Developing a carbon stocks and flows model for Australian wood products

Gary P. Richards[1,2,3], Chris Borough[4], David Evans[5], Ainslie Reddin[1], Fabiano Ximenes[6] and David Gardner[6]

[1]Australian Greenhouse Office, GPO Box 787, Canberra, ACT 2601, Australia
[2]The Fenner School of Environment and Society, The Australian National University, Canberra, ACT 0200, Australia
[3]Email: gary.richards@environment.gov.au
[4]MBAC Consulting, PO Box 262, Deakin West, ACT 2600, Australia
[5]david.evans@sciencespeak.com
[6]CRC for Greenhouse Accounting, Forest Resources Research, NSW Department of Primary Industries, PO Box 100, Beecroft, NSW 2119, Australia

Revised manuscript received 8 February 2007

Summary

This paper describes the development of a model for estimating Australia's stocks and flows of carbon in harvested wood products, including estimates of atmospheric emissions. The model estimates emissions in various forms, including those from wood products contained in Australia, encompassing both domestically produced (net of exports) and imported wood products. This estimate is the basis of Australia's National Greenhouse Gas Inventory report on wood products. The model can also estimate emissions from all (and only) wood products produced in Australia, and a third variant that presumes emissions from wood products at the time of harvest.

The model represents a collaborative effort, involving relevant Commonwealth and state government agencies, industry groups and research bodies. The model uses available statistics on log flows from forest harvest and estimates of the carbon content of the various wood products processed (for example, sawn timber, plywood, pulp and paper and woodchips) to determine carbon inputs to wood products. The model uses estimates of the decay period of various classes of wood product to calculate the pool of carbon in wood products. Crosschecking with independent input data was done wherever possible to test the robustness of various input data used in the model development.

The model is built in Microsoft Excel with all rate and age parameters easily accessed and varied for sensitivity testing using the @Risk software. Wood products in use are assigned to young-, medium- and old-age pools. Simulated losses of wood products from their service life occur from each of the young-, medium- and old-age pools. Material leaving service is either transferred to bioenergy, added to landfill, recycled or emitted to the atmosphere. Losses of carbon can also occur from the landfill pool.

The recorded imports and exports of wood products are used to calculate emissions under two approaches. The first is from wood products produced in Australia (but not necessarily remaining within Australia), and the second from wood products stored in Australia (wherever they were produced). Further simulations, with and without consideration of storage and emissions from landfill, are then run for each approach. The results show that an accounting approach that presumes emissions from wood products at harvest over-estimates emissions to the atmosphere when compared with approaches that consider the service life of wood products. The storage of wood products in landfill is also significant.

Keywords: models; forest products; stocks; lifespan; carbon; flow; greenhouse gases; Australia

Introduction

Wood product carbon emissions are included under the 1996 (Revised) Intergovernmental Panel on Climate Change (IPCC) Guidelines for the United Nations Framework Convention on Climate Change (IPCC 1997). They are reported in the Land Use, Land Use Change and Forestry part of Australia's National Greenhouse Gas Inventory (NGGI) where they arise from the service life of products. The Waste section of the NGGI reports emissions from landfill.

Under the inventory guidelines countries may elect to report harvested wood products, but only if the national stock of products is increasing. Although wood products may be reported in an NGGI, they are excluded from accounting under the Kyoto Protocol (UNFCCC 1997). This is prescribed in the Marrakech Accords (UNFCCC 2002) and the IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry (IPCC 2003). The Marrakech Accords defer further decisions on the accounting treatment of harvested wood products to future negotiations. Some later technical documentation has been prepared (UNFCCC 2003) and submissions on potential accounting treatments sought. The IPCC 2006 Inventory Guidelines (IPCC 2006) provide some methodological guidance, but do not specify accounting treatments. The methodological guidance expands on that of the early IPCC (Dakar) workshop (Brown *et al*. 1998) that considered potential accounting treatments.

Australia's NGGI reports emissions when (in the year of inventory) and from where (the country) they occur. Therefore, Australia's NGGI reports emissions from wood products held in Australia. Internationally, accounting options under consideration include treating the transfer of carbon in harvested wood across national boundaries as a carbon credit (stocks increase) in the receiving country, and as a stock loss (treated as an emission) in the producing country. Other options include the producing countries monitoring and reporting emissions from harvested wood products they produce as emissions occur in other countries.

This paper focuses on developing a national wood products carbon account for Australia's NGGI, and provides contrasting outcomes for accounting treatments beyond those of when and where the emissions occur. To consider the life cycle effects of harvested wood products after their service life (that are reported as Waste under the IPCC Guidelines) the model is extended to include disposal in landfill.

Countries other than Australia report on wood products in their NGGIs (for example, USEPA 2006) or have otherwise prepared national estimates (for example, Pingoud *et al*. 2003). The input data, modelling methods and accounting frameworks used vary considerably. As developing the Australian model did not draw on these international parallels, they are not reviewed here.

A national database of domestic wood production and trade, including import and export quantities, has been kept since 1944 by the Australian Bureau of Agriculture and Resource Economics (ABARE). This consistent and detailed collection of time-series data provides a sound basis for developing a national wood products model. Jaakko Pöyry Consulting were initially engaged by the National Carbon Accounting System (NCAS) to develop a national carbon accounting model for wood products, and that work provides the forerunner model to that adapted and described here. The early model development is reported in detail in the National Carbon Accounting System Technical Reports No. 8 (Jaakko Pöyry 1999) and No. 24 (Jaakko Pöyry 2000). Updates and model refinement were subsequently undertaken by MBAC Consulting and the NCAS. Jaakko Pöyry provided a quality assurance review of the model as described here.

Approaches to carbon accounting

Accounting approaches for carbon emissions from timber harvesting and wood products reported in this paper include:

1. Presumed emissions at harvest

This approach records all domestic and exported wood and wood products and associated emissions in an Australian account, and therefore reflects the wood product produced in Australia. No wood products carbon pools develop using this approach. This is the IPCC default approach.

2. From wood products grown in Australia (wherever the product decays)

This approach accounts for all wood products and their emissions arising from wood grown in Australia, regardless of the country in which the product finally decays. Both the destination of exported raw material and wood products, and the final products that they are converted into, need to be known. This approach needs a division of all wood products grown in Australia into two categories: wood remaining in Australia, and wood exported from Australia. However, as only the destination and not the fate of wood products exported from Australia is known, it is presumed here that the life cycle of products will be the same as if they were kept in Australia.

This assumption may not hold where products exported from Australia are used for different end-uses and are affected by different environments at their final destination. Decay rates for each country would be needed to determine the rate at which carbon is released into the atmosphere under local conditions, and these processes separately modelled. An added complication is the need to track wood products re-imported to Australia (for example, Australian woodchips exported to Japan, converted to paper, and subsequently imported by Australia). For simplicity, and because of lack of knowledge of product use and decay in other countries, decomposition of all products is treated according to Australian uses and conditions.

3. From wood products stored in Australia (wherever the source)

This approach accounts for emissions from all wood products within Australia, regardless of their country of origin. Exported wood products are accounted for by the importing country. The amount of material exported is deducted from the total production, with total imports added, to derive the amount of material available for emissions within Australia. The origin of imported wood products is irrelevant. However, Australia must monitor the total flow of imported wood products into various pools.

Model components

Information for the following components of the model has been obtained and examined:

- log flow from the forest: current annual production data were obtained by species groupings and product classes, for example, sawlogs, veneer logs, pulp logs, roundwood and other (including sleepers etc.)
- fibre flow from processing: data on the intake of raw materials to the various processing options and the output of products and by-products have been used in the model to estimate the total tonnes of carbon produced each year under various end product classes
- import and export quantities of wood products
- recycling
- entry to and decomposition in landfill
- use for bioenergy
- other losses to the atmosphere.

Life cycles, wood flows and the wood products carbon pool

Estimates of the life cycles and wood flows for each class of wood product are reported in Jaakko Pöyry (1999, 2000), and methods for estimating the existing pool of carbon in wood products proposed. Data for annual log removals are available through the Australian Forests Products Statistics published quarterly by ABARE. Data are also available through the Levies Management Unit of the Australian Department of Agriculture, Fisheries and Forests, for the Forest and Wood Products Research and Development Corporation (FWPRDC). Relevant state forest services also publish data on log removals, and these provide a valuable crosscheck on ABARE data.

ABARE includes cypress pine in coniferous logs and does not provide separate figures for these species. The volume of cypress pine log removals was estimated by applying a conversion factor to sawnwood consumption.

Wood flow

The model develops wood flows separately for each sector of the forest products industry and these are integrated to account for cross-linkages. This is important in accounting for waste or by-products which themselves may be used as resources by other parts of the industry. In conjunction with the wood flows and the estimated life cycle of timber products, this model enables the total and future carbon pools to be estimated. Import and export data were obtained from the ABARE reports by end-use categories. Details of the flows can be found in Jaakko Pöyry (1999, 2000).

In broad terms, the parts of the model developed for each sector are similar, using:

- an estimate of raw materials input, whether of sawlogs, woodchips ex-sawmill or pulp logs
- an estimate of the products of processing, for example, ‘x’% sawdust, shavings or sander dust for on-site energy generation or compost, ‘y’% woodchips for other manufacturing processes, ‘z’% of sawn timber products, panel products, paper, etc.
- an estimate of the fraction of products by product categories, depending on whether their expected end-use is long-term or short-term; for example, framing timber, dry dressed boards, cases and pallet stock, panel products for use in house construction, panelboards for use in furniture and cabinets, newsprint paper, writing and printing paper, etc.
- a final figure for total Australian consumption by end-use categories, converted to wood-fibre content (oven-dry weight) and to tonnes of carbon.

Teatment of bark

Bark has not been separately accounted for in this study. We regarded all bark as being a part of logging slash (harvesting residue) and accounted for under in-forest logging operations, for the following reasons:

- logs are sold with log volumes recorded on an underbark basis
- in most hardwood operations, logs are debarked in the field
- in softwood operations, some bark is lost before the logs reach the mill; most of this loss occurs during mechanised delimbing and log docking operations
- most softwood bark recovered at the mill is used for garden mulch which has decay characteristics similar to those of logging slash.

Softwood bark is a significant source of carbon, with total bark varying from about 35% of underbark log volume (not oven-dry weight) in Caribbean pine to 20% in radiata pine and hoop pine. As the fraction of softwood bark used for energy co-generation is likely to increase, it may be reasonable to review this treatment in future.

While this approach is suitable for accounting for wood products at a continental scale, it is a general assumption that should not be applied when calculating a stand-based carbon balance. The fraction of bark removed from the site may have a significant impact on stand carbon balance.

Basic density and carbon content

Estimates of basic density and carbon content (Table 1) are relevant to all the processing options, and the choice of values has a significant bearing on the outcome. For all sawn timber, treated softwood and hardwood poles, etc., weighted basic densities for the species involved have been applied across each category. Basic density is defined as oven-dry weight divided by green volume and the values adopted are based on Ilic *et al.* (2000). A different approach was used for board products and paper, however, because these have been subjected to varying amounts of compression during manufacture: their basic densities were derived from the air-dry density of the finished products.

The carbon content of dry matter is assigned values ranging from 0.4 to 0.53 of the oven-dry (bone-dry) weight in the literature. A figure of 0.5 is used in the model: this value is commonly used elsewhere and is a median value among those of Gifford (2001).

Values for manufacturing parameters other than basic density and carbon content came from interviews with representatives of various industry associations and individual sawmilling companies. The issues addressed included:

- recoveries of green sawn timber, sawdust and chip
- sawn sizes and corresponding dressed sizes
- the range and proportions of products produced.

Weighted averages of the information received provided realistic estimates for the various species and industry sectors except hardwood sawmilling.

Wood flows from processing

Wood flows in the various wood products produced in Australia have been developed under the following species or industry headings:

- Softwood sawmilling
- Hardwood sawmilling
- Cypress sawmilling
- Plywood
- Particleboard and medium-density fibreboard (MDF)
- Pulp and paper
- Preservative-treated softwood
- Hardboard
- Hardwood poles, sleepers and miscellaneous
- Export of woodchips and logs.

Table 1. The basic densities, and moisture and carbon contents used in the model

Property and product	Value
Carbon fraction	
Softwood sawn timber: fraction of dry matter that is carbon, by weight	0.50
Particleboard: fraction of dry matter that is carbon, by weight	0.40
MDF: fraction of dry matter that is carbon, by weight	0.40
Basic density (kg m^{-3})*	
Softwood sawn timber	460
Hardwood sawn timber	630
Cypress sawn timber	600
Plywood (softwood and hardwood) and veneer	540
Particleboard	520
Medium-density fibreboard (MDF)	600
Hardboard	930
Softboard	230
Pulp and paper: paper	1000
Pulp and paper: softwood	430
Pulp and paper: hardwood	500
Pulp and paper: wastepaper	1000
Pulp and paper: pulp	1000
Paper and paperboard imports and exports, on average	1000
Chips and logs for export: softwood logs	415
Chips and logs for export: hardwood logs	630
Hardwood poles, sleepers and miscellaneous	790
Moisture content of green wood (ratios)	
Softwood chips — weight of water : weight of wood substance	1.10
Hardwood chips — weight of water : weight of wood substance	0.90

*Basic density = (mass of oven-dry wood in kg) / (volume of green wood in m^3)

Softwood sawmilling

Softwood processing is very efficient, and nearly all softwood mills now have no waste. All slabs and edgings are chipped for paper pulp or panelboard feedstock, and sawdust and shavings are used for boiler fuel to provide energy for kiln drying. The destinations of sawlogs and sawn timber products were derived from representative sawmills in South Australia, Tasmania, Queensland and the ACT, and from Pine Australia. Import and export figures were derived from ABARE's Forest Products Statistics. The basic density of 415 kg m^{-3} used ('chips and logs for export: softwood logs') is from Ilic *et al.* (2000) and Gardner and Ximenes (*pers. obs.*), being a weighted average of the respective densities at harvest of radiata pine, slash pine, Caribbean pine and hoop pine.

Hardwood sawmilling

Hardwood plantation production has been included in the total hardwood removals. Most of this material is currently of pulp log quality, but more sawlogs will be harvested as the resource matures. The hardwood sawmilling sector is far more complex and varied than any of the other sectors of the industry. There are at least ten major forest species throughout the country, all having different densities and shrinkage rates, and to a great extent having different end-uses. Assumptions on the product outturn from hardwood sawmilling were based on information from the Victorian Association of Forest Industries and a large sawmilling company running mills in Queensland, NSW and Tasmania. Data on sawlog volumes produced, imports and exports were from ABARE.

A basic density of 630 kg m^{-3} was assumed for hardwood sawlogs. This is an average of data for the following ten commonly logged hardwoods: spotted gum (*Corymbia maculata*), blackbutt (*Eucalyptus pilularis*), rose gum or flooded gum (*E. grandis*), jarrah (*E. marginata*), karri (*E. diversicolor*), mountain ash (*E. regnans*), alpine ash (*E. delegatensis*), silvertop ash (*E. sieberi*), brown barrel (*E. fastigata*) and messmate stringybark (*E. obliqua*). The basic density assumed for poles and sleepers was 790 kg m^{-3}. This is an average of figures for spotted gum, ironbark, and blackbutt — the main species used. Hardwood chips have lower average density than sawlogs, poles or sleepers as they contain a wider range of species as well as younger regrowth and plantation material. An average basic density of 630 kg m^{-3} was adopted.

Cypress sawmilling

The quantity of logs removed is small and the data are included in the coniferous forest information in ABARE quarterly reports. Some cypress pine chips are used in panelboard manufacture, but the products are principally green framing, high-value flooring and dressed panelling.

Plywood (softwood and hardwood) and veneer

The Australian plywood industry is based principally on plantation-grown softwood and about 8% hardwood, both native and plantation grown. As well as plywood veneer, sliced or rotary-peeled decorative veneer is produced in small quantities for furniture, door and panel overlays. This production is not recorded separately by ABARE. Jaakko Pöyry (2000) estimated annual production to be less than 10 000 m^3. Data used in the model for plywood were from ABARE and the Plywood Association of Australia.

Particleboard and medium-density fibreboard (MDF)

The characteristics of these two wood panelboards, including their density, are different, but their feedstock and end-use product categories are similar. Input is either small logs unsuited to sawmilling, or woodchips produced as a by-product of sawmilling. Most of the feedstock is from softwood plantations, although some regrowth hardwood is being used in a plant in Tasmania and some cypress pine is being used in a plant in Queensland. The industry source used for information on processing assumptions in the model was the Australian Wood Panels Association.

Pulp and paper

Plantation-grown softwood fibre provides the major resource, but hardwood fibre and recycled fibre are also important. Accounting for this sector is complicated as recycled fibre is exported and pulp is imported. While ABARE data provide some information, the Pulp and Paper Manufacturers Federation of Australia (PPMFA) provided more detailed figures. Production data in this study are derived from assumed raw material use and conversion figures rather than reported industry figures. The model-derived paper production estimates are 15% lower than the ABARE or PPMFA figures. This is because the model calculates the wood-only raw material for pulp and paper in oven-dry tonnes. The ABARE and PPMFA reported figures are in air-dry tonnes which contain about 10% moisture and 2–25% of non-wood fillers depending on the process.

A complicating factor in the assumptions on waste with the pulp and paper stream is that mills vary dramatically in their recovery according to type. Kraft pulp mills typically have a low yield of fibre (≈ 50%) whereas thermomechanical mills have a high yield (≈ 95%). The manufacture of paper from recycled material also results in a lower yield of fibre. Based on weighted inputs, a yield of 70% was adopted.

Preservative-treated softwood

Both hardwood and softwood can be treated with preservative, but only softwood has been assigned a separate category in this project. This is because treated sawn softwood has some use categories which are different to those for untreated softwood. Hardwood is usually treated so the sapwood can be protected against borer attack or decay, and its use is then the same as for untreated hardwood.

Treated softwood poles and posts have also been included with sawn softwood, but treated hardwood poles and piles have been included with sleepers and other miscellaneous hardwood products. The information used in the model was obtained from the Timber Preservers Association of Australia.

Hardboard

Hardwood is used for feedstock; supplies are derived from pulp logs and sawmill residue.

Hardwood poles, sleepers and miscellaneous

The existing stock of hardwood transmission poles in Australia is reputed to number about 6 000 000 and production is estimated to be about 100 000 poles yearly, equivalent to about 75 000 m^3 of log. Railway sleepers also represent a large resource, and although concrete sleepers are now used for all new work, timber sleepers will continue to be used to maintain secondary lines. ‘Miscellaneous’ includes products such as mining, fencing and landscaping timbers.

Log and woodchip exports

Export woodchips form a significant portion of the annual harvest from Australian forests. The ABARE quarterly forest products statistics report both bone-dry tonnes (BDt) of softwood chips and BDt of hardwood chips exported. The model used the ABARE-reported export figures directly in bone-dry tonnes.

Total exports of coniferous logs reported by ABARE consist of both sawlog and pulp log. New South Wales exports about 7000 m^3 of short poles annually.

Lifespan of timber products (recycling and landfill)

The lifespan of wood products must be considered when ascertaining the quantity of carbon stored in timber products. We have given considerable attention to subdividing the various timber products pools into different classes based on product and decay rates. The decay rates used assume that losses of material from service will increase with product age. Therefore the entry and exit of material from production to loss from each product pool is tracked and aged according to three age classes — young, medium and old. The fraction of material lost annually from each pool may vary (for example, there may be little loss from young pools (excluding those to the medium-age class)). Material is lost at a constant rate and may be placed in landfill, recycled, used for bioenergy or lost to the atmosphere (for example, burnt with no energy capture) (Fig. 1).

For shorter-term products, the impact of the size of historic stocks is slight as recent additions to the pools are the major source of material available for loss. For long-term products, an estimate of the size of the historic pool is essential, but difficult. The size of the housing pool uses housing starts data. Other pools are also only estimates. The fraction of the pool that has stemmed from Australian-grown wood is needed to implement an approach that separately deals with imported wood products. However, this component is difficult to estimate and estimates should be treated with some caution.

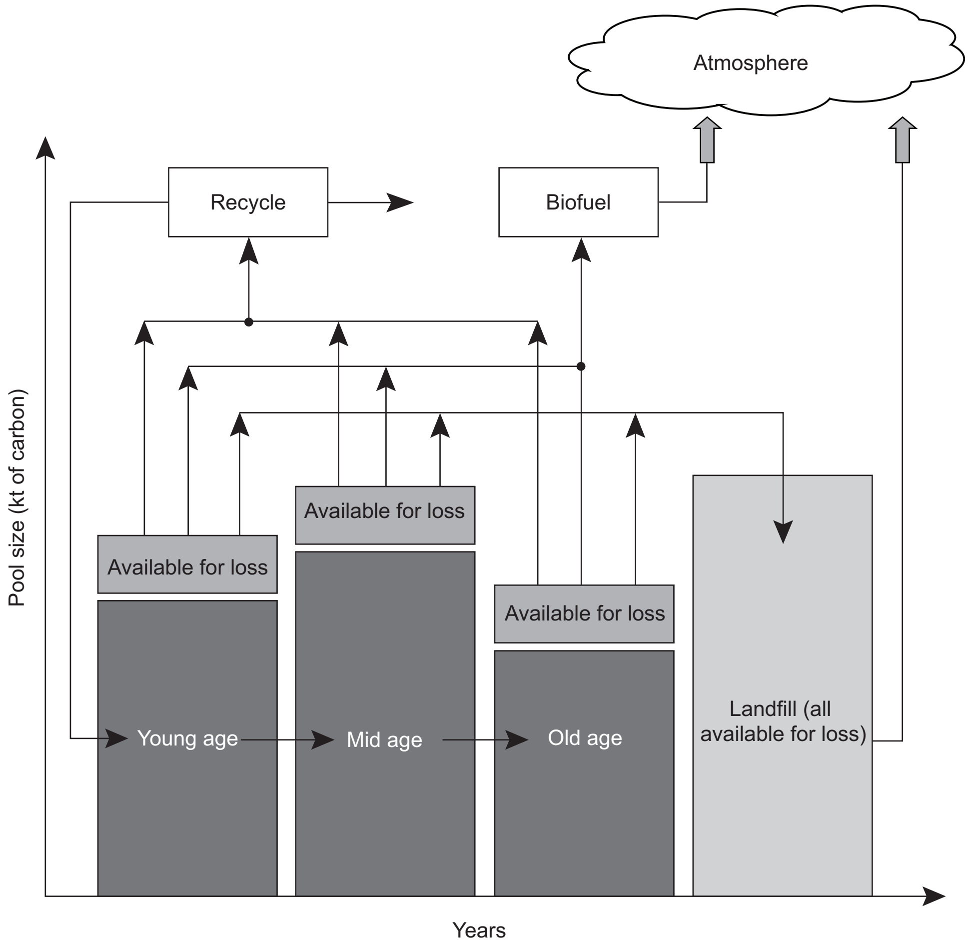

Figure 1. Major pools and flows in the wood products model

Lifespan pools assumed for the carbon model

Very short-term products — Pool 1

- Softwood — pallets and cases
- Plywood — formboard
- Paper and paper products

Age[1] (y): young = 1; medium = 2; old = 3

Short-term products — Pool 2

- Hardwood — pallets and palings
- Particleboard and MDF — shop fitting, DIY, miscellaneous
- Hardboard — packaging

Age (y): young = 3; medium = 6; old = 10

Medium-term products — Pool 3

- Plywood — other (noise barriers)
- Particleboard and MDF — kitchen and bathroom cabinets, furniture
- Preservative-treated pine — decking and palings
- Hardwood — sleepers and other miscellaneous hardwood products

Age (y): young = 10; medium = 20; old = 30

Long-term products — Pool 4

- Preservative treated pine — poles and roundwood
- Softwood — furniture
- Hardwood — poles, piles and girders

Age (y): young = 20; medium = 30; old = 50

Very long-term products — Pool 5

- Softwood — framing, dressed products (flooring, lining, mouldings)
- Cypress — green framing, dressed products (flooring, lining)
- Hardwood — green framing, dried framing, flooring and boards, furniture timber
- Plywood — structural, laminated veneer lumber (LVL), flooring, bracing, lining
- Particleboard and MDF — flooring and lining
- Hardboard — weathertex, lining, bracing, underlay
- Preservative-treated pine — sawn structural timber

Age (y): young = 30; medium = 50; old =90

[1] 'Age' is the upper bound of the age class.

Table 2. The maximum fraction of each pool available for loss (that is, exposed to decomposition, see Fig. 1) and decomposition rates (annual loss as a fraction of the amount of material exposed to decomposition in each pool)

Lifespan pool	Young		Medium		Old		Landfill loss (y^{-1})
	Available for loss	Loss (y^{-1})	Available for loss	Loss (y^{-1})	Available for loss	Loss (y^{-1})	
1	0.60	1.0	0.65	0.500	0.90	0.333	0.002
2	0.30	0.333	0.50	0.167	0.90	0.100	0.002
3	0.15	0.10	0.65	0.050	0.45	0.033	0.002
4	0.25	0.05	0.65	0.033	0.80	0.020	0.002
5	0.20	0.033	0.55	0.020	0.95	0.011	0.002

Table 3. Fraction of annual losses from each lifespan pool to landfill, recycling and biofuel

Lifespan pool	Landfill	Recycling	Bioenergy
1	0.44	0.49	0.04
2	0.75	0.20	0.05
3	0.95	0.05	0
4	0.85	0.15	0
5	0.85	0.10	0.05

A specified fraction of material may be lost yearly (an exponential loss) from each age class of each product pool. The amount lost from each age class for each product pool can be capped and different fractions can be lost according to age. This feature of the model provides for 'steps' in product loss rather than using either a simple linear or exponential loss applied to a whole product pool, irrespective of the average age of the pool. If inputs vary over time the average age of products will vary, and this is represented by the amounts of material in each age class of each product pool.

Initial stock assumptions

Input data were available for the model since 1944. This had the benefit of allowing the model to establish new equilibrium pools as the input material may be 'turned-over' several times before an equilibrium stock is reached for recent years. Initial stock estimation (for 1944) is most important for Pool 5 as this material may remain in use now.

Model parameterisation

Once the data on production inputs, processing flows and initial stocks were determined other parameters needed for the model included the:

- age at which material moved from young to medium and from medium to old pools
- fraction of each age class for each product pool exposed to loss
- rate of loss from each age class in each product pool
- fraction of losses from each age class in each product pool to each of landfill, recycling, bioenergy and the atmosphere
- rate of loss from landfill.

The estimates used for the model are presented in Tables 2 and 3. Many of the estimates are based on expert judgement. In fact, often little empirical basis or opportunity for verification of estimates exists. The maximum possible loss of carbon in wood products placed in landfill was based on research carried out by the CRC for Greenhouse Accounting (unpublished) in two landfill sites in Sydney.

To understand the impact of uncertainties, Monte Carlo analysis using the Palisade @Risk software (Palisade 1997) was applied. This approach is also able to identify model sensitivities. Through this, it is possible to identify where uncertainty in parameter estimation may be most significant for a probability distribution of expected outcomes, and to focus future data collection on areas that will best reduce uncertainties.

Model results

By integrating the carbon pools, life cycles and wood flows of wood products, the model enabled the total carbon pools and emissions to the atmosphere to be estimated. Table 4 shows the annual additions and losses and carbon pool sizes for the three accounting approaches.

Table 4 shows the significant potential of wood products to act as a store of carbon when the presumed 'emissions at harvest' result is compared with the other two accounting options. As emissions do eventually occur from stocks built up in the carbon stores, when a sufficiently large stock of carbon is emitting, estimates of emissions may exceed those from the presumed emission at harvest. When this occurs is a function of the rates of both input and decomposition (the higher the rates the earlier this will occur) and when inputs to the carbon stocks are first recorded.

Uncertainty analysis

With the consistent and comprehensive monitoring of wood production in Australia since 1944, and the confidence in this data gained through cross-verification with other datasets, little uncertainty is likely to be derived from the production data. The most likely sources of uncertainty will be the allocation to decomposition and recycling pools, and the rates of decomposition in those pools. To test the relative importance of the pool ages and decomposition rates, Monte Carlo analysis was undertaken using the @Risk add-in software (Palisade 1997) to the Excel spreadsheet wood products carbon model. The principal model parameters of interest were the decomposition rates within pools

Table 4. The flow of new material, and national carbon stock and emissions outcomes for each accounting approach

Year	New material, Australia (kt of carbon)			Accounting approach (kt of carbon)										
				1. 'Emissions at harvest'	2. 'Wood products produced in Australia'					3. 'Wood products stored in Australia'				
	Domestic production of new wood products	Imports of new wood products	Exports of new wood products	(IPCC default)	Increase due to carbon from forest	Emissions (excl. landfill, e.g., burning of waste	Decrease due to decay (emissions incl. from landfill)	Carbon pool (excl. landfill)	Carbon pool (incl. landfill)	Increase due to new wood products	Emissions (excl. landfill, e.g. burning of waste)	Decrease due to decay (emissions incl. from landfill)	Carbon pool (excl. landfill)	Carbon pool (incl. landfill)
1990	4837	726	1591	4798	4798	480	691	66760	164120	3972	358	563	79399	181561
1991	4914	786	1619	4804	4804	486	704	67637	167913	4082	362	572	80395	185044
1992	5129	824	1708	5089	5089	499	724	68640	171914	4295	370	585	81505	188696
1993	5369	827	1856	5316	5316	509	741	69811	176145	4340	373	593	82674	192426
1994	5592	989	2184	5606	5606	528	766	71071	180590	4397	378	602	83848	196190
1995	5516	778	1998	5478	5478	538	784	72181	184925	4297	383	614	84863	199833
1996	5640	838	2137	5551	5551	546	799	73314	189341	4341	389	625	85878	203512
1997	6136	910	2603	6094	6094	573	833	74661	194134	4442	393	634	86973	207295
1998	6080	894	2468	6038	6038	581	849	76006	198978	4507	398	645	88071	211119
1999	6228	1069	2621	6216	6216	591	866	77441	203971	4676	405	657	89280	215095
2000	6852	944	3137	6803	6803	625	908	79039	209337	4659	411	669	90412	219038
2001	7089	870	3090	7059	7059	647	939	80803	215007	4869	419	602	91691	223175
2002	7717	1020	3485	7649	7649	683	983	82783	221116	5252	433	702	93195	227629
2003	7262	1020	3485	7686	7686	707	1107	84699	227312	5297	443	718	94686	232136

(for example, losses from service and landfill) and transfers (for example, to recycling, bioenergy and landfill). Monte Carlo analysis samples values from within specified ranges (probability distributions) for nominated parameters within repeated applications of the model. Probability distributions for values within ranges for each variable can be nominated, as can positive and negative correlations between variables so sampling can reflect these correlations. In this application, the nominated probability distributions were 'triangular', that is, values within the ranges sampled formed a triangular distribution around a central expected value. As there was no known correlation between variables, no correlations were specified, so value selection was random within the triangular probability distributions. The absence of specified correlations has a tendency to increase the range of possible outcomes.

The life cycle pools and the distributions of their possible values for the Monte Carlo analysis are shown in Tables 5, 6, 7 and 8. Distributions of possible outcomes were stabilised over 100 000 model iterations. The 'tornado' graphs (Figs 2 and 3) shows the relative importance of each input variable to the overall uncertainty in the model outcome.

Figure 2 shows the results of the sensitivity analysis for 'wood produced in Australia' and Figure 3 the results for 'wood stored in Australia'. The results are presented with both inclusion and exclusion of the landfill pool, and for both carbon pools and emissions.

All the tornado sensitivity graphs for both 'wood products produced in Australia' and for those 'stored in Australia' when landfill is included, and for both carbon pools and emissions (Figs 2(a), 2(c), 3(a), 3(c)) show a similar pattern. The highest sensitivity was to the fractions of Pool 1 (very short-term products) that are recycled or lost to landfill. The potential model results (Figs 2(b), 2(d), 3(b), 3(d)) show a similar large range of possible model outcomes. As noted earlier, this is in part attributable to the absence of any specified correlations between variables in the Monte Carlo analysis.

Of note is the similarity in the carbon pool results for 'wood products produced in Australia' (2(d)) and for those 'stored in Australia' (3(d)), whereas the emissions from 'wood products produced in Australia' (2(b)) are higher than the emissions from 'wood products stored in Australia' (3(b)). This reflects the proportionally great importance of Pool 1 (very short-term products) in wood product exports. It also shows that the size of carbon pools in wood products is not a direct surrogate for greenhouse gas emissions.

The sensitivity results are quite different when the landfill pool is excluded (2(e), 3(e)) — with the maximum age (retention time), Pool 1 and Pool 2 products become most important. Of note is that excluding the landfill pool significantly reduced the range of potential outcomes of the wood product pool size (Figs 2(f), 3(f)). This reflects the high sensitivity of the rates of input to landfill, which is in turn a reflection of the high retention time in landfill.

Table 5. Uncertainty ranges of pool age (y) used in the Monte Carlo analysis

Life cycle pool	Lower bound			Expected value*			Upper bound		
	Young	Medium	Old	Young	Medium	Old	Young	Medium	Old
Very short term	0.5	1	2	1	2	3	1.5	3	4
Short term	1	3	5	2	6	10	3	9	15
Medium term	5	15	20	10	20	30	15	25	40
Long term	15	20	40	20	30	50	25	40	60
Very long term	20	40	75	30	50	90	40	60	105

*As assigned in the text under the heading 'Life spans for the carbon model'

Table 6. Uncertainty ranges of pool size (as fractions) exposed to decomposition used in the Monte Carlo analysis

Age	Life cycle pool	Lower bound	Expected value (as in Table 2)	Upper bound
Young	1	0.500	0.600	0.700
	2	0.250	0.300	0.350
	3	0.120	0.150	0.180
	4	0.225	0.250	0.275
	5	0.175	0.200	0.225
Medium	1	0.550	0.650	0.750
	2	0.400	0.500	0.600
	3	0.550	0.650	0.750
	4	0.550	0.650	0.750
	5	0.450	0.550	0.650
Old	1	0.800	0.900	1.100
	2	0.800	0.900	1.100
	3	0.400	0.450	0.500
	4	0.700	0.800	0.900
	5	0.800	0.950	1.150

Table 7. Uncertainty ranges of annual decomposition rate used in the Monte Carlo analysis

Age	Life cycle pool	Lower bound	Expected value (as in Table 2)	Upper bound
Young	1	2.000	1.000	0.667
	2	1.000	0.333	0.333
	3	0.200	0.100	0.067
	4	0.067	0.050	0.040
	5	0.050	0.033	0.025
Medium	1	1.000	0.500	0.333
	2	0.333	0.167	0.111
	3	0.067	0.050	0.040
	4	0.050	0.033	0.020
	5	0.025	0.020	0.017
Old	1	0.500	0.333	0.250
	2	0.200	0.100	0.067
	3	0.050	0.033	0.025
	4	0.025	0.020	0.017
	5	0.013	0.011	0.010
Landfill		0.0015	0.002	0.0025

Table 8. Uncertainty ranges for destination fraction used in the Monte Carlo analysis for 'wood products produced in Australia' accounting approach

Life cycle pool	Landfill			Recycle			Biofuel		
	Lower bound	Expected value	Upper bound	Lower bound	Expected value	Upper bound	Lower bound	Expected value	Upper bound
1	0.38	0.44	0.50	0.45	0.49	0.53	0.63	0.04	0.05
2	0.60	0.75	0.90	0.18	0.20	0.22	0.04	0.05	0.06
3	0.80	0.95	1.10	0.40	0.05	0.06	-	0	-
4	0.70	0.85	1.00	0.13	0.15	0.17	-	0	-
5	0.70	0.85	1.00	0.09	0.10	0.11	0.04	0.05	0.06

Conclusions

With the comprehensive and consistent collections of forest production statistics since 1944 it was possible to build a robust model of carbon stocks and flows for wood products by deriving suitable conversion factors, allocating products to decomposition pools, and estimating the rates of decomposition for each pool. The benefits of a long run of wood products records is that, for all but the long-term pools, products pools have reached an equilibrium for recent years. In the longer-term pools, where this is not the case, the model will be more sensitive (more so for stocks than emissions) to the initial conditions. As pool size is directly proportional to the emissions, it is important to note that the model is sensitive to the time when inputs to the pools begin. The longer the pools have to increase (that is, the earlier the model begins) the larger the overall carbon store that will experience the same rate of emissions.

The inclusion or exclusion of the landfill carbon store (and therefore emissions from landfill) is clearly very significant. The increase in the landfill carbon store provides a base for additional emissions. Depending on the balance of rates of emission against

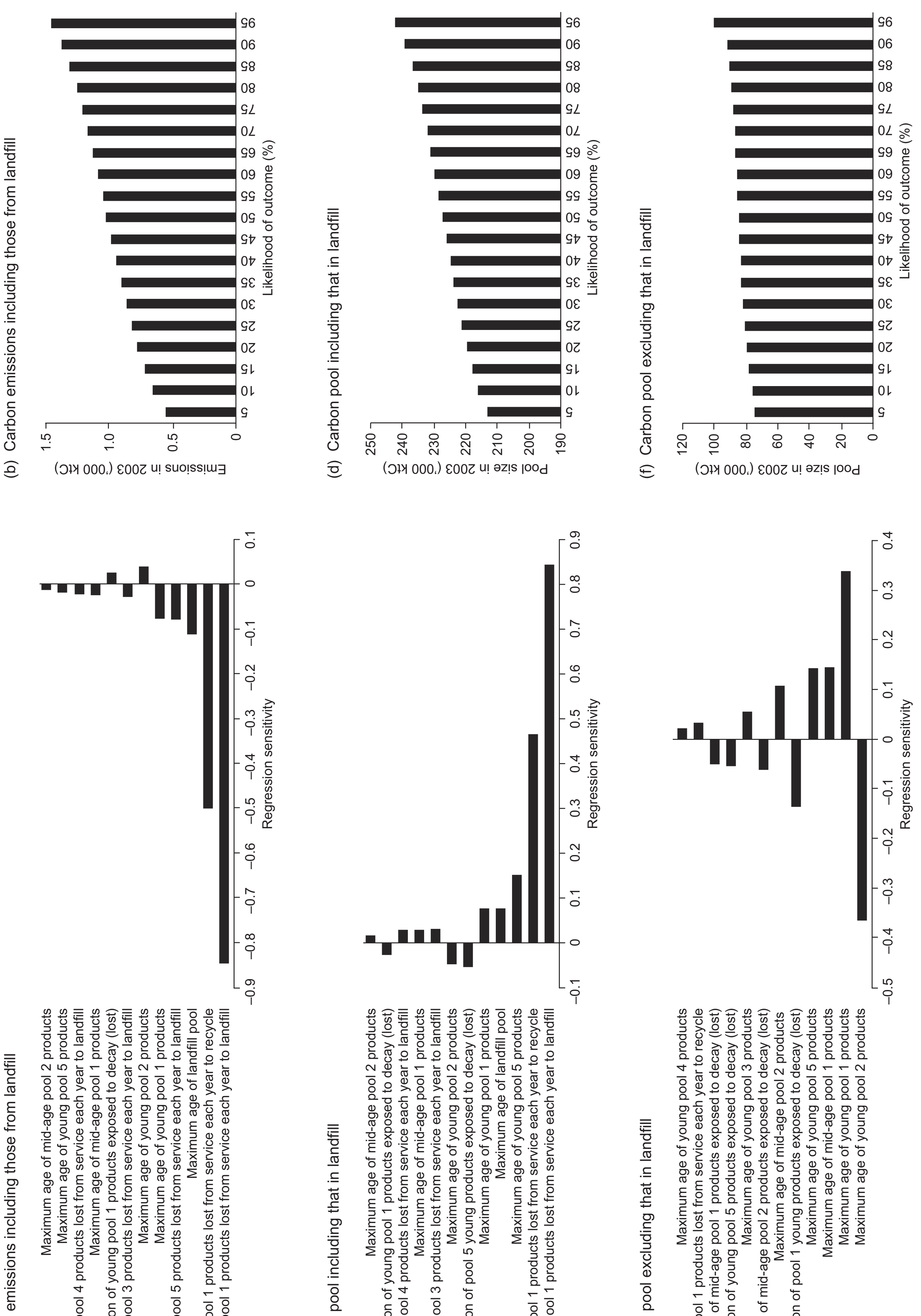

Figure 2. Results of the @Risk sensitivity analysis for the 'wood products produced in Australia' accounting approach. The tornado graphs are truncated at 12 factors. Negative sensitivity indicates a negative correlation with the output result.

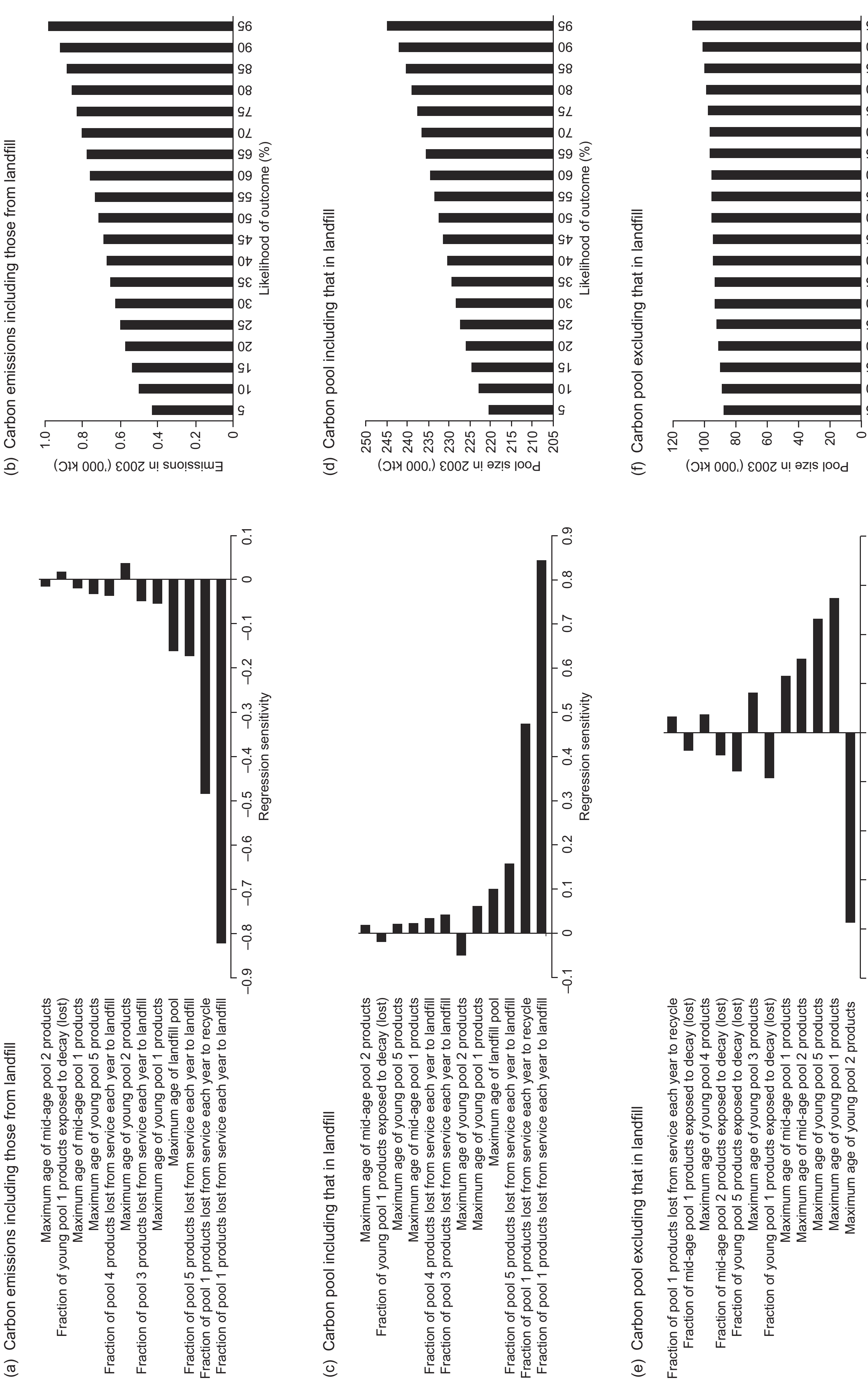

Figure 3. Results of the @Risk sensitivity analysis for the 'wood products stored in Australia' accounting approach. The tornado graphs are truncated at 12 factors. Negative sensitivity indicates a negative correlation with the output result.

the rates of input material, future annual emissions from this carbon store could potentially exceed inputs.

The emissions estimates derived in this paper consider only carbon pools and carbon pool changes (losses being considered as emissions); no corrections for global warming potentials have been applied. If the forms of gas containing carbon in emissions are considered, atmospheric emissions in the form of methane have a global warming potential (CO_2 equivalence) 21 times that of CO_2. Losses of carbon as methane would therefore be of potential significance.

The effects of the accounting approach ('emissions at harvest', 'wood products produced in Australia', or 'wood products stored in Australia') show that adopting the method that presumes emissions at harvest gives a greater emission than other approaches. This difference in outcome reflects the real-world delay in actual emissions following harvest because many wood products are stored in service for a significant time; the delay is increased when retention in landfill is also considered.

Highest emissions arise from the effects of 'wood products produced in Australia' compared with 'wood products stored in Australia'. This would be expected because Australian exports tend to be short-term (pulp and chip) products, while imports are longer-term products. The results highlight the importance of landfill as a carbon storage mechanism, and the uncertainties associated with this store. This uncertainty, and the possible effects on greenhouse gas emissions of increased methane production (though potentially captured on emission) point to clear directions for future research.

Priority areas for further research and development identified during the model development and sensitivity analysis include:

- the lifespan of timber products (both long-term products such as framing timber in housing and products with a shorter lifespan such as paper and packaging)
- the methods of final disposal of wood products, some of which (for example, landfills) may significantly extend the life of products before carbon release
- the rate and extent of decomposition of wood and paper in landfill
- the method for determining the level of carbon sequestered in housing
- the fraction of carbon that is lost as either carbon dioxide or methane.

References

Brown, S., Lim, B. and Schlamadinger, B. (1998) *Evaluating Approaches for Estimating Net Emissions of Carbon Dioxide from Forest Harvesting and Wood Products*. Meeting Report, IPCC/OECD/IEA Programme on National Greenhouse Gas Inventories, Dakar, Senegal, 5–7 May 1998. http://www.ipcc-nggip.iges.or.jp/public/mtdocs/pdffiles/dakar.pdf.

Gifford, R. (2001) *Carbon Content of Above-ground Tissues of Forest and Woodland Trees*. NCAS Technical Report No. 22. Australian Greenhouse Office, Canberra, 28 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.

IPCC (Intergovernmental Panel on Climate Change) (1997) *Greenhouse Gas Inventory Workbook*: *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*. Institute for Global Environmental Strategies (IGES), Hayama, Kanagawa, Japan.

IPCC (Intergovernmental Panel on Climate Change) (2003) *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. Penman, J., Gtarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. and Wagner, F. (eds). Prepared by the National Greenhouse Gas Inventories Programme. Institute for Global Environmental Strategies (IGES), Hayama, Kanagawa, Japan. http://www.grida.no/climate/gpg/english.htm.

IPCC (Intergovernmental Panel on Climate Change) (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories. Vol. 4. Agriculture, Forestry and other Land Use*. Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T. and Tanabe, K. (eds). Prepared by the National Greenhouse Gas Inventories Programme. Institute for Global Environmental Strategies (IGES), Hayama, Kanagawa, Japan.

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.

Palisade Corporation (1997) *@Risk for Windows*. Version 3.5.2 Newfield, NY.

Pingoud, K, Perala, A.-L., Soimakallio, S. and Pussinen, A. (2003) *Greenhouse Gas Impacts of Harvested Wood Products: Evaluation and Development of Methods*. Espoo 2003. VTT Tiedotteita – Research Notes 2189, http://www.vtt.fi/vtt_show_record.jps?target=julk&form=sdefe&search=48482, 136 pp.

UNFCCC (United Nations Framework Convention on Climate Change) (1997) *The Kyoto Protocol*. Reprinted as UNEP/IUC/98/2, 1998, Climate Change Secretariat, Bonn, Germany. Also http://unfccc.int/resource/docs/convkp/kpeng.pdf.

UNFCCC (United Nations Framework Convention on Climate Change) (2002) [Marrakech Accords]. *Report of the Conference of the Parties on its Seventh Session, held at Marrakesh from 29 October to 10 November 2001. Part one: Proceedings; Part two Addendum — Action taken by the Conference of the Parties. Volume I. and II.* United Nations, Geneva. Documents FCCC/CP/2001/13, FCCC/CP/2001/13/Add.1, FCCC/CP/2001/13/Add.2. http://unfccc.int/resource/docs/cop7/13.pdf, 68 pp.

UNFCCC (United Nations Framework Convention on Climate Change) (2003) *Estimation, Reporting and Accounting of Harvested Wood Products*. Technical Paper FCCC/TP/2003/7, 23 October 2003. Available from site library http://unfccc.int/documentation/documents/advanced_search/items/3594.php.

USEPA (US Environmental Protection Agency) (2006) *Inventory of US Greenhouse Gas Emissions and Sinks: 1990–2004*. The Agency, 1200 Pennsylvania Avenue, NW, Washington DC, USA.