearfall @ 25 y
<i>Pinus</i> spp. (not <i>P. radiata</i> )	South Australia	Average sites — 54% thin @ 13 y, 25% @ 18 y, 28% @ 23 y, clearfall @ 30 y
<i>Eucalyptus</i> spp.	South Australia	All sites — clearfall @ 20 y
<i>Eucalyptus</i> spp.	South Australia	All sites — clearfall @ 15 y
<i>Eucalyptus</i> spp.	Queensland	All sites — clearfall @ 20 y
Southern pines	Queensland	All sites — 35% thin @ 18 y, clearfall @ 35 y
<i>Eucalyptus</i> spp.	NSW	All sites — clearfall @ 20 y
<i>Eucalyptus</i> spp.	Queensland	All sites — 67% thin @ 20 y, 47% @ 35 y, clearfall @ 45 y
Southern pine	NSW Northern Tableland	Average sites — 27% thin @ 14 y, 47% @ 20 y, clearfall @ 30 y
<i>Eucalyptus</i> spp.	NSW	All sites — 67% thin @ 20 y, 47% @ 35 y, clearfall @ 45 y
<i>Pinus radiata</i>	Green Triangle	Average sites — 54% thin @ 13 y, 25% @ 18 y, 28% @ 23 y, clearfall @ 30 y
<i>Pinus</i> spp. (not <i>P. radiata</i> )	Green Triangle	Average sites — 54% thin @ 13 y, 25% @ 18 y, 28% @ 23 y, clearfall @ 30 y

(2001). The changing trends in data are often quite dramatic, and averaging often leads to large ‘step’ functions in the data. This will be refined when the spatial application is implemented.

Allocations of the SRH, LRH and SW classes are made to the region and species-specific management regimes described by Turner and James (2001). Table 2 shows the 38 management regimes for which growth increment (yield) tables are available.

Within the FullCAM model, as implemented to derive a carbon account for the national plantation estate, CAMFor equivalent models for each of the 38 identified management regimes were developed. Additional information, beyond the growth tables and thinning regimes of Turner and James (2001) shown in Table 2 and the example datasheets (Figures 4a,b,c), for each Forest Type included:

- wood density
- conversion of stem mass to whole-tree mass
- carbon contents
- destinations of wood product, and
- estimates of leaf and root turnover.

For each of the management regimes, Figure 4 shows snapshots of the relevant inputs and the resultant carbon balances on a per-hectare basis. These snapshots are integrations of the information collated by the NCAS as individual implementations of the model for each management regime.

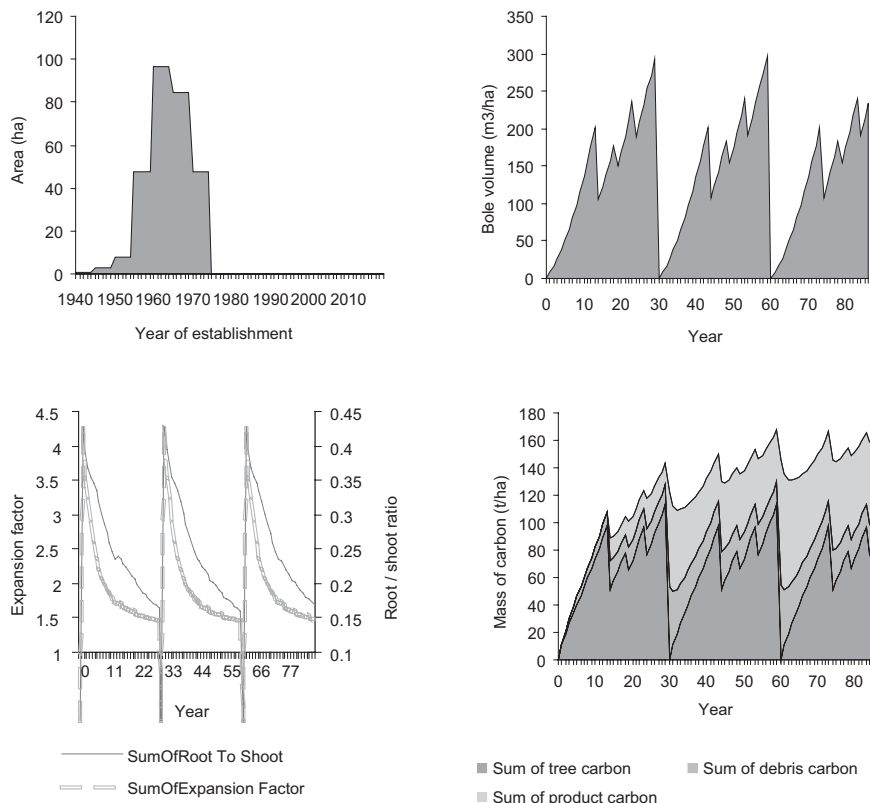
The ‘Estate’ module of CAMFor, as contained within the FullCAM, is then used to determine the consequence of

implementing the individual management regime models on the basis of the new areas of forest established under each regime over time. To do this, the model interrogates the carbon balance for each management regime at the relevant point in time to derive the overall account. The per-hectare outcome, by the relevant age (as determined by the year of planting for each regime), is multiplied by the number of hectares planted in the corresponding year to calculate the change for the whole of the estate in any one year. A fuller explanation of the operation of the ‘Estate’ module of CAMFor can be found in Richards and Evans (2000).

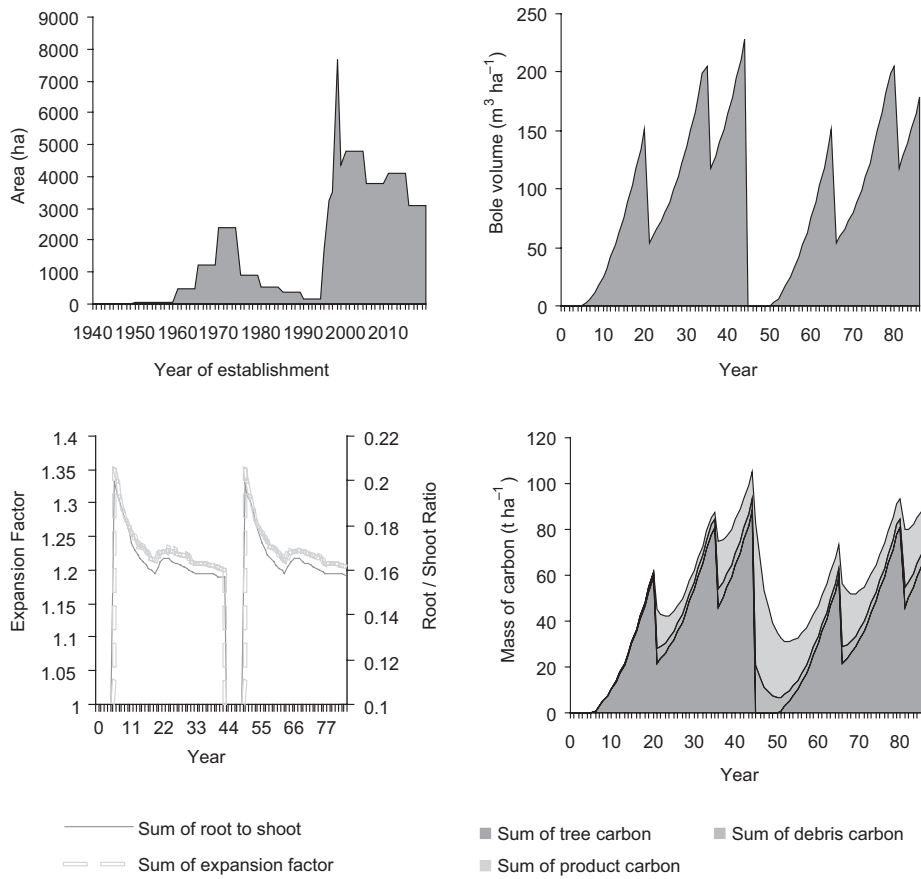
**Growth tables and thinning regimes**

Turner and James (2001) were commissioned by the NCAS to reinterpret their previous work for the NFI wood flow estimates (NFI 1997a) to provide current annual increments (CAI) of stem volume for each management regime represented. To determine the CAI, estimates of total volume produced (from either a thinning or a clearfall) by age were fitted to growth curves. The method of fitting growth curves to the known points of wood yield for each management regime is described in Turner and James (2001).

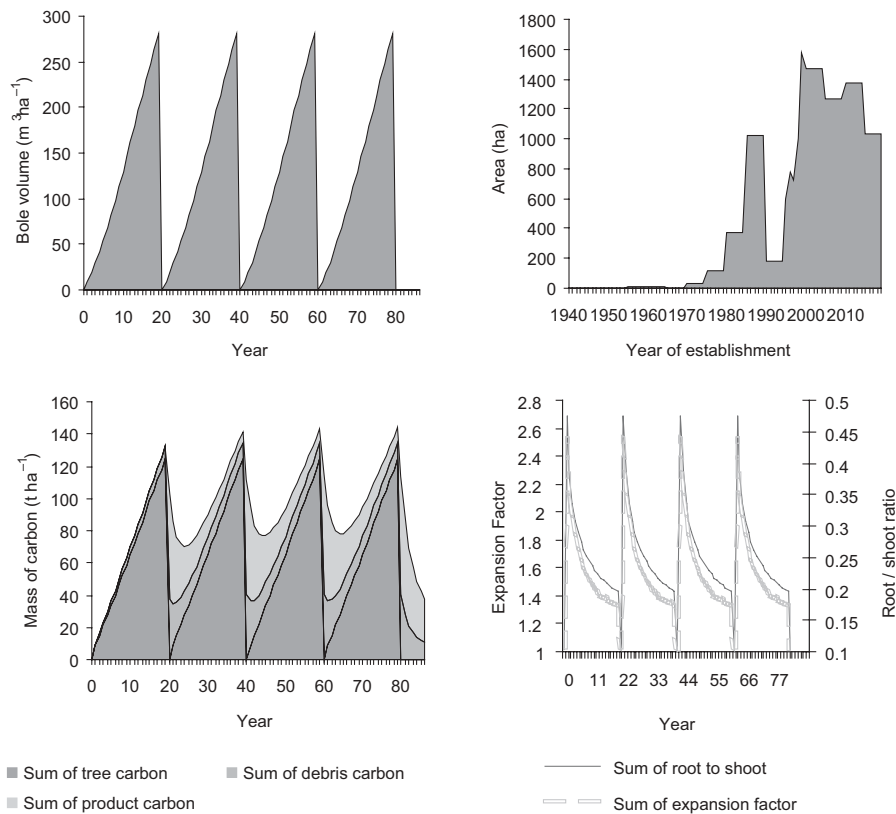
The information to support the estimates of wood flow was collected through grower survey, and would largely be the result of actual inventory. As such, the estimates would generally reflect inventory data collected to the point of plantation maturity. The data would therefore be representative of the growing stock, site and silvicultural treatments over the life of the plantation, many aspects of which will have improved since that time. As growth projections, the estimates are therefore likely to be conservative



**Figure 4a.** Example model inputs and carbon balances for short-rotation hardwood (SRH): *Eucalyptus* plantation, NSW9101112 (All sites: 67% @ 20y; 47% @ 35 y; CF @ 45 y)



**Figure 4b.** Example model inputs and carbon balances for long-rotation hardwood (LRH): *Eucalyptus nitens* plantation, Tasmania (All sites: CF @ 30y)



**Figure 4c.** Example model inputs and outcomes for softwood (SW): *Pinus* spp. (not *P. radiata*) plantations, Green Triangle (Average: 54% thinning @ 13 y; 25% @ 18 y; 28% @ 23 y; CF @ 30y)

because of expected improvement in plantation performance. However, this benefit may be moderated by a constrained availability of optimum sites for future plantation establishment.

The empiricism of the estimates also masks the influences of climate variability over the time of measurement. A variable climate is associated with a variability in growth over time. While it is unlikely that the volume at maturity (reflecting the longer-term climate average) would be much affected, over a shorter period such as the first Commitment Period of the Kyoto Protocol (2008–2012) yield may be above or below the expected growth due to the prevailing climate conditions. The potential impact of prevailing climate conditions during the time of reporting has been studied and is reported in Brack and Richards (2002).

### Estimates of wood density and carbon content

Wood density estimates were extracted from the compendium prepared by Ilic *et al.* (2000) for the NCAS. While many native forest species have few—in some instances no—reported wood density estimates, plantation species are relatively well studied and reported. However, wood density is most commonly measured at the time of harvest, reflecting a mature state.

As it is commonly accepted that wood density increases with tree age, up to a certain point, it is possible that the adopted wood densities are over-estimates for the early stages of plantation growth. However, the overall effect is unlikely to be significant as lower densities occur when mass is least; that is, during early growth stages. Also, as plantations are generally harvested well before individual tree maturity (generally before annual growth increment begins to decline) it is possible that the maximum potential density may not be achieved by the time of harvest. Table 3 shows the wood density values used for the major plantation species in the management regimes.

The carbon contents of various tree components below and above ground were examined by Gifford (2000a) and Gifford (2000b) respectively in studies for the NCAS. Carbon contents were tested for various species and growing conditions, with recommended estimates given within the range of values yielded in test results. There was little variability in the results and more importantly no cause to suspect bias in any set of environmental conditions or plant groups. These results could be considered as robust and reliable estimates, providing little uncertainty in the carbon models.

### Stem to whole-tree mass conversions

Studies completed for the NCAS on the above- and below-ground partitioning of biomass (Grierson *et al.* 2000; Keith *et al.* 2000; Eamus *et al.* 2000; Snowdon *et al.* 2000) have shown that both below-ground and non-stem allocations reduce as site biomass increases. Greatest uniformity, and therefore least variability, tends to occur in even-aged and productive stands. Figures 4a,b,c illustrate the non-stem allocations (root/shoot ratio) used in each management regime model.

The ratio of stem (merchantable) quantities to non-merchantable components is particularly important for the calculation of the amounts of forest slash generated by thinning and harvesting activity. The potential accumulation of slash can make a considerable contribution to increased carbon stock, particularly on former pasture sites.

### Wood product destinations

Jaakko Pöyry Pty Ltd (1999, 2000) were contracted by the NCAS to develop a life-cycle analysis model for forest products. The timber pool descriptions developed (e.g. timber framing, furniture, pulp and paper, mill residue) were subsequently incorporated into the CAMFor model, and hence FullCAM. The pool turnover rates (Table 4) were also incorporated, providing a stand-based wood product life cycle capacity within CAMFor / FullCAM. These turnover rates are applied annually, so the trajectory of decomposition is exponential.

The principal limitation of the approach as used is that the turnover rates are estimates with potentially large variability. A number of factors such as building engineering design life and rates of recycling can produce vastly different turnover rates. Also, only the serviceable life of products has been considered. As yet there is only a very preliminary understanding of the rates of breakdown after disposal.

### Leaf and root turnover

The turnover rate of leaves affects both the amount of fine litter on the forest floor and subsequently most of the aboveground contribution to soil carbon. The turnover of roots (largely fine roots) is a direct input to soil carbon.

As this implementation of the model has not considered soil carbon, the rates of turnover of both leaves and fine roots are relatively unimportant. The key attributes of the assigned rates (Table 5) are that they are realistic and neither reduce the mass of attached leaves and live roots below reasonable expectation, nor create unrealistically high or low levels of litter.

A simple reality check can be performed directly from observations of model results. While leaf turnover rates have been the subject of measurement and can be compared to observations, the difficulty in measuring root turnover means that there are very few reported measures for comparison. However, as the stock of 'dead' fine root material is accounted for as soil organic matter, this becomes irrelevant until soil carbon accounting is attempted. Testing of the more comprehensive modelling capability of the Australian Greenhouse Office's GRC3 model by Paul *et al.* (2003a,b), and ongoing NCAS studies with CSIRO and the Australian National University, provide a basis for developing this capacity in future.

### Slash decomposition

Subsequent to harvest there are often large quantities of slash (stumps, branches, etc.) left on the forest floor to decompose. The rates of decomposition applied in the model have been guided by the work of Mackensen and Bauhus (1999) for the NCAS. Table 6 shows the decomposition rates applied.

### Harvesting sub-rule

Under Article 3.3 of the Kyoto Protocol, there is a harvesting sub-rule that plantations established after 1990 (with a positive carbon stock change since 1990) may, because of a thinning or harvest activity in the first Commitment Period (2008–2012), yield a negative carbon stock change result for that period.

**Table 3.** Wood densities and carbon contents for each management regime

Region(s)	Species	Density	Carbon content (%)								Regime description
			Leaf	Twig	Brch	Sap	Wood	Bark	Fine	Coarse	
Green Triangle	<i>Pinus radiata</i>	440	52	52	51	51	52	53	46	49	Average sites — 54% thinning @ 13 y, 25% @ 18 y, 28% @ 23 y, CF @ 30 y
Green Triangle	<i>Pinus</i> spp. (not <i>P. radiata</i> )	440	52	52	51	51	52	53	46	49	Average sites — 54% thinning @ 13 y, 25% @ 18 y, 28% @ 23 y, CF @ 30 y
NSW Northern Tableland	Southern pine ( <i>P. elliotii</i> , <i>P. taeda</i> ), <i>Araucaria cunninghamii</i>	440	52	52	51	51	52	53	46	49	Average sites — 27% thinning @ 14 y, 47% @ 20 y, CF @ 30 y
NSW	<i>Eucalyptus</i> plantations	550	52	52	47	52	52	49	46	49	All sites — 67% @ 20 y, 47% @ 35 y, CF @ 45 y
NSW	<i>Eucalyptus</i> plantations	550	52	52	47	52	52	49	46	49	All sites — CF @ 20 y
Queensland	<i>Eucalyptus</i> plantations	550	52	52	47	52	52	49	46	49	All sites — 67% @ 20 y, 47% @ 35 y, CF @ 45 y
Queensland	<i>Eucalyptus</i> plantations	550	52	52	47	52	52	49	46	49	All sites — CF @ 20 y
Queensland	Southern pine ( <i>P. elliotii</i> , <i>P. taeda</i> ), <i>Araucaria cunninghamii</i>	440	52	52	51	51	52	53	46	49	All sites — 35% @ 18 y, CF @ 35 y
South Australia	<i>Eucalyptus</i> plantations	550	52	52	47	52	52	49	46	49	All sites — CF @ 20 y
South Australia	<i>Eucalyptus</i> plantations	550	52	52	47	52	52	49	46	49	All sites — CF @ 15 y
South Australia	<i>Eucalyptus</i> plantations	550	52	52	47	52	52	49	46	49	All sites — CF @ 25 y
South Australia	<i>Pinus</i> spp. (not <i>P. radiata</i> )	440	52	52	51	51	52	53	46	49	Average sites — 54% thinning @ 13 y, 25% @ 18 y, 28% @ 23 y, CF @ 30 y
Tasmania	<i>Eucalyptus nitens</i>	550	52	52	47	52	52	49	46	49	All sites — CF @ 30 y
Tasmania	<i>Eucalyptus nitens</i>	550	52	52	47	52	52	49	46	49	All sites — CF @ 15 y
Tasmania	<i>Eucalyptus nitens</i>	550	52	52	47	52	52	49	46	49	All sites — CF @ 25 y
Tasmania	<i>Pinus radiata</i>	440	52	52	51	51	52	53	46	49	Average sites — CF @ 35 y
Tasmania	<i>Pinus</i> (not <i>P. radiata</i> )	440	52	52	51	51	52	53	46	49	All sites — CF @ 35 y
Victoria (Central)	<i>Pinus radiata</i>	440	52	52	51	51	52	53	46	49	Average sites — 34% thinning @ 15 y, 18% @ 22 y, 24% @ 28 y, CF @ 35 y
Victoria (Central)	<i>Pinus radiata</i>	440	52	52	51	51	52	53	46	49	Average sites — CF @ 30 y
Victoria (Central Gippsland)	<i>Eucalyptus</i> plantations	550	52	52	47	52	52	49	46	49	All sites — CF @ 25 y
Victoria (Central Gippsland)	<i>Eucalyptus</i> plantations	550	52	52	47	52	52	49	46	49	All sites — CF @ 20 y
Victoria (Central Gippsland)	<i>Eucalyptus</i> plantations	550	52	52	47	52	52	49	46	49	All sites — CF @ 30 y
Victoria (Central Gippsland)	<i>Eucalyptus</i> plantations	550	52	52	47	52	52	49	46	49	All sites — CF @ 35 y
Victoria (Central Gippsland)	<i>Pinus radiata</i>	440	52	52	51	51	52	53	46	49	Average sites — 33% thinning @ 15 y, 37% @ 20 y, CF @ 30 y
Murray Valley	<i>Pinus radiata</i>	440	52	52	51	51	52	53	46	49	Average sites — 47% thinning @ 14 y, 35% @ 22 y, 29% @ 29 y, CF @ 30 y
Murray Valley	<i>Pinus radiata</i>	440	52	52	51	51	52	53	46	49	Average sites — 47% thinning @ 14 y, 35% @ 22 y, CF @ 30 y
Murray Valley	<i>Pinus radiata</i>	440	52	52	51	51	52	53	46	49	Very good sites — 44% thinning @ 14 y, 31% @ 18 y, 27% @ 23 y, CF @ 30 y
Victoria and NSW	<i>Pinus radiata</i>	440	52	52	51	51	52	53	46	49	Average sites — CF @ 30 y
Victoria and NSW	<i>Pinus radiata</i>	440	52	52	51	51	52	53	46	49	Average sites — 65% thinning @ 16 y, CF @ 30 y
Victoria and NSW	<i>Pinus radiata</i>	440	52	52	51	51	52	53	46	49	Average sites — 65% thinning @ 16 y, 57% @ 24 y, CF @ 30 y
Victoria and NSW	<i>Pinus radiata</i>	440	52	52	51	51	52	53	46	49	Average sites — 65% thinning @ 16 y, 57% @ 24 y, 27% @ 30 y, CF @ 35 y
Victoria and NSW	<i>Pinus radiata</i>	440	52	52	51	51	52	53	46	49	Poor sites — 26% thinning @ 18 y, 32% @ 24 y, CF @ 30 y
Victoria and NSW	<i>Pinus radiata</i>	440	52	52	51	51	52	53	46	49	Poor sites — CF @ 30 y
Western Australia	<i>Eucalyptus globulus</i>	550	52.8	49.8	47	48.7	50.7	49	46	49	Clear fall @ 10 y
Western Australia	<i>Pinus pinaster</i>	470	52	52	51	51	52	53	46	49	Average sites — 65% thinning @ 18 y, 37% @ 25 y, CF @ 40 y
Western Australia	<i>Pinus radiata</i>	440	52	52	51	51	52	53	46	49	Average sites — 51% thinning @ 12 y, 39% @ 18 y, 32% @ 24 y, CF @ 35 y

**Table 4.** Decomposition rates for wood products

Product type	Decomposition rate (fraction y <sup>-1</sup> )
Biofuel	1.0
Pulp and paper	0.33
Packing wood	0.2
Furniture, poles	0.05
Fibreboard	0.07
Construction wood	0.02
Mill residue	1.0

**Table 5.** Turnover rates for tree components

Tree component	Turnover (fraction y <sup>-1</sup> )
Branches	0.03
Bark	0.1
Leaves and twigs	0.5
Coarse roots	0.05
Fine roots	0.1

**Table 6.** Decomposition rates for slash

Slash component	Decomposition rate (fraction y <sup>-1</sup> )
Deadwood	0.1
Bark litter	0.5
Leaf litter	1.0
Coarse dead roots	0.5
Fine dead roots	1.0

The sub-rule operates on a stand-by-stand basis, and any stand that qualifies for Article 3.3 afforestation or reforestation but has a negative stock change result will be excluded from the accounting.

To deal with this in CAMFor ‘Estate’ (as implemented within FullCAM), an additional reporting routine has been added whereby each age class (annual) for each management regime is reviewed for cases where the carbon stock in 2012 is less than the carbon stock in 2008. In such instances the negative stock change is automatically replaced with a zero stock change. This approach gives effect to the sub-rule in a stand-based approach.

**Uncertainty analysis**

Brack and Richards (2002) have provided the basis for uncertainty analysis using the @Risk (Palisade 1997) ‘Monte Carlo’ capabilities attached to the CAMFor model. The analysis described the potential ‘variance’ within many parameters in terms of a probability distribution.

Dealing with quantified variances within Monte Carlo analyses also makes it possible to consider the correlation between variables and parameters, and the likelihood of any single or interacting circumstance occurring. When the Monte Carlo analysis, running multiple variants of possible inputs in combination, is not guided by correlation, simplistic, yet unrealistic, scenarios may be induced. For example, under a high rainfall, growth rate will likely

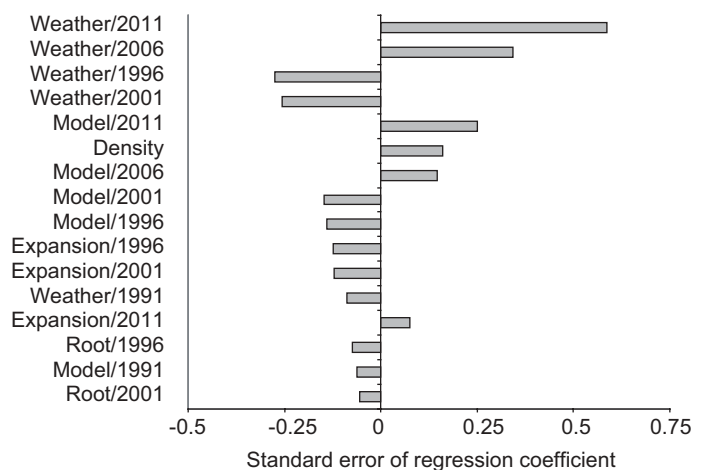
increase, as will decomposition rates. If the Monte Carlo analyses are informed that these parameters are positively correlated, then the random selection of high growth values will be associated with increased decomposition values.

If correlations are not prescribed, combinations such as increased growth and decreased decomposition rates (a negative correlation) are as likely to be selected as a positive correlation, although they are unlikely to occur in reality. The inclusion of unrealistic scenarios (i.e. presuming all variables are independent) in the Monte Carlo analyses will considerably increase uncertainty attributed to model outcomes by not acknowledging the frequently ameliorating effects of correlated inputs.

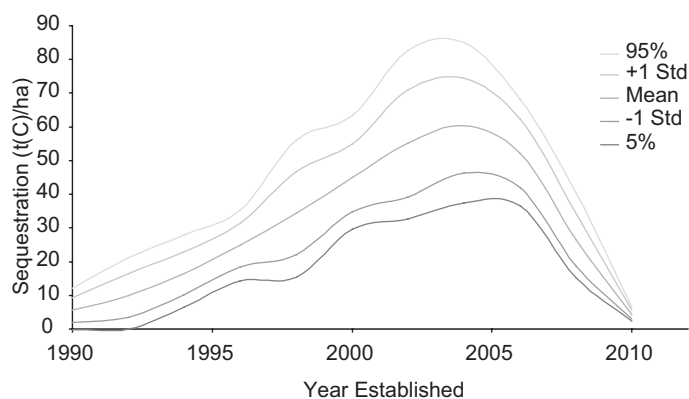
Brack and Richards (2002) modelled the performance of an individual stand, using growth rates determined according to the observed growth variance around rainfall variability, error in allocating a growth index for the relevant growth model, and known variance or uncertainty in other key parameters.

The ‘tornado’ diagram (Fig. 5) shows the sources of uncertainty of model parameters in order of their importance to uncertainty in the model outcome. It is clear from the analysis that, on an individual stand basis and in this instance, predictions are more prone to climate-based variation than any other influence.

Figure 6 shows the means and standard deviations for projected performance, providing the logical conclusion that stands established in the early 1990s and thus aged around their maximum potential growth rate during the first Commitment Period of the Kyoto Protocol would be most affected (with the largest standard deviation) by variability, largely driven by climate.



**Figure 5.** Tornado diagram derived from @Risk simulations of the correlation between uncertainty of the inputs and distribution of sequestration estimates between 2008 and 2012 for a plantation established in 1990. Weather/xxxx denotes the variation in weather during the 5-y period commencing xxxx. Model/xxxx denotes the variation in the modelled site index during the 5-y period commencing xxxx. Expansion/xxxx denotes the variation in the expansion factors (caused as a result of the variation in increment of bark, branches, twigs and leaves) during the 5-y period commencing xxxx. Roots/xxxx denotes the variation in root increment and decay during the 5-y period commencing xxxx.



**Figure 6.** Variability in stand performance by age of stand (from Brack and Richards 2002)

To extrapolate such individual-stand-based analyses to a national scale by simplistically running high and low ranges of outcomes for the first Commitment Period would yield unrealistic results. The use of say a 'low' base and the lower standard deviation is founded on the unlikely potential for below-average rainfall for all plantation areas for the whole of the first Commitment Period across the whole continent.

The appropriate approach would be to determine the climate projections and uncertainties for each plantation region and apply that range of potential outcomes to the relevant forest types for each region. Despite their complexity, such analyses will still be unable to determine the effect of access to groundwater on plantation growth. The effects of groundwater availability are not widely understood and may considerably ameliorate the climate-induced variability shown in the example above.

Given the vast areas covered by plantations, it is a reasonable expectation that across the continent, over the first Commitment Period, 'near average' conditions will be achieved. Extreme climate events, like risks of fire or insect attack, are more appropriately dealt with by security / risk-based analyses than included in the uncertainty analysis. The results derived from the independent risk and uncertainty analyses would be mostly additive, although care may need to be taken that factors that increase risk, for example dry conditions, are not strongly correlated with particular uncertainty outcomes.

Of more concern in terms of uncertainty is the variability in the projected plantation establishment rates, and the uncertainty in the current estimates of plantation area. If the current figures for the area of the plantation estate are accepted, projected plantation areas are as presented in Table 1.

### Model outcomes

The carbon outcomes for each management regime model by time are shown in Figure 4. The areas allocated to each management regime from each region for SRH, LRH and SW classes are given in Table 1.

The results for the carbon stock present each year in the post-1990 plantation estate are shown in Table 7. Table 8 shows the effect of the Kyoto Protocol harvesting sub-rule on the scenarios.

**Table 7.** Carbon stock (Mt C) projections for the post-1990 plantation estate

Year	Carbon stock: plantations + products	Carbon stock: wood products <sup>a</sup> only
1990	0.2	0
1991	0.7	0
1992	1.3	0
1993	2.0	0
1994	2.9	0
1995	4.0	0
1996	5.6	0
1997	7.6	0
1998	10.0	0
1999	12.0	0.4
2000	16.4	0.7
2001	20.2	0.9
2002	25.2	1.2
2003	30.3	1.4
2004	35.5	1.8
2005	40.2	2.8
2006	44.8	3.7
2007	49.5	4.6
2008	54.1	5.7
2009	59.0	6.3
2010	64.5	7.0
2011	70.2	7.7
2012	76.1	8.3
2013	83.5	9.1
2014	90.6	9.8
2015	96.9	11.1
2016	102.8	12.5
2017	108.5	13.9
2018	113.6	15.8
2019	118.9	17.3

<sup>a</sup>Wood products are materials moved offsite during harvest and include mill residues and material in service life. Wood products disposed of in landfill are already accounted for under the Waste sector reporting of national inventories.

The sub-rule specifies that for a forest stand, reported carbon stock losses (e.g. due to harvest) cannot be greater than the positive carbon stock change for that stand over the same period.

### Conclusions

The development of the capacity to provide a credible current carbon account for Australia's plantations and capability to project future outcomes has been a major undertaking, requiring the collation, synthesis and interpretation of large and diverse data sets. The development of the accounting framework and models to assimilate this information to provide the systems capacity for carbon accounting has also been a complex task, requiring considerable iterative development and testing. Extensive and international reviews of the model have been undertaken (Brack 2000).

The national-level modelling can be considered as less subject to extreme risks and variability than stand-level modelling, as risks are spread and the large number of unbiased estimates and climate

**Table 8.** Impacts of the harvest sub-rule on the 2008–2012 carbon stocks of post-1990 plantations

Scenario	Plantation (Mt C)	Plantation + wood products (Mt C)
First Commitment Period with sub-rule	29.1	28.3
First Commitment Period without sub-rule	23.0	26.7

conditions over vast areas draw the results closer to the median estimated value. These moderating effects of scale do not equally apply to individual or small (particularly clustered) areas of plantations.

The modelling described here provides the first comprehensive review of plantation carbon accounting at a national scale. As such it provides a state-of-knowledge summary and sets benchmarks which can assist industry understanding of the possible implications of the emerging market in carbon trading. In particular, it provides the tools to allow individual growers an early opportunity to consider the implications of the Kyoto Protocol on their particular plantation estates, together with time to respond via their management and expansion activities.

Further developments in accounting for forest plantation activities will include:

- the use of remote sensing to determine the age, type and location of plantations (including previous land cover);
- comprehensive modelling on a spatial basis, including the use of annual forest productivity indices at a 1 km resolution to determine rates of forest growth, and the incorporation of soil carbon models.

## References

- Brack, C.L. (2000) Report to the Australian Greenhouse Office on the Task 25 (International Energy Authority) Modelling Workshop. Zagreb, Croatia.
- Brack, C. (2001) Forecasting carbon sequestration from individual eucalypt plantations. In: Richards, G. (ed.) *Biomass Estimation: Approaches for Assessment of Stocks and Stock Change*. National Carbon Accounting System Technical Report No. 27. Australian Greenhouse Office, Canberra. Chapter 7, pp. 105–116.
- Brack, C. and Richards, G. (2001) Development of a national forest model. In: Richards, G. (ed.) *Biomass Estimation: Approaches for Assessment of Stocks and Stock Change*. National Carbon Accounting System Technical Report No. 27. Australian Greenhouse Office, Canberra. Chapter 9, pp. 133–139.
- Brack, C. and Richards, G. (2002) Carbon accounting model for forests in Australia. *Environmental Pollution* **116**, 187–194.
- Coops, N.C., Waring, R.H. and Landsberg, J.J. (1998) Assessing forest productivity in Australia and New Zealand using a physiologically-based model driven with averaged monthly weather data and satellite derived estimates of canopy photosynthetic capacity. *Forest Ecology and Management* **104**, 113–127.
- Coops, N.C., Waring, R.H., Brown, S. and Running, S.W. (2001) Comparisons of predictions of net primary production and seasonal patterns in water use derived with two forest growth models in south-western Oregon. *Ecological Modelling* **142**, 61–81.
- Emaus, D., McGuiness, K. and Burrows, W. (2000) *Review of Allometric Relationships for Woody Biomass for Queensland, the Northern Territory and Western Australia*. NCAS Technical Report No. 5a, Australian Greenhouse Office, Canberra, 60 pp.
- Furby, S. (2001a) Remote sensing of land cover change (1970–2000). In: Richards, G. (ed.) *Biomass Estimation: Approaches for Assessment of Stocks and Stock Change*. National Carbon Accounting System Technical Report No. 27. Australian Greenhouse Office, Canberra. Chapter 8, pp. 117–133.
- Furby, S. (2001b) *Land Cover Change: Specifications for Remote Sensing Analysis*. National Carbon Accounting System Technical Report No. 9, Australian Greenhouse Office, Canberra, 218 pp.
- Gifford, R. (2000a) *Carbon Content of Woody Roots: Revised Analysis and a Comparison with Woody Shoot Components (Revision 1)*. NCAS Technical Report No. 7, Australian Greenhouse Office, Canberra, 10 pp.
- Gifford, R. (2000b) *Carbon Content of Above-ground Tissues of Forest and Woodland Trees*. NCAS Technical Report No. 22, Australian Greenhouse Office, Canberra, 28 pp.
- Grierson, P.F., Williams, K. and Adams, M.A. (2000) *Review of Unpublished Biomass Related Information: Western Australia, South Australia, New South Wales and Queensland*. NCAS Technical Report No. 25, Australian Greenhouse Office, Canberra, 114 pp.
- Ilic, J., Boland, D.J., McDonald, M. and Downes, G. (2000) *Wood Density — State of Knowledge*. NCAS Technical Report No. 18, Australian Greenhouse Office, Canberra, 55 pp.
- Jaakko Pöyry (1999) *Usage and Life Cycle Analysis of Wood Products*. NCAS Technical Report No. 8, Australian Greenhouse Office, Canberra, 78 pp.
- Jaakko Pöyry (2000) *Analysis of Wood Product Accounting Options for the National Carbon Accounting System*. NCAS Technical Report No. 24, Australian Greenhouse Office, Canberra, 37 pp.
- Jenkinson, D.S., Adams, D.E. and Wild, A. (1991) Model estimates of CO<sub>2</sub> emissions from soil in response to global warming. *Nature* **351**, 304–306.
- Jenkinson, D.S., Hart, P.B.S., Rayner, J.H. and Parry, L.C. (1987) Modelling the turnover of organic matter in long-term experiments at Rothamsted. *INTERCOL Bulletin* **15**, 1–8.
- Keith, H., Barrett, D. and Keenan, R. (2000) *Review: Allometric Relationships for Woody Biomass for New South Wales, the Australian Capital Territory, Victoria, Tasmania and South Australia*. NCAS Technical Report No. 5b, Australian Greenhouse Office, 119 pp.
- Landsberg, J. and Kesteven, J. (2001) Spatial estimation of plant productivity. In: Richards, G. (ed.) *Biomass Estimation: Approaches for Assessment of Stocks and Stock Change*. National Carbon Accounting System Technical Report No. 27. Australian Greenhouse Office, Canberra, Chapter 2, pp. 33–50.
- Landsberg, J.J. and Waring, R.H. (1997) A generalized model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance, and partitioning. *Forest Ecology and Management* **95**, 209–228.
- Landsberg, J.J., Johnsen, K.H., Albaugh, T.J., Allen, H.L. and McKeand, S.E. (2001) Applying 3-PG, a simple process-based model designed to produce practical results, to data from loblolly pine experiments. *Forest Science* **47**, 43–51.
- Mackensen, J. and Bauhus, J. (1999) *The Decay of Coarse Woody Debris*. NCAS Technical Report No. 6, Australian Greenhouse Office, Canberra, 41 pp.
- Moorhead, D.L. and Reynolds, J.F. (1991) A general model of litter decomposition in the northern Chihuahuan desert. *Ecological Modelling* **59**, 197–219.

- Moorhead, D.L., Currie, W.S., Rastetter, E.B., Parton, W.J. and Harmon, M.E. (1999) Climate and litter quality controls on decomposition: an analysis of modeling approaches. *Global Biogeochemical Cycles* **13**, 575–589.
- NFI (National Forest Inventory) (1997a) *Forecasting of Wood Flows from Australia's Plantations — A Report to the 1997 National Plantation Inventory*. Bureau of Resource Sciences, Canberra. 22 pp.
- NFI (National Forest Inventory) (1997b) *National Plantation Inventory of Australia*. Bureau of Rural Sciences, Canberra.
- NFI (National Forest Inventory) (2000) *National Plantation Inventory Tabular Report—March 2000*. Bureau of Rural Sciences, Canberra.
- Palisade Corporation (1997) *@Risk for Windows*. Version 3.5.2. The Corporation, Newfield, NY.
- Paul, K., Polglase, P., Coops, N., O'Connell, T., Grove, T., Mendham, D., Carlyle, C., May, B., Smethurst, P. and Baillie, C. (2002) *Modelling Change in Soil Carbon Following Afforestation or Reforestation: Preliminary Simulations Using GRC3 and Sensitivity Analyses*. National Carbon Accounting System Technical Report No. 29, Australian Greenhouse Office, Canberra, 102 pp.
- Paul, K.I., Polglase, P.J. and Richards, G.P. (2003a) Predicting change in soil carbon following afforestation or reforestation. *Forestry Ecology and Management* **177**, 485–501.
- Paul, K.I., Polglase, P.J. and Richards, G.P. (2003b). Sensitivity analysis of predicted change in soil carbon following afforestation and analysis of controlling factors by linking a C accounting model (CAMFor) to models of forest growth (3PG), litter decomposition (GENDEC) and soil C turnover (Roth C). *Ecological Modelling* **164**, 137–152.
- Polglase, P.J., Paul, K.I., Khanna, P.K., Nyakuengama, J.G., O'Connell, A.M., Grove, T.S. and Battaglia, M. (2000) *Change in Soil Carbon Following Afforestation and Reforestation*. NCAS Technical Report No. 20, Australian Greenhouse Office, Canberra, 89 pp.
- Richards, G.P. (ed.) (2001) *Biomass Estimation: Approaches for Assessment of Stocks and Change*. National Carbon Accounting System Technical Report No. 27. Australian Greenhouse Office, Canberra.
- Richards, G.P. (2002) *The FULLCAM Carbon Accounting Model: Development, Calibration and Implementation for the National Carbon Accounting System*. NCAS Technical Report No. 28, Australian Greenhouse Office, Canberra, 50 pp.
- Richards, G.P. and Evans, D.W. (2000) *CAMFor User Manual v 3.35*. National Carbon Accounting System Technical Report No. 26, Australian Greenhouse Office, Canberra, 47 pp.
- Skjemstad, J. and Spouncer, L. (2003) *Integrated Soils Modelling for the National Carbon Accounting System (Estimating Changes in Soil Carbon Resulting from Changes in Land Use)*. National Carbon Accounting System Technical Report No. 36, Australian Greenhouse Office, Canberra, 672 pp.
- Skjemstad, J.O., Spouncer, L.R. and Beech, T.A. (2000) *Carbon Conversion Factors for Historical Soil Carbon Data*. National Carbon Accounting System Technical Report No. 15, Australian Greenhouse Office, Canberra, 17 pp.
- Snowdon, P., Eamus, D., Gibbons, P., Khanna, P.K., Keith, H., Raison, R.J. and Kirschbaum, M.U.F. (2000) *Synthesis of Allometrics, Review of Root Biomass and Design of Future Woody Biomass Sampling Strategies*. NCAS Technical Report No. 17, Australian Greenhouse Office, Canberra, 142 pp.
- Spencer, R., Keenan, R., Ranatunga, K. and Wood, M. (2001) *Plantation projections in Australia*. Unpublished report, Bureau of Rural Sciences, Canberra.
- Swift, R. and Skjemstad, J. (2001) *Agricultural Land Use and Management Information*. NCAS Technical Report No. 13, Australian Greenhouse Office, Canberra, 446 pp.
- Turner, B. and James, R. (2001) Derivation of indicative yields for major plantation species. In: Richards, G. (ed.) *Biomass Estimation: Approaches for Assessment of Stocks and Change*. National Carbon Accounting System Technical Report No. 27, Australian Greenhouse Office, Canberra, Chapter 5, pp. 71–77.
- Webb, A. (2002) *Pre-clearing Soil Carbon Levels in Australia*. National Carbon Accounting System Technical Report No. 12, Australian Greenhouse Office, Canberra, 204 pp.