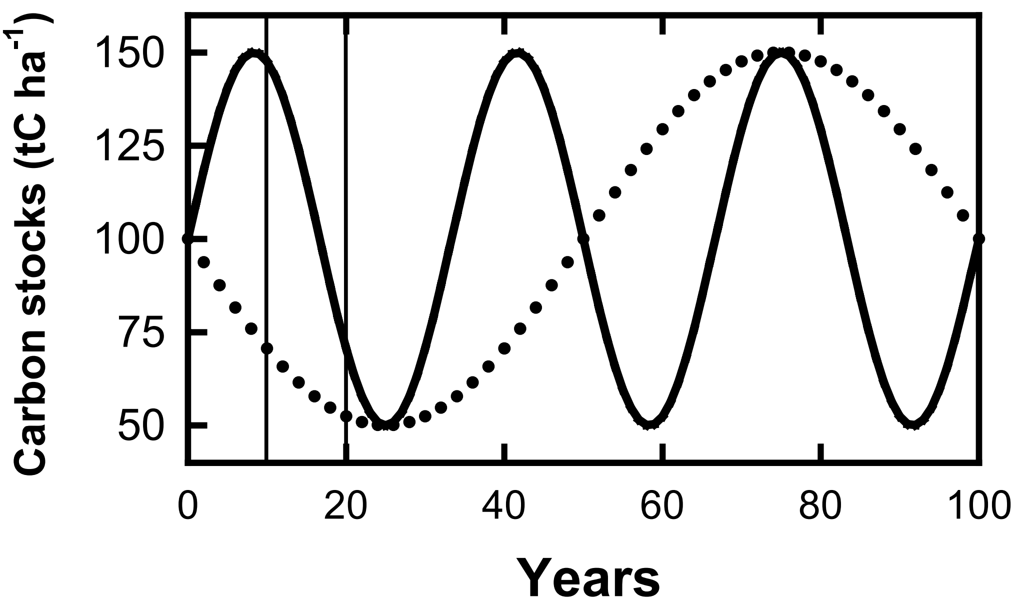
8. Greenhouse Gas Balances

The Accounting Framework

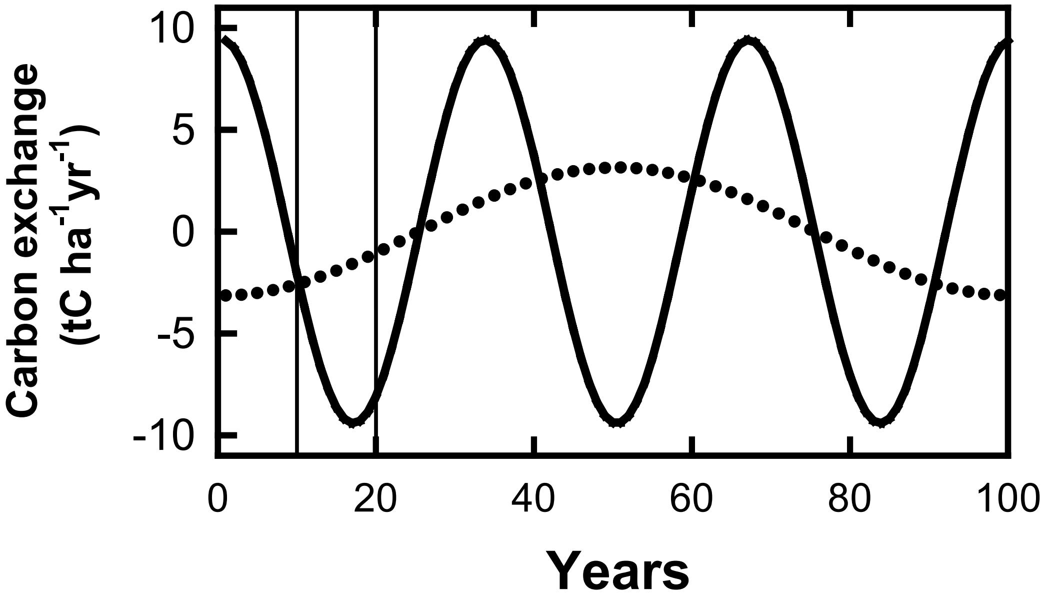
Before going into details of stand-level Greenhouse gas implication of various management regimes, a few general points need to be made. To assess the Greenhouse implications of any proposal, the chosen time horizon for the analysis is crucial. This is illustrated in Figures 2 and 3.

Figure 2: Notional change in carbon stocks under two different notional management regimes. The vertical lines delimit two possible assessment periods that could be used. A third alternative is assessment over a 100-year period.



This illustrates how different management regimes can lead to different trajectories in carbon stocks. One management regime leads to rapid fluctuations in carbon stocks, the other one leading to only gradual changes, but both attain the same carbon stocks at the end of a 100-year period. They could represent, in stylised form, the contrasting management regimes of plantation management and regrowth natural forest.

Figure 3. Carbon fluxes under two different notional management regimes. The fluxes are derived from the carbon stocks shown in Figure 2.



In the notional two management options, one (shown in pink) leads to high initial carbon uptake over the first 10 years, but large losses over the next 10 years. The other regime (in blue) leads to small, but on-going losses over the first 25 years and gains over the next 50 years. The losses of regime 2 are much smaller from the years 10 to 20 than those of management scenario 1.

It shows that there is not a unique answer to the question of Greenhouse outcomes? It is important to recognise that the same information about future carbon stocks can be interpreted differently to derive different apparent greenhouse outcomes by simply considering different periods for analysis.

One may consider the initial emissions over, say, the first year in the life of a project as the relevant emissions as they are a direct and immediate result of the management choices. However, in Greenhouse terms that is not particularly relevant as climate change is a longer-term problem and does not respond directly to the emissions over a short period of a few years. If a system leads to increasing carbon stocks over a short period (say, a plantation) but the carbon stocks are pre-planned to be reduced again after a short period of time then the short-term benefit does not lead to a lasting benefit.

Alternatively, one may consider the 2008-2012 period as the relevant assessment period as that is the first commitment period defined in the Kyoto Protocol (UNFCCC 1997). Calculations under Kyoto rules are relatively simple for the present assessment as changes in carbon stocks in forest systems do not need to be quantified provided that no land-use change is involved (Schlamadinger et al. 2000). Any emissions avoided as a result of substituting fossil-fuel derived electricity by electricity generated from fuelwood can be counted as a gain whereas changes in forest carbon storage do not need to be considered. Changes in non-CO_2

Greenhouse gas emissions and ancillary emissions do need to be assessed together with the potential for fossil-fuel substitution.

However, that simple case is only relevant under the specific accounting rules of the Kyoto Protocol. The analysis done here therefore takes a broader perspective and tries to assess the effect that utilisation of fuelwood would have on climate change in the longer term. In terms of the notional diagrams (Figs. 2 and 3), it is the net changes in carbon stocks over 100 years that are relevant for ultimate climatic impact and that are being assessed here.

Climate change is a longer-term problem that will only fully manifest itself over periods of many decades to centuries. Hence, it is not the rate of CO_2 emissions in particular years that constitutes a concern in terms of climate change, but the resultant atmospheric CO_2 concentration that results from many years of emissions. Hence, the relevant question is how the use of wood for electricity generation would affect net emissions of CO_2 and other Greenhouse gases over a long time period. For that reason, a 100-year time horizon is applied for the present analysis.

There is also the question of how to credit and debit changes in carbon stocks relative to accounting for offset changes in avoided CO_2 emissions the result from substitution of fossil fuels. For each land use, such as unlogged natural forest, or a regrowth forest with energy-wood usage, it is possible to calculate an average carbon density associated with that land use. A change in land use can then be calculated to lead to a loss or gain in stored carbon (Kirschbaum et al 2001). That is a once-off change in carbon storage.

The offset for fossil-fuel emissions and change in non-CO_2 Greenhouse gas and ancillary emissions, on the other hand, are multiple effects that potentially accrue at each rotation, and thereby multiple times. One could have taken the position that fuelwood is utilised only on one single occasion then the land-use can revert back to the land use that would have been practiced without the energy-wood removal. In that circumstance, there would be no lasting change in site carbon storage.

Hence, there is the difficulty of combining one Greenhouse implication that has no time horizon, the change in carbon storage, with another implication that accumulates over each successive rotation. This problem was resolved here by applying a 100-year planning horizon and calculating the fossil-fuel substitution benefit over a 100-year period by dividing 100 years by the planned rotation length. For plantations, the planned rotation length was taken to be 30 years and for regrowth forest an expected rotation length of 90 years was used. Hence, for plantations the fossil-fuel substitution benefit and other effects that occur with each rotation were multiplied by 3.33, and for regrowth forest by 1.11.

Energy Substitution

The question of the amount of CO_2 emissions that can be avoided as a result of using fuelwood does firstly involve an estimation of the conversion efficiency. How many kW hr of electricity can be produced per ton of dry wood? That depends on the specific calorific energy content of wood and on the specifications of different power plants, with plants utilising more modern, and more expensive technology being able to generate more energy per unit of wood burnt. It is assumed here that the proposed Southwood power plant could obtain a conversion efficiency of 1.425 MWhr per tonne DW of wood[3].

To assess the fossil fuel saving made possible by that 1.425 MWhr being generated also requires an assessment of how the substituted marginal unit of electricity would have been produced. In other words: which power plant would be switched off as a result of the energy-wood power plant being switched on, and what energy source would have been used by that replaced energy plant?

Table 5: Conversion efficiencies for a range of power sources that might be substituted by fuelwood. Data by URS (2001).

Electricity source	Carbon content per unit of energy (kg CO_2 GJ^{-1})	System efficiency	CO_2 release per unit of electricity produced (kg CO_2 $kWhr^{-1}$)	CO_2 release for electricity delivered via Basslink (kg CO_2 $kWhr^{-1}$)
Brown coal in Victoria	114.7	30.1%	1.37	1.41
Black coal in NSW	94.3	35.2%	0.96	0.99
Thermal gas on mainland	57.0	36%	0.57	0.59
CCGT gas on mainland	57.0	53%	0.39	0.40
OCGT gas in Victoria	57.0	32%	0.64	0.66
Oil in Bell Bay	77.4	36.4%	0.77	n/a
CCGT gas in Bell Bay	57.0	53%	0.39	n/a
Diesel in Tasmania	73.3	30%	0.88	n/a
hydro, wind	0	n/a	0	0

Calculations for the last column have assumed 2.8% transmission loss as given by URS (2001) for a southward flow of 300 MW. Transmission losses for northbound transmission are given as 4.7% at 600 MW.

Currently, essentially all of the electricity used in Tasmania is generated using hydro energy, with installed generating capacity and available dammed water resources capable of delivering 10,205 GW hr yr^{-1} compared to a current Tasmanian electricity demand of about 10,000 GW hr yr^{-1} (URS 2001). In addition, a 76 MW wind farm is currently being constructed in Tasmania, with plans to install at least another 400 MW over the next six years. An installed capacity of 476 MW with realistic yield estimation is projected to supply an additional 1,800 GW hr yr^{-1} when fully

---

[3] Quantities in this Sections have been expressed in different units as relevant in specific contexts. They can be converted as 1 tonne carbon (1 tC) = 3.667 $tCO_2 \approx 2$ tDW $\approx$ 4 t(green, or fresh, weight of wood). The exact conversions differ because of variable carbon content of biomass and different moisture contents of wood. 1 t (tonne) = 1000 kg. Energy can be expressed in units of either kWhr, the unit usually used for measuring electricity, or in Joules (J), a more general descriptor of energy content. They can be converted as 1 kWhr = 3.6 MJ. Conversion efficiency for the power plant was calculated as basic energy content of wood times plant efficiency and converted to units of kWhr tDW^{-1}: 19.0 MJ $(kgDW)^{-1}$ x 27% / 3.6. Energy contents and typical plant efficiencies were obtained from http://www.ieabioenergy-task32.com/overview.html and http://www.ieabioenergy-task32.com/database/biomass.php.

operational (URS 2001). Hence, over the foreseeable future, Tasmania is likely to have excess generating capacity from renewable sources to meet its domestic needs. An oil-fired power station at Bell Bay is used to provide stand-by capacity during any supply problems with hydro energy, but that facility does not generally need to be utilised.

The Tasmanian energy system is currently separated from the power grid on the mainland so that any additional electricity could only be utilised within Tasmania. There are advanced plans, however, for the Tasmanian electricity system to be linked to the mainland via an undersea cable (Basslink). A gas pipeline is also currently being constructed that will allow future marginal electricity needs in Tasmania to be met with a gas-fired power station.

A number of different scenarios then need to be considered (Table 6).

Table 6: Different energy substitution scenarios.

	Bass-link used	Power replaced	Electricity utilised	Carbon saving per kW hr of electricity generated [kgCO$_2$ (kW hr)$^{-1}$]	CO$_2$ saving from energy generation from fuelwood (tCO$_2$ tDW^{-1})	Transmiss. losses via Basslink
Case 1	N	Hydro, wind	Tasmania	0	0	0
Case 2	N	Oil	Tasmania	0.77	1.10	0
Case 3	N	Gas	Tasmania	0.39	0.56	0
Case 4a	Y	NSW black coal	Tasmania	0.99	1.41	+2.8%
Case 4b	Y	Vic. brown coal	Tasmania	1.41	2.01	+2.8%
Case 5a	Y	NSW black coal	Mainland	0.96	1.30	-4.7%
Case 5b	Y	Vic. brown coal	Mainland	1.37	1.86	-4.7%

Assumptions: the energy conversion efficiencies from Table 5 are used. The second-last column assumes an energy conversion efficiency of 1.425 MWhr (tDW)$^{-1}$ and transmission losses of 2.8 and 4.7% for southward and northward transmission, respectively. Transmission losses are given as positive if electricity is replaced that would be generated on the mainland but consumed in Tasmania, and as a negative for electricity flows in the opposite direction.

Case 1 applies if there is no Basslink, or if an existing link is already saturated with delivering renewable power from the other available sources (normal capacity of Basslink is 480 MW). If the electricity of wood-derived energy would replace electricity that would otherwise be generated from hydro or wind energy, then there would be no saving in fossil fuel use and hence no saving in Greenhouse gas emissions. This case might apply in the absence of a Basslink cable and in years when there is an excess of electricity available from other renewable sources.

Case 2 applies if wood-derived electricity were to substitute for electricity generated from oil produced within Tasmania. That case might be relevant if there is demand growth in Tasmania that exceeds the anticipated growth in renewable energy generating capacity.

Case 3 is similar to case 2 but anticipates the expected conversion of the Bell Bay power station from oil to gas. The saving is less than for case 2 because gas causes lower CO$_2$ emissions per unit of electricity produced.

Cases 4 and 5 are both predicated on the Basslink being constructed and utilised. Case 4 assumes that there would be considerable growth in electricity demand in Tasmania and that this growth exceeds even the increasing supply of renewable energy, and that the marginal additional energy would be generated on the mainland rather than in Tasmania. Case 4a assumes that the extra supply comes from black coal in NSW and case 4b that it comes from brown coal in Victoria.

Case 5 assumes that Tasmania would have an excess of renewable energy that could be exported to the mainland, but not to the extent that it reaches the 480 MW capacity of the Basslink cable. As for case 4, electricity supplies originating from NSW and Victoria are distinguished

In other words, Greenhouse gas savings could range from 0 to 2.01 tCO_2 tDW^{-1} depending on the specific circumstances with respect to national energy demand and supply, and whether the Basslink project will proceed.

Of these different cases, case 5 seems the most likely even though at the time of writing, it is not yet certain that the Basslink project will go ahead. If the Basslink is going to be constructed, and with the work currently under way and plans to install further wind-based generating capacity in Tasmania, it seems likely that Tasmania’s generating capacity of renewable energy will continue to exceed the State’s electricity demand for the foreseeable future.

It is less certain, however, that Tasmania’s total excess generating capacity of renewable energy will not exceed the load rating of the Basslink cable. However, if that were the case, then there might also be a strong case for constructing further cables to link Tasmania and the mainland.

Simulation of forest carbon balances

To assess the effect of the proposed management regimes on carbon balances, simulations were run on unmanaged natural forest, regrowth forest and plantation forests. For all the simulation done here, a simple model of forest growth was used that keeps track of all the key carbon pools in the system. Details of the model are provided in Appendix 1. Forests of mixed-use history are also quantitatively important in supplying wood in the south-west of Tasmania. However, because of their diverse individual circumstances, it was not possible to choose one set of conditions that could adequately represented this category.

For the simulations in the following, parameters were chosen to obtain as far as possible consistent agreement with observations of biomass amounts supplied by Forestry Tasmania (Table 1) and post-harvest residues from Slijepcevic (2002).

The estimates of average stand growth are low compared to other published estimates for the growth of these forests (Borough et al. 1978; Turnbull et al. 1988; West and Mattay 1993). This difference in estimates is due to the estimates by Forestry Tasmania include all forests within the study area irrespective of their conditions. In interpretation of the numbers provided in the following it must be kept in mind that they represent the average over all wet eucalypt forests in Tasmania.

However, no equivalent compilation exists for plantations, which created a particular difficulty in comparing the trends in plantations with those from regrowth forests.

The few available numbers suggest scope for considerable enhancement of growth rates when stands are established through planted stock with optimal stocking, which ensures early site occupancy, and further facilitated by fertilisation and thinning (Tibbits 1986; Turnbull et al. 1986, 1993).

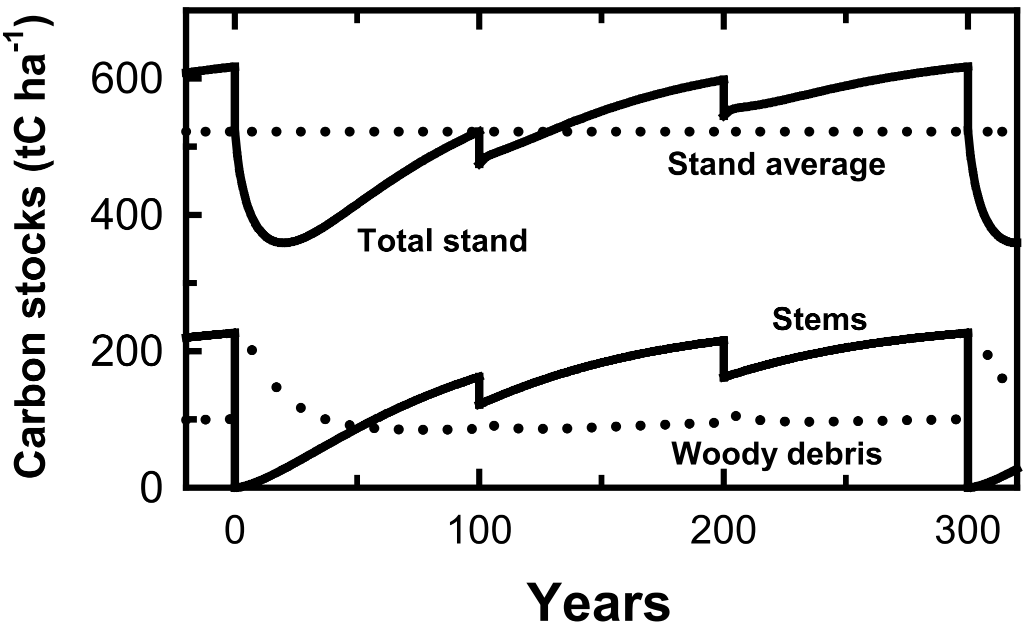
Observed plantation performance is further boosted by a site selection process whereby only good sites with good expected growth potential are selected and used for plantation establishment. Hence, it is not valid to compare the growth or carbon storage of plantations on good sites with the growth or carbon storage of regrowth forests on all sites, including poorly productive ones.

The two internally consistent analyses are to compare regrowth forests and plantations on only good sites, or comparing regrowth forests and plantations on sites of average quality. Of those two options the latter has been chosen. This means, however, that plantation growth reports shown in the following may be less than can typically be observed in plantations on good sites.

Unmanaged natural forest

The natural unmanaged forest was assumed to be subject to regular fires every 100 years, with those fires killing 25% of living biomass. 40% of the killed biomass was assumed to be consumed in the fires and 60% to fall as litter. Every 300 years, a stand-replacing fire was assumed to kill the whole stand. Figure 4 shows the changes in all relevant pools in the system.

Figure 4: Time course of key carbon pools in an unmanaged natural forest. The only disturbances included are fires every 100 years that kill 25% of trees, and stand-replacing fires every 300 years. The horizontal dotted line is the long-term average carbon density of the stand as a whole. It is shown here for a simulation run when all carbon pools had come to an equilibrium under the simulated conditions.



For the natural stand, total site carbon storage was 521.8 tC ha^{-1} on average (first column in Table 4), with peaks of about 617 tC ha^{-1} just before the advent of a stand-replacing wildfire and a minimum of about 359 tC ha^{-1} some years after the previous stand-replacing wildfire. Individual pools show slight ups and downs in response to the various fires. Following a stand-replacing fire (at year 0), large amounts of litter were produced that largely decay away over the subsequent 50 or so years. However, woody litter remained at an average density of 100.4 tC ha^{-1} fed by on-going inputs due to natural mortality and greater inputs during fires. Fires also consume a proportion of litter and there are on-going losses through normal decay.

The tree component undergoes the greatest changes with growth from 0 reaching 329 tC ha^{-1} in live biomass after 300 years (Fig. 4). On average over the simulated 300-year sequence, tree biomass is 239.6 tC ha^{-1} (Table 8).

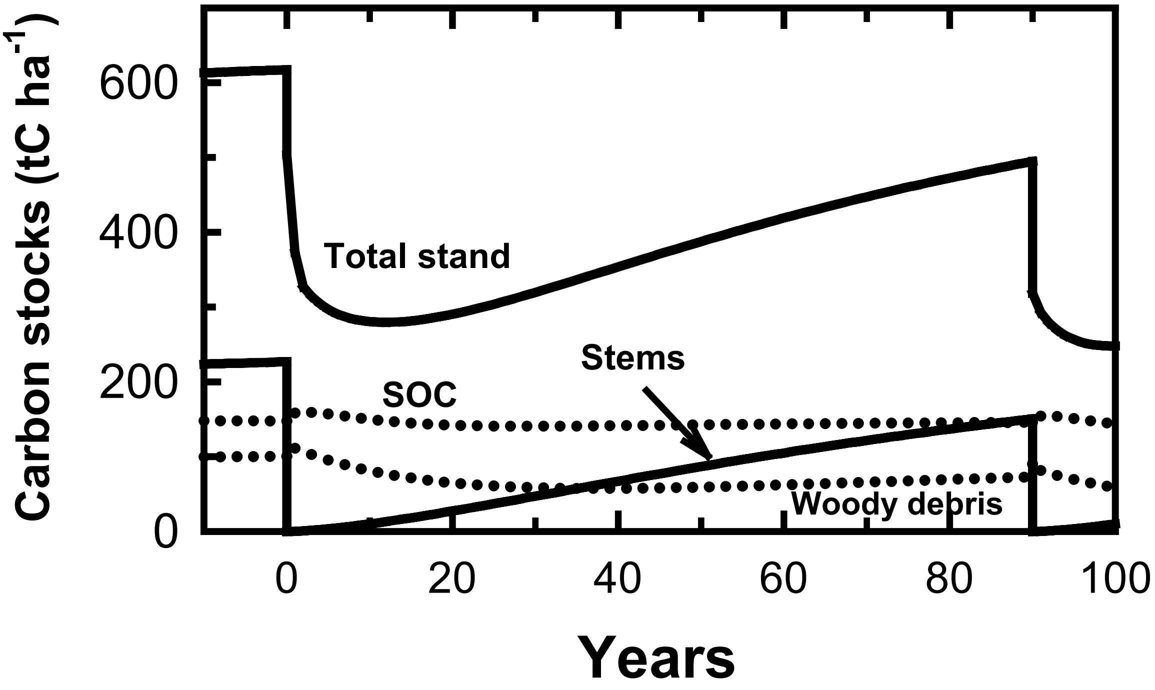
Logging mature forest

A range of forest growth scenarios are considered here. Firstly, the conversion of mature forest to regrowth forest, grown over 90 years. It uses the size of the natural forest shown in the previous Section as the starting point. Figure 5 shows the changes in key pools in the system during a first regrowth cycle.

An uncertain question is whether wood products should be considered as part of the overall system. It generally is more consistent if wood products are not included in a comparison of this kind. Otherwise, the decay of previously produced wood products would also have to be considered so that the case where there is no overall increase in stored wood products would result in zero calculated net emissions. For completeness wood products are shown in the Tables as well, but they are not included in subsequent calculations.

In any case, the important comparison in the present context is that between the cases of with and without energy-wood removal. As fuelwood is completely consumed within one year, the decision about the treatment of wood products makes no difference for the values calculated here.

Figure 5: Time course of key carbon pools following the logging of mature forest, with re-establishment of regrowth forest thereafter under standard current logging conditions.



Total site carbon storage was 617 tC ha^{-1} just before logging, reaching a minimum of about 280 tC ha^{-1} about 10-15 years after logging and then recovering to about 495 tC ha^{-1} just before the next harvest (Fig. 5). On average carbon amounts, converting mature to regrowth forest leads to an estimated carbon loss of 162.9 tC ha^{-1}, dominated by a loss of 103.8 tC ha^{-1} in the living-tree component, but also slight losses in the woody and other litter and soil carbon pools. This would be partly negated by slight gains in the wood-products pool if one were to consider that pool.

Additional utilisation of fuelwood would cause a further loss of 8.8 tC ha^{-1}, mainly due to a reduction of 6.3 tC ha^{-1} of woody litter. Soil carbon was also calculated to be decreased by 2.5 tC ha^{-1}. These changes in soil carbon are, however, highly uncertain as is discussed further below. The calculated difference of 8.8 tC ha^{-1} translates into a loss of 0.14 tC per tC in fuelwood.

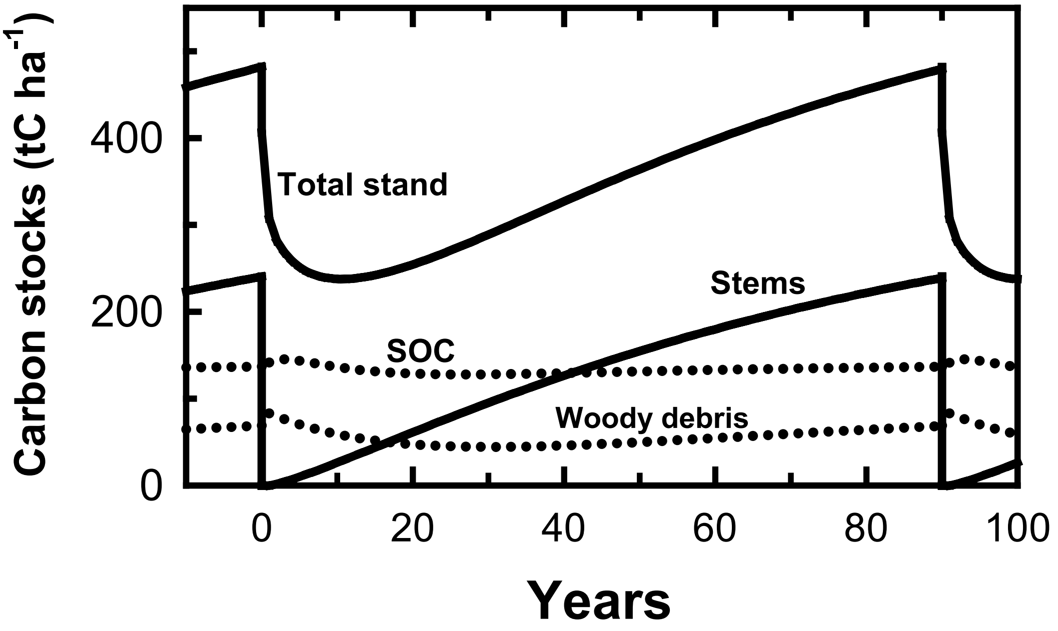
Table 8: Changes in the main carbon pools with the conversion from mature to regrowth forest. All numbers give the long-term averages under respective management systems. In this system, 61 tC ha^{-1} could be used for fuelwood. The last column expresses changes in carbon storage relative to the amount of fuelwood removed.

		Standard current logging		With energy-wood removal			
	Initial	Under regrowth	Change	Under regrowth	Change	Diff. between standard and fuelwood	
	tC ha^{-1}						tC (tC fuelwood)$^{-1}$
Total	521.8	358.9	-162.9	350.1	-171.7	-8.8	-0.14
Stand	521.8	351.1	-170.7	342.3	-179.5	-8.8	-0.14
Trees	239.6	135.8	-103.8	135.8	-103.8	0.0	0.00
Woody litter	100.4	55.0	-45.4	48.7	-51.7	-6.3	-0.10
Other litter	36.3	27.5	-8.8	27.5	-8.8	0.0	0.00
Soil C	145.5	132.8	-12.7	130.3	-15.2	-2.5	-0.04
Products	0.0	7.8	7.8	7.8	7.8	0.0	0.00

Logging regrowth forest

Most forest operations in Tasmania involve the logging of regrowth forest and reestablishment of a further rotation of regrowth forest, grown over about 90 years. For the simulation done here, the final values calculated 90 years after an initial logging of mature forest formed the starting values for a regrowth-logging cycle. Figure 6 shows the changes in key pools in the system.

Figure 6: Time course of various carbon pools following the logging of regrowth forest, with re-establishment of a further rotation of regrowth forest thereafter.



In the regrowth simulation, total site carbon storage was about 490 tC ha^{-1} before logging and essentially the same after the next rotation under the same growth conditions. Woody litter carbon at first increased during logging, but most of that was then lost again during the subsequent regeneration fire. It dropped further over subsequent years due to on-going decay before stabilising as on-going losses were matched by new input from individual-tree mortality.

Table 9: Size of the main carbon pools in regrowth forest and the difference in pool sizes if energy-wood harvesting is included. The basic numbers are the same as in Table 8, but expressed per unit of fuelwood removal the number are different because in the regrowth forest only 42 tC ha^{-1} would be available for use as fuelwood.

	Average pool sizes	Diff. between standard and fuelwood	
	tC ha^{-1}		tC (tC fuelwood)$^{-1}$
Total	358.9	-8.8	-0.21
Stand	351.1	-8.8	-0.21
Trees	135.8	0.0	0.00
Woody litter	55.0	-6.3	-0.15
Other litter	27.5	0.0	0.00
Soil C	132.8	-2.5	-0.06
Products	7.8	0.0	0.00

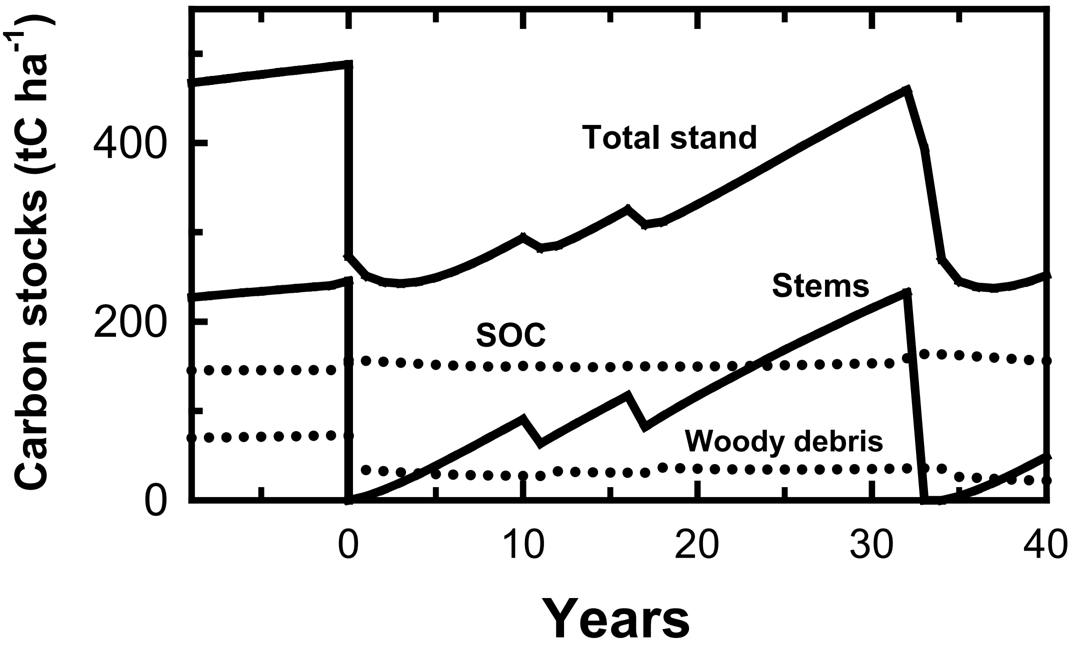
Repeated logging under the same repeated schedule would have no on-going effect on changing carbon stocks as carbon gains during the growth phase are completely matched by the losses in subsequent harvests. There could be longer-term changes in soil carbon, but the available evidence suggest those to be small or not to occur at all (see below).

Hence, the only question of interest in the case of logging regrowth forest is the change in carbon stocks as a result of inclusion energy -wood utilisation, and the relevant numbers for that are the same as for the use of fuelwood in logging mature forest. There would be a loss of about 6.3 tC ha^{-1} from woody litter and 2.5 tC ha^{-1} from soil organic carbon, but because less wood would be available for energy-wood utilisation, it translates into a slightly larger loss in carbon per unit of fuelwood removal (Table 9).

Logging regrowth forest and converting it to a plantation

For the simulation done here, a plantation was assumed to be established after logging a regrowth forest. This new plantation was grown for only 30 years before being logged. Figure 7 shows the changes in all relevant pools in the system.

Figure 7: Time course of various carbon pools following the logging of regrowth forest and subsequent establishment of a plantation.



For the plantation, total average site carbon storage slightly increased from 350 tC ha^{-1} for a regrowth stand to about 374 tC ha^{-1} under plantation without energy-wood utilisation (Fig. 7, Table 10). Plantations have a much higher growth rate than a regrowth forest so that despite the short rotation time of only 30 years, the plantation stand has about the same carbon stocks as a regrowth forest.
In making this statement, two factors need to be kept in mind, however. Firstly, there are no published growth rates available for plantations across the study area in Tasmania. Secondly, the growth estimates that are available refer to plantations established on good sites as those sites are preferentially selected for plantations. Growth estimates for regrowth forests, on the other hand, refer to an average estimated across all forests of all varying quality. These considerations affect the comparison between plantations and regrowth forests but they do not affect estimates of the additional effect of energy-wood removal.

The removal of fuelwood was estimated to reduce total site carbon stocks by 13.4 tC ha^{-1} with reductions mainly in soil organic carbon (-9.2 tC ha^{-1}) and also woody debris (-4.2 tC ha^{-1}). As the plantation system can deliver relatively large amounts of fuelwood, the difference in terms of changes in carbon stocks per unit of fuelwood {0.1 tC (tC fuelwood)$^{-1}$} than for the effect on regrowth forests.

Table 10: Changes in the average values in the main carbon pools in converting a regrowth forest to a plantation. In this system, 42.0 tC ha^{-1} could be used for fuelwood at the first harvest and 38.0 tC ha^{-1} at each of the next harvests of plantation wood. The last column expresses changes in carbon storage relative to the amount of fuelwood removed in these three harvests.

		Standard current practice		With energy-wood removal			
	Initial (regrowth)	Under plantation	Change	Under plantation	Change	Diff. between standard and fuelwood	
	tC ha^{-1}						tC (tC fuelwood)$^{-1}$
Total	350.1	374.3	24.2	360.9	10.8	-13.4	-0.10
Stand	342.3	350.1	7.8	336.7	-5.6	-13.4	-0.10
Trees	135.8	111.7	-24.1	111.7	-24.1	0.0	0.00
Woody litter	48.7	26.6	-22.2	22.3	-26.4	-4.2	-0.03
Other litter	27.5	31.1	3.7	31.1	3.7	0.0	0.00
Soil C	130.3	180.8	50.4	171.6	41.2	-9.2	-0.07
Products	7.8	24.2	16.4	24.2	20.6	4.2	0.03

Non-CO_2 Greenhouse gases

In addition to carbon balances, the emission of other Greenhouse gases also need to be assessed. This principally involves the Greenhouse gases methane and nitrous oxide that are released during burning (Galbally et al. 1992; Prather et al. 2001). Other pollutant gases are also released, principally NO_x, CO and NMVOC, but they are not Greenhouse gases. The release of these gases is calculated here with reference to the calculations in the National Greenhouse Gas Inventory (NGGI 1996a, 1996b) which lists specific emission factors for both forest fires and burning under industrial conditions. The result of these calculations is given in Table 11, with more details provided in Appendix 1.

Table 11: Release of non-CO_2 gases during forest fires and combustion in industrial boilers. All values are expressed per tDW.

Basic information						
CO_2 emission from burning wood (kgCO_2 tDW^{-1})						**1,687**
	CH_4	N_2O	NO_x	CO	NMVOC	Total non-CO_2
C fraction	0.46	0.46	0.46	0.46	0.46	
GWP	21	310	0	0	0	
Forest fires						
N:C ratio	n/a	0.011	0.011	n/a	n/a	
Emission factor	0.01	0.007	0.1	0.1	0.022	
Mass ratio	1.33	1.57	3.29	2.33	1.17	
Total emission (kg tDW^{-1})	6.1	0.06	1.7	107	11.8	
CO_2 equil. (kgCO_2 tDW^{-1})	**128.5**	**17.2**				**145.7 (8.6%)**
Industrial burning						
Derived energy (GJ tDW^{-1})	17.9	17.9	17.9	17.9	17.9	
Emission (g GJ^{-1})	4.20	4.10	75	680	6.8	
Emission (kg tDW^{-1})	0.08	0.07	1.35	12.2	0.12	
CO_2 equil. (kgCO_2 tDW^{-1})	**1.6**	**22.8**				**24.4 (1.4%)**
Difference between forest and industrial burning (kgCO_2 tDW^{-1})						**121.3**

Calculations are based on detailed sample calculation sheets given in NGGI (1996a, 1996b).

For each tonne of wood (dry weight) that is burnt in forest fires, it is estimated that 6.1 kg methane and 0.06 kg nitrous oxide are released as well. Taking their respective greenhouse warming potential into account, that amounts to emissions of 128 and 17 kgCO_2 equivalent tDW^{-1} of methane and nitrous oxide respectively for a total of 146 kgCO_2 equivalent tDW^{-1}. This needs to be compared with the 1.69 tCO_2 tDW^{-1} that would be released as CO_2 if all fuel were converted to CO_2 during burning. This adds a further 8.6% to the Greenhouse gas emissions resulting from forest fires.

Because of the more efficient burning process in industrial boilers, methane emissions under those conditions are much reduced if wood is burnt for energy generation, but it has little effect on nitrous oxide emissions. Total emissions are only 24.4 kgCO_2 tDW^{-1} for consumption under industrial conditions and add 1.45% to total Greenhouse gas emissions. So, for each tDW of wood that is burnt in an industrial boiler rather than in the forest, a Greenhouse saving of 121.3 kgCO_2 tDW^{-1} accrues.

While not important as Greenhouse gases, there are also other gases emitted during fires (Table 10). Carbon monoxide and non-methane volatile organic compounds (NMVOC) are essentially products of incomplete combustion, and their emissions can be greatly reduced if wood is burnt in industrial boilers that allows more complete combustion. NO_x emissions are high even under industrial conditions, but that can be reduced through scrubbing exhaust fumes.

Table 11 gives sensitivity of non-CO_2 Greenhouse gas emissions per unit of wood burnt during regeneration fires or for electricity generation. This is quantified further in Table 12 for the specific scenarios investigated above. The cases of regrowth forest re-established as natural forest for a further rotation or converted to a plantation are not distinguished in Table 12 as they have identical initial emissions of non-CO_2 gases.

Table 12: Comparison of the release of non-CO_2 gases as a result of logging mature or regrowth forest and with either all woody litter retained in the forest or partly used for electricity generation. These calculations are based on a 100-year horizon so that effects are multiplied by the number of rotations expected over 100 years. It only calculated the non-CO_2 implications of fresh woody litter added due to logging operations.

		Woody litter	burnt in forest	burnt at power plant	Forest		Power plant			
					CH_4	N_20	CH_4	N_20	Total	Difference
		tDW ha^{-1}			tCO_2 equivalents ha^{-1}					
Mature	Current	245.7	122.9	0.0	15.8	2.1	0.00	0.00	17.9	
	Fuelwood	122.9	61.4	122.9	7.9	1.1	0.19	2.8	11.9	-6.0
Regrowth	Current	168.6	84.3	0.0	10.8	1.5	0.00	0.00	12.3	
	Fuelwood	84.3	42.1	84.3	5.4	0.7	0.13	1.9	8.2	-4.1
Plantation	Current	521.2	390.9	0.0	50.2	6.7	0.00	0.00	57.0	
	Fuelwood	260.6	195.4	260.6	25.1	3.4	0.41	5.9	34.8	-22.1

Calculations are based on details given in Table 11, the initial woody litter amounts calculated in the Sections given above and with the assumptions that 50% of woody litter could be used as fuelwood and that 50% of remaining woody litter would be consumed during regeneration burns in logging mature or regrowth forests. For plantations, it was assumed that 75% would be consumed during regeneration fires.

The data in Table 12 show that there are considerable emissions of non-CO_2 Greenhouse gases that are emitted during regeneration burns after fires. They amount to estimated totals of 17.9 and 12.3 tCO_2 equivalents per hectare during the regeneration burns carried out after logging mature and regrowth forests, respectively (Table 11). These emissions can be reduced by 6.0 and 4.1 tCO_2 equivalents per hectare if half of the residual woody residue is used as fuelwood instead.

Because of the larger productivity and the larger proportion burnt in regeneration fires for the establishment of plantations, non-CO_2 Greenhouse gas emissions are even more important for plantations, with emissions of 57.0 tCO_2 equivalents per hectare under current practice which could be reduced by 22.1 tCO_2 equivalents per hectare (over a 100-year period) through the harvesting and use of fuelwood.

For forests in swampy locations there could potentially be further methane emissions if any woody litter decomposes under anaerobic conditions. The general wetness and cool conditions of the region makes that a possibility, but that is not quantified here.

The calculations done here are based on the default methodology used in constructing Australia's National Greenhouse Gas Inventories. It is the standard recognised methodology, but it is also recognised that trace-gas emissions can vary greatly with specific conditions under which those fires take place. Emissions of methane, carbon monoxide and NMVOCs, in particular, are products of incomplete combustion, and there emissions are thus dependent on the heat and oxygen availability during fires. Fires are usually set on days and under conditions that allow good combustion, but it is not clear how these conditions compare with those when other forest fires occur in Australia which would generally also meet those conditions.

The estimates given in Tables 11 and 12 may therefore be either under- or overestimates of true emissions. As they are quantitatively quite large compared to carbon stocks changes and relative to other emissions related to the burning of biomass, it seems warranted to undertake further targeted research work to determine emissions of these trace gases with greater certainty.

Ancillary CO_2 emissions

In handling and transporting wood from the forest to a power plant, there are other Greenhouse gas emissions involved. Energy is principally needed for wood handling on site, haulage to a power plant and chipping of wood (Table 13).

Table 13: Estimates of CO_2 release in transporting wood from the forest to a power plant.

	Handling	Hauling	Chipping	Total	Additional	$kgCO_2$ $(tDW)^{-1}$
	litres diesel per tonne green wood					
Minimum	2.5	1	1	4.5	1.3%	24.2
Average	3.25	2.5	1.5	7.25	2.1%	39.0
Maximum	4	4	2	10	2.9%	53.8

Estimates for fuel consumption in hauling are based on hauling distances between 25-100 km (for minimum and maximum values). Total extra emissions are the sum of handling, hauling and chipping. It is assumed that 1 L diesel emits 2.69 $kgCO_2$

upon combustion, that a green tonne of wood consists of 50% water and dry weight to be 50% carbon so that the additional emissions from transport and handling could be calculated as extra CO_2 emissions relative to the CO_2 emissions from the burning of wood itself. Minimum and maximum give reasonable upper and lower limits and average is simply the average of these two estimates. If chipping is done by an electric rather than a diesel motor, it is assumed here that the same additional emissions would be involved.

If fuelwood is to be utilised, it will require additional handling of wood in the forest. The estimates for handling are probably somewhat overestimating because they are based on wood handling from normal logging operations. As much of the logging work needs to be undertaken in any case, the addition wood handling can probably be done at somewhat higher efficiency than the base work. These estimates might become higher, however, if attempts would be made to also recover smaller-diameter wood or extricate stumps. The calculations done here are predicated on the assumption that an excess of wood residue will be available and that only easily collectable material will be used.

Estimates of haulage are based on haulage distances of 25 for the minimum estimate and 100 km for the maximum estimate. The distances within the Southwood catchment are probably at the lower end of those estimates, but actual numbers will also depend on whether wood can be sources preferentially from site nearer the power station, or whether it will be necessary to collect all available material from the whole of the area.

The estimate for extra emissions related to chipping wood before feeding it into boilers is based on a diesel-driven chipper. If an electric chipper is used then the calculations should be done on the basis of the reduced electricity available from the Southwood power station, and that would lead back to the question as to which fuel source would be replaced. To avoid these extra complications, the power use and CO_2 emissions related to the use of a diesel-driven chipper are used here.

One of the benefits of using wood-derived energy is that obviates the need for mining and transport of coal or other fossil fuels that are being replaced and an additional saving accrues through the saving of the ancillary emissions involved in the mining and transport of the replaced fossil fuel sources. This is only noted here, but no detailed calculations are carried out.

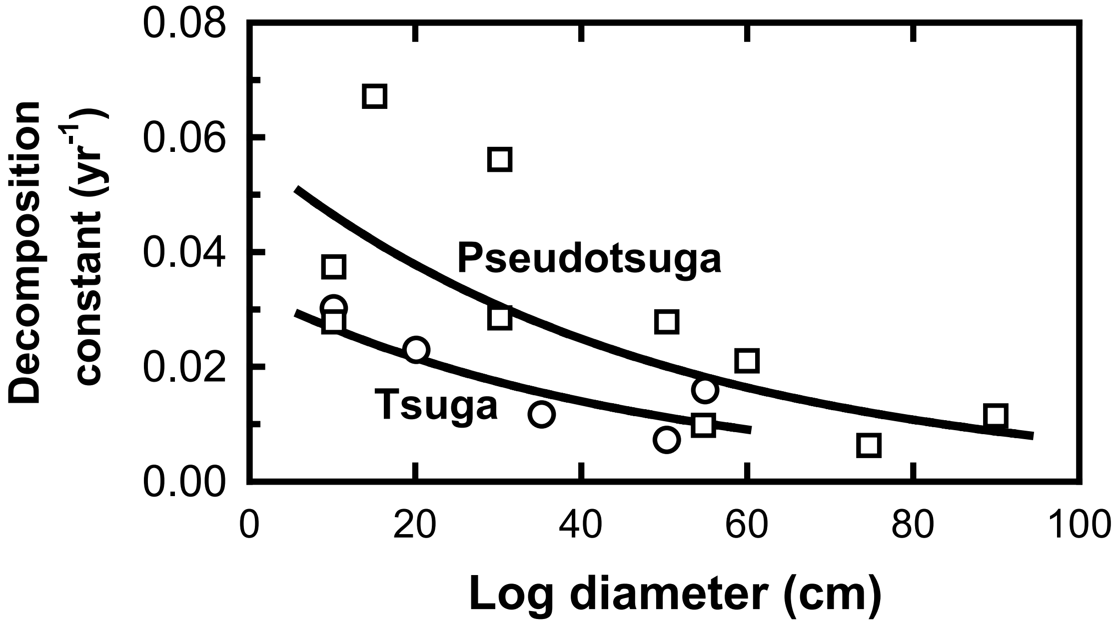
Coarse Woody Debris Decay

For the purposed of the current assessment, trends in coarse woody debris over time are one of the most important parameter to estimate. Unfortunately, there is not much known about the decay rates of coarse woody debris. This is partly due to the methodological difficulties in measuring the decay of woody debris over many decades. This is made more difficult by the fact that much coarse woody debris starts as standing dead wood where it decays only slowly. When dead trees finally fall over, a faster rate of decay can commence.

Until recently, there has also been a lack of interest in the fate of coarse woody debris in forest ecosystem. It is only with a recent upsurge in interest in coarse woody debris dynamics due to the recognition of the importance of coarse woody debris for some unique species of the forest ecosystem (Harmon et al. 1986; Grove et al. 2002). Coarse woody debris has also been recognised as a quantitatively important component of the forest's carbon stocks, so that there has been increasing interest in the dynamics of coarse woody debris.

A recent review of available information was being undertaken by Mackensen and Bauhaus (1999). They reported a general dearth of information, especially from Australian studies. Slightly more information was found from overseas studies, especially the north-western United States where the majority of studies had been carried out. The work carried out there provided some general knowledge of the factors that can influence decay rates. One important relationship is the decrease in decay rates with increasing log size (Fig. 8), and a weak relationship between decomposition rate decreasing with increasing wood density (Mackensen and Bauhaus 1999).

Figure 8: Dependence of coarse-woody debris decay constant on log diameter for *Pseudotsuga menziesii* and *Tsuga heterophylla*, two well-studied north-American species. Redrawn from Mackensen and Bauhaus (1999).



Mackensen and Bauhaus (1999) also carried out a small number of additional experiments to overcome some of the dearth of knowledge on Australian species. They used a single exponential decay model to describe the findings of their own work and to summarise much of the evidence they had obtained from the literature. A study on *Eucalyptus regnans* yielded a decay constant of 0.0407 (Mackensen and Bauhaus 1999).

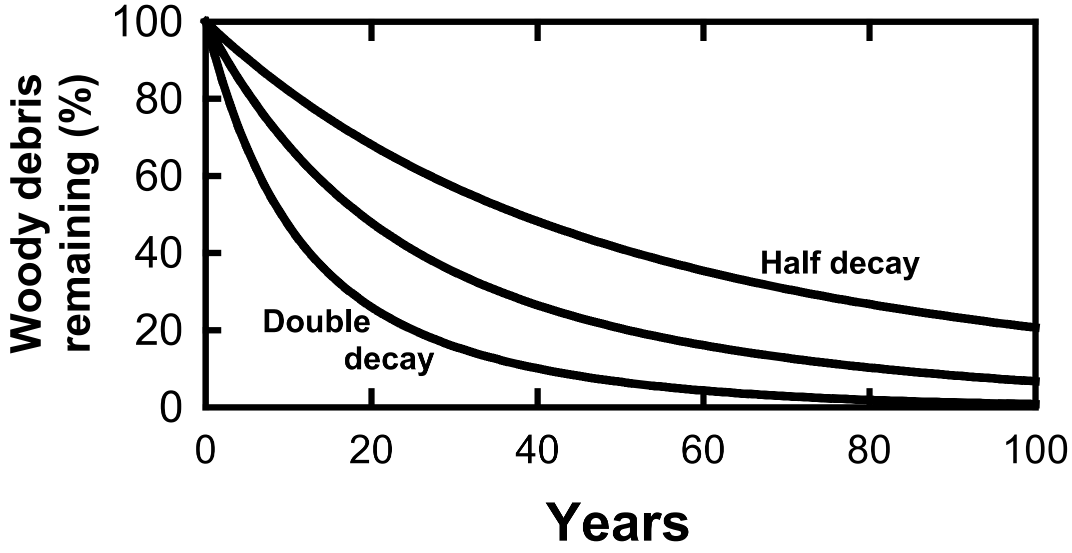
According to durability tests carried out on different wood samples (da Costa 1979; Thornton et al. 1997) *Eucalyptus obliqua*, and *E. regnans* are two of the least durable Australian hardwoods. Hence, the decay rate for *E. regnans* may be similarly applicable for *E. obliqua* which constitutes the quantitatively most important component of the wet eucalypt forests in Tasmania.

A constant decay rate of 0.0407 translates into 95% weight loss over about 75 years which is difficult to reconcile with the large amounts of coarse woody debris that are readily observable in wet eucalypt forests (Woldendorp et al. 2001). That apparent contradiction may be related a number of factors:

- there may be a relatively high input rates from dieing trees, or standing dead trees from a previous fire (Grove et al. 2002) that decay little while standing but provide a constant source of new material;
- decay rates may be lower in Tasmania than in Victoria's *E. regnans* forests because of the lower temperatures in Tasmania;
- decay may be significantly slower in large-diameter trees (see Fig. 8) which may constitute the bulk of the coarse woody debris remaining after extended periods;
- decay may not be adequately described by a single exponential decay function but a two-component exponential function may be more appropriate, with the faster-decomposing fraction, essentially corresponding to the sapwood of trees accounting for the fast decay observed in relatively short observation, and the slower-decomposing component, corresponding to the heartwood, accounting for the coarse woody debris remaining after extended periods.

Consequently, for the present analysis, the decay of coarse woody debris was described a two-component system with different turn-over times. The resultant loss of coarse woody debris over 100 years is shown in Figure 9. The Figure also shows the sensitivity of carbon loss to doubling or halving decay rates.

Figure 9: Time course of loss of coarse woody debris over 100 years. Half of fresh wood was assumed to be decomposable and half more resistant material, with assumed decay rates of 0.02 and 0.06, respectively.



With these parameters, there is some initial fairly rapid loss of carbon, with about 60% loss over the first 20 years, but the rate of loss diminishes rapidly thereafter, with about 6.5% of carbon still remaining after 100 years.

That initial loss corresponds to the loss from more decomposable components, such as branches and smaller stems, wood in direct contact with the soil where it can remain moist for longer and facilitate decomposition. The material still remaining after even 100 years corresponds to large stems, especially where that is in elevated positions that prevent continuous wetness and retards decay.

Figure 9 also shows the sensitivity of the response to change in the parameter values, with the base parameters either doubled or halved. With decay rates halved, 19% of initial debris would still remain after 100 years, but less than 1% with decay rates doubled. Hence, the system dynamics show great sensitivity to this uncertain parameter.

Figure 10: Comparing the time course of loss of coarse woody debris over 100 years with a single and double exponential decay models. The single decay-model uses 0.0407 as the parameters. The parameters for the double decay model are as given in Figure 9.

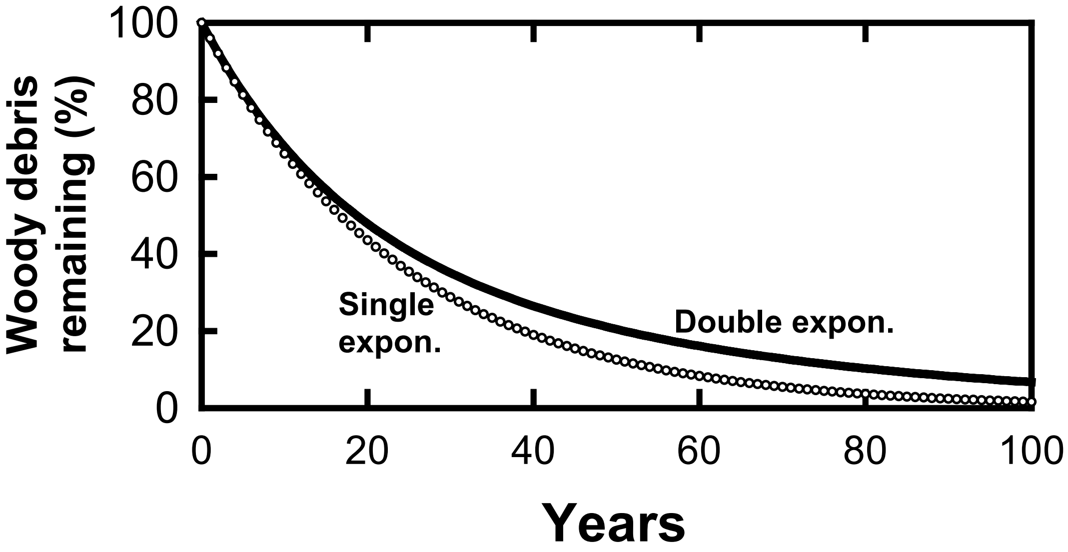


Figure 10 compares the time course of decay with a single and double-exponential decay models. The parameters were chosen in such a way to get comparable decay rates over the first 20 years over which all the experimental observations are available. The comparison shows that the models have similar patterns over the first 20 years, but at the end of 100 years there is only 1.5% of wood remaining if described with the single exponential model but about 6.5% for the double exponential model.

It is likely that the best description of decay patterns could be obtained if coarse wood decay were modelled by

1) using a double-exponential decay model;
2) explicitly including log diameter as a factor affecting decay rates (Fig. 8);
3) including the slower decay of dead standing trees (as had been done by Grove et al. 2002).

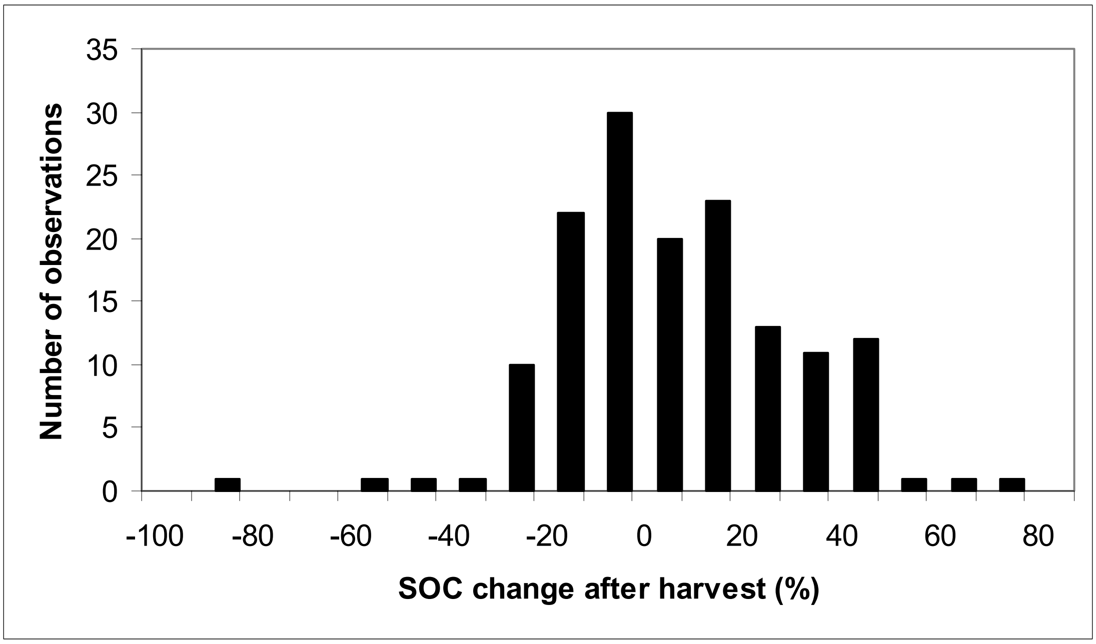
Soil Organic Carbon Changes

Changes in soil carbon are potentially very important for Greenhouse balances because soil carbon tends to be more stable than other carbon pools so that any increases or decreases in soil carbon are potentially longer-lasting than changes in other carbon pools. Soil carbon also plays an important role in contributing to soil fertility both chemically and physically.

Changes in soil carbon have already been assessed in preceding Sections, showing generally only slight changes in soil carbon following logging, or between the cases of removing woody litter or retaining it all on site. However, because of the importance of accurately assessing changes in soil organic carbon, and because the model used for the preceding simulations, the issue of changes in soil organic matter were investigated further.

Reviews of the literature generally confirm that there is generally only a slight change, if any, in soil organic matter storage following normal forestry operations (Johnson, 1992; Johnson & Curtis, 2001). Johnson (1992) reviewed the literature and collated the finding from studies that followed the change in soil organic carbon storage after forest operations. That work was repeated and expanded in 2001 (Johnson and Curtis, 2001). Figure 11 shows the main findings from their review.

Figure 11: Review of studies that investigated changes in soil carbon after forestry operations. Shown are the number of observations that reported changes in specified ranges. Redrawn from Johnson and Curtis (2001).



Individual studies reported findings ranging from losses of over 80% of soil carbon to gains of more than 70% of soil carbon. The average across all the studies centred on 0 change and suggest that under normal harvest operations there would be no change in soil carbon.

Murty et al. (2002) recently completed a review of changes in soil organic carbon after the more drastic management change of changing land use from forest to agriculture. Murty et al. (2002) found no change in soil carbon if forests were converted to uncultivated pasture, but there was a loss of soil carbon by 20-30% if forest was changed to cultivated land-uses. It is not clear whether it is the cultivation itself that acts to stimulate decomposition activity and thereby lowers soil organic carbon storage, or whether that is merely a surrogate for more intensive land management. It is worth noting, however, that Johnson (1992) also observed that the inclusion of soil cultivation as part of forestry operations led to reduced soil organic carbon storage. This emphasises the importance of care being taken with management systems that disturb the forest soil.

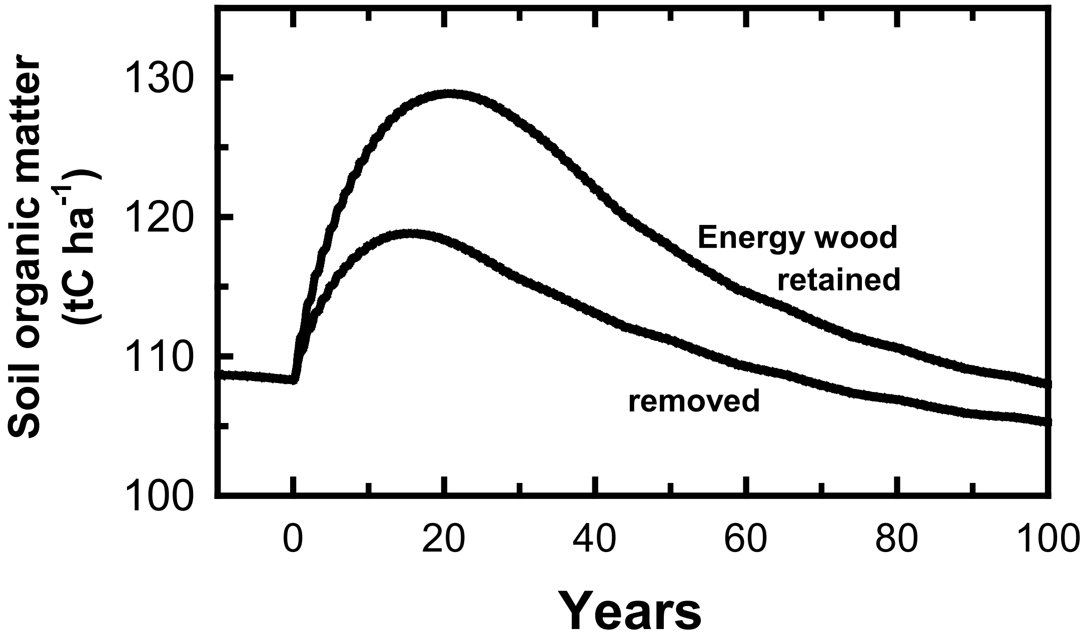
Johnson and Curtis (2001) also looked at studies that reported changes in soil carbon after fires and also could find no consistent effect on soil carbon amounts. Of all management options investigated, soil carbon increases were only observed if fertiliser was added to the system, or if nitrogen-fixing legumes were introduced into the forest. This underscores the importance of ensuring that legumes are re-established early after logging so that nitrogen essential for good regrowth is quickly restored in the system.

Within the studies reviewed by Johnson and Curtis (2001), there were indications that whole-tree harvesting had a relatively more negative effect on soil carbon storage than sawlog harvesting only. Whole-tree harvesting in these studies involved removal of bark, branches and foliage. These biomass components are rich in nutrients, and their removal can understandably lead to impoverishment of any site in nutrients with consequent effects on site carbon storage. Hence, it is important that removal of biomass components other than the stem be avoided. If only stems are removed, then effects on site nutrient budgets and consequently on soil organic carbon storage should remain minimal.

These simulations were also repeated with the CenW forest growth model (Kirschbaum 1999; Kirschbaum and Paul 2002) that has more a more complete representation of plant and soils processes than was used for the modelling in the preceding Sections. Importantly, it includes the nitrogen cycle concurrent with the carbon cycle based on the CENTURY model (Parton et al. 1987) which puts an additional constraint on changes in soil carbon which is more realistic than the unconstrained simulations that have been used above.

Only a single simulation was run: logging of a mature forest and allowing it to regrow for a further 100 years. Upon logging under current conditions, it was assumed that 25% of wood was removed in products and 25% lost in a regeneration burns. With the use of fuelwood, it was assumed that a further 25% of wood was removed as fuelwood. Figure 12 shows changes in soil organic matter over 100 years following the logging operation under the two management scenario.

Figure 12: Time course of changes in soil organic carbon pools following the logging of a mature forest and regenerating it as regrowth forest either under standard current practice or with additional energy-wood removal. Harvesting occurred in year 10.



Upon logging in year 10, there was an immediate increase in soil carbon due to the addition of fresh readily decomposable litter (leaves, fine roots) produced during the logging operation. There was a further increase in soil carbon over the next 20 years, especially in the case without harvesting of fuelwood. The difference between the two cases reached a maximum of about 10 tC ha^{-1} about 25 years after harvesting. However, that differences was not maintained and the two cases became more similar again as more and more of the originally retained woody debris is lost to decay.

A difference of about 3 tC ha^{-1} remained until the end of the 100-year run. That difference is related to a difference of about 55 kgN ha^{-1} in total site nitrogen balance (about 1% of total site nitrogen stores) between the two cases (data not shown). This difference in nitrogen is approximately equal to the amount originally removed in the removal of wood (see the Section on nutrient balances). As soil organic matter contains both carbon and nitrogen in fairly well-defined ratios, available site nitrogen reserves put a strong constraint on potential changes in soil organic carbon storage.

Summary and Recommendations

The key findings of this analysis on Greenhouse gas balances are summarised in Table 14.

Table 14: Summary findings of key effects of using fuelwood on CO_2 equivalent emissions. Negative numbers refer to savings and positive numbers to additional emissions.

	GHG saving	Woody litter	Soil organic carbon	non-CO_2 GHGs	Ancillary	Total	Total	Southwood
	tCO_2-e $(tDW)^{-1}$						tCO_2-e ha^{-1}	$ktCO_2$-e yr^{-1}
Mature to regrowth	-1.304	0.188	0.074	-0.121	0.039	-1.124	-69.0	-228
Regrowth to regrowth	-1.304	0.274	0.108	-0.121	0.039	-1.004	-42.3	-204
Regrowth to plantation	-1.304	0.060	0.129	-0.121	0.039	-1.197	-156.0	-243

GHG savings are based on case 5a (see above), assuming a energy conversion efficiency of 1.425 MW hr $(tDW)^{-1}$ and total Greenhouse gas impact of the Southwood project is based on annual consumption of 203,000 tDW (assuming that the plant produces 36 MW of electricity and operates for 92% of the year).

Overall, Greenhouse balances are dominated by the saving due to the offset of fossil fuel emissions. However, that finding depends firstly on the type of electricity generation that will be replaced by the new power plant based on energy-wood generation, and on the assessment horizon. A significant Greenhouse emission offset results if the system is analysed over a long time horizon which is considered appropriate for mitigation of a long-term problem such as climate change, and if the energy offset is a fossil fuel which seems likely given the establishment of Basslink and increasing energy demand in Tasmania.

The benefit of a fossil-fuel offset must be balanced against slight carbon losses from the reduction in coarse woody litter and soil organic carbon in the forest as well as additional emissions related to transport and handling, but these offsets are likely to be small. There is, however, insufficient knowledge of decay rates of coarse woody debris of Australian species in general, or those in the wet eucalypt forest, in particular. Similarly, the relationship between the decay of coarse woody debris and soil organic matter dynamics is incompletely understood. It is considered unlikely, however, that better detailed knowledge of these relationships would result in very different conclusions.

Based on the use of standard methodology for greenhouse gas inventories, there are significant further savings due to reduced emission of non-CO_2 Greenhouse gases, essentially because combustion in industrial boilers provides a cleaner burn than the often incomplete combustion in forest fires that can leads to significant releases of products of partial combustion, especially methane. It is unclear, however, whether application of standard methodology is likely to under-or overestimate those emissions, but since emissions are strongly affected by the particular conditions during fires, it would seem unlikely that standard methodology would provide the correct estimate.

Recommendation 16. *The use of fuelwood is likely to have considerable greenhouse benefits. However, because of the potentially large contribution of non-greenhouse gases to total greenhouse gas balances, further research to better quantify non-CO_2 emissions under a range of field burning conditions is warranted.*

The overall benefit can be expressed as being between 1.0 tCO_2-e $(tDW)^{-1}$ for wood derived from regrowth forests and 1.20 tCO_2-e $(tDW)^{-1}$ for wood from plantations. These slight differences arise because of the differential effects on woody debris and soil organic carbon pools in the different forest systems, but numbers are very similar because they are dominated by fossil-fuel substitution benefit, and there are no differences in that benefit.

When the data are expressed in terms of Greenhouse saving per hectare, they range from 42.3 tCO_2-e ha^{-1} for regrowth forests over 69.0 tCO_2-e ha^{-1} for logging mature forests to 156.0 tCO_2-e ha^{-1} for plantation wood. The difference between regrowth and mature forests is due to the different amounts of fuelwood likely to be available from those different systems, whereas the larger benefit from the plantation system is due to the fact that benefits can accrue over multiple rotations within the considered 100-year assessment horizon.

The proposed Southwood plant would require an estimated 203,000 tDW of wood resources per year of its operation. In terms of the total Greenhouse benefit, this would translate into an offset saving between 204 and 243 $ktCO_2$-e yr^{-1}, depending on the source of the wood material. Excluding emissions from land-use change, Australia's total Greenhouse gas emissions were 458.2 $MtCO_2$-e in 1999 of which stationary energy sources contributed 259.8 $MtCO_2$-e (NGGI 1999). The proposed Southwood power station could thus substitute for approximately 0.1% of Australia's Greenhouse gas emissions from stationary sources, and 0.05% of Australia's total Greenhouse gas emissions.

References

Borough, C.J., Incoll, W.D., May, J.R. and Bird, T. (1978). Yield Statistics. In: *Eucalypts for Wood Production.* (Eds: Hillis, W.E. and Brown, A.G.), CSIRO, Australia, pp. 201-225.

da Costa, E.W.B. (1979). Comparative decay resistance of Australian timbers in accelerated laboratory tests. Australian Forest Research 9: 119-135.

Galbally, I.E., Fraser, P.J., Meyer, C.P., and Griffith, D.W.T. (1992). Biosphere/ atmosphere exchange of trace gases over Australia. In: *Australia's Renewable Resources: Sustainability and Global Change.* (Eds: Gifford, R.M. and Barson, M.M.), Bureau of Rural Resources, Canberra, pp. 171-149.

Grove, S., Meggs, J. & Goodwin, A. (2002). A review of biodiversity conservation issues relating to coarse woody debris management in the wet eucalypt production forests of Tasmania. Draft Technical Report to Forestry Tasmania, 8 April 2002, 72 pp.

Harmon, M.E., Franklin, J.F., Swanson, F.J., Sollins, P., Gregory, S.V., Lattin, J.D., Anderson, N.H., Cline, S.P., Aumen, N.G., Sedell, J.R., Lienkaemper, G.W., Cromack, J.R and Cummins, K.W. (1986). Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research **15**: 133-302.

Ilic, J., Boland, D., McDonald, M., Downes, G. & Blakemore, P. (2000). Wood Density Phase 1 - State of Knowledge. National Carbon Accounting System Technical Report No. 18, Commonwealth of Australia, 218 pp.

Johnson, D.W. (1992). Effects of forest management on soil carbon storage. Water, Air, and Soil Pollution **64**: 83-120.

Johnson, D.W. & Curtis, P. S. (2001). Effects of forest management on soil C and N storage: meta analysis. Forest Ecology and Management **140**: 227-238.

Kirschbaum, M.U.F. (1999). CenW, a forest growth model with linked carbon, energy, nutrient and water cycles. *Ecological Modelling* **181**: 17-59.

Kirschbaum, M.U.F. and Paul, K.I. (2001). Modelling carbon and nitrogen dynamics in forest soils with a modified version of the CENTURY model. *Soil Biology & Biochemistry* (Accepted).

Kirschbaum, M.U.F., Schlamadinger, B., Cannell, M.G.R., Hamburg, S.P., Karjalainen, T., Kurz, W.A., Prisley, S., Schulze, E.-D., and Singh, T.P. (2001): A generalised approach of accounting for biospheric carbon stock changes under the Kyoto Protocol. *Environmental Science and Policy* 4: 73-85.

Mackensen, J. and Bauhaus, J. (1999). The Decay of Coarse Woody Debris. National Carbon Accounting System Technical Report No. 6, Commonwealth of Australia, 41 pp.

Murty, D., Kirschbaum, M.U.F., McMurtrie, R.E. and McGilvray, H. (2002). Does forest conversion to agricultural land change soil organic carbon and nitrogen? A review of the literature. *Global Change Biology* **8:** 105-123.

NGGI (1996a). Workbook for fuel combustion activities (stationary sources). Workbook 1.1, revision 1. National Greenhouse Gas Inventory Committee, Commonwealth of Australia, 85 pp.

NGGI (1996b). Workbook for non-carbon dioxide gases from the atmosphere. Workbook 5.1, revision 1. National Greenhouse Gas Inventory Committee, Commonwealth of Australia, 74 pp.

NGGI (1999). Overview: 1999 National Greenhouse Gas Inventory. Fact Sheet 1. Australian Greenhouse Office

Parton W.J., Schimel D.S., Cole C.V. and Ojima, D.S. (1987) Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Science Society of America Journal **51**: 1173-1179.

Prather, M., Ehhalt, D., Dentener, F., Derwent, R., Dlugokencky, E., Holland, E., Isaksen, I., Katima, J., Kirchhoff, V., Matson, P., Midgley, P. and Wang, M. (2001). Atmospheric chemistry and Greenhouse gases. In: *Climate Change 2001. The Scientific Basis* (Eds: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K. and Johnson, C.A.), Intergovernmental Panel on Climate Change, Cambridge University Press, pp. 239- 287.

Schlamadinger, B., Karjalainen, T., Birdsey, R., Cannell, M., Galinski, W., Gintings, A., Hamburg, S., Jallow, B., Kirschbaum, M., Krug, T., Kurz, W., Prisley, S., Schulze, D., Singh, K.D., Singh, T.P., Solomon, A.M., Villers, L., Yamagata, Y. (2000). Afforestation, reforestation, and deforestation (ARD) activities. In: *Land Use, Land-Use Change and Forestry* (Watson, R.T., Noble, I.R., Bolin, B., Ravindranath, N.H., Verardo, D.J. and Dokken, D.J., eds.), Cambridge University Press, Cambridge, UK, pp. 127-179.

Slijepcevic, A. (2002). Loss of carbon during controlled regeneration burns in *Eucalyptus obliqua* forest. Tasforests 13: 281-290.

Thornton et al. (1996) Revised natural durability ratings for the outer heartwood of mature Australian timbers in ground contact. In: Proceedings of the 25th Forest Products Conference, CSIRO Forestry and Forest Products, Clayton, Victoria, 12 pp.

Tibbits, W.N. (1986). Eucalypt plantations in Tasmania. Australian Forestry 49: 219-225.

Turnbull, C.R.A., Beadle, C.L., Bird, T. and McLeod, D.E. (1988). Volume production in intensively-managed eucalypt plantations. Appita 41: 447-450.

Turnbull, C.R.A., McLeod, D.E., Beadle, C.L., Ratkowsky, D.A., Mummery, D.C. and Bird, T. (1993). Comaprative early growth of *Eucalyptus* species of the subgenera *Monocalyptus* and *Symhyomyrtus* in intensively-managed plantations in southern Tasmania. Australian Forestry 56: 276-286.

UNFCCC (1997) The Kyoto Protocol to the United Nations Framework Convention on Climate Change, UNEP/WMO.

URS (2001). An assessment of the CO_2 implications of Basslink. Supporting study #15, Basslink Pty. Ltd.

West, P.W. & Mattay, J.P. (1993). Yield prediction models and comparative growth rates for six eucalypt species. Australian Forestry 56: 211-225.

Woldendorp, G., Keenan, R. and Ryan, M. (2001). Coarse Woody Debris in Australian Forest Ecosystems. A Report for the National Greenhouse Strategy, Module 6.6 (Criteria and Indicators of Sustainable Forest Management), Bureau of Rural Sciences, 80 pp.